

SPECIAL REPORT 218

TRANSPORTATION IN AN AGING SOCIETY

*Improving Mobility and Safety
for Older Persons*

Volume 2



Transportation Research Board
National Research Council



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SPECIAL REPORT 218

TRANSPORTATION IN AN AGING SOCIETY

***Improving Mobility and Safety
for Older Persons***

**Volume 2
Technical Papers**

**Committee for the Study on Improving Mobility
and Safety for Older Persons**

**Transportation Research Board
National Research Council
Washington, D.C. 1988**

Transportation Research Board Special Report 218

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Printed in the United States of America

1988

Second printing January 1990

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study was supported by funds from the National Research Council Fund, a pool of private, discretionary, nonfederal funds that is used to support a program of Academy-initiated studies of national issues in which science and technology figure significantly. The NRC Fund consists of contributions from a consortium of private foundations including the Carnegie Corporation of New York, the Charles E. Culpepper Foundation, the William and Flora Hewlett Foundation, the John D. and Catherine T. MacArthur Foundation, the Andrew W. Mellon Foundation, and the Rockefeller Foundation; the Academy Industry Program, which seeks annual contributions from companies that are concerned with the health of U.S. science and technology and with public policy issues with technological content; and the National Academy of Sciences and the National Academy of Engineering endowments.

This study was also sponsored by the Federal Highway Administration and the National Highway Traffic Safety Administration of the U.S. Department of Transportation, the Administration on Aging of the U.S. Department of Health and Human Services, Motor Vehicle Manufacturers Association, 3M Foundation, Hartford Insurance Companies, and Amerace Corporation. The contents of the report do not necessarily reflect the position or policy of the federal government; no official endorsement should be inferred.

Library of Congress Cataloging-in-Publication Data

National Research Council (U.S.). Transportation Research Board,

Committee for the Study on Improving Mobility and Safety for Older Persons.

Transportation in an aging society : improving mobility and safety for older persons / Committee for the Study on Improving Mobility and Safety for Older Persons.

p. cm.—(Special report / Transportation Research Board, National Research Council ; 218)

Contents: v.1. Committee report and recommendations — v.2. Technical papers.

ISBN 0-309-04664-5 (set)

1. Aged—United States—Transportation. 2. Aged automobile drivers—United States. 3. Traffic safety—United States. I. Title. II. Series: Special report (National Research Council (U.S.). Transportation Research Board) ; 218

HQ1063.5.N37 1988

362.6'3—dc 19

88-23497

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Study on Improving Mobility and Safety for Older Persons

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Preface

The quality of life in any society is reflected in that society's treatment of its older members. This study is about the needs and problems of older Americans in relation to our system of roadway transportation. The project was initiated in June 1986 by the Transportation Research Board (TRB), which appointed a committee of experts to review the design and operational features of that system and to recommend steps toward improving the mobility and safety of older persons—drivers, passengers, and pedestrians—all of whom are an integral part of the system.

Some months later Congress responded to the growing national concern about older drivers by including in the Surface Transportation Assistance Act of 1987 a request for “a comprehensive study and investigation of (1) problems which may inhibit the safety and mobility of older drivers using the Nation's roads and (2) means of addressing these problems.”

The study committee comprised authorities in gerontology, medicine, highway engineering, vehicle design, traffic operations, urban planning, public transportation, driver education, licensing, and related areas. Their intention was to

1. Evaluate available data and research on the safety needs of the older person in traffic;
2. Identify potential measures to improve highways, vehicles, driver and pedestrian performance, and alternatives to the private automobile;

3. Weigh the public policy questions about costs, trade-offs between safety and mobility objectives, and the sometimes conflicting needs of individuals, different age groups, and the public generally;
4. Recommend improvements in highway conditions, vehicle design, licensing, testing, educational activities, and transportation alternatives; and
5. Identify promising areas for further research.

In short, this was probably one of the most ambitious programs ever undertaken on behalf of elderly drivers, riders, and pedestrians. Financial support was obtained from government agencies, private industry, and the National Research Council.

After hearing the opinions and suggestions of the committee members; consulting with professionals from relevant outside organizations, public and private; and making an intensive search of the appropriate literature, the TRB staff produced preliminary background papers and an annotated bibliography to help identify the issues.

On the basis of their expertise and interests, committee members were assigned to one or more of four subcommittees: Driver and Pedestrian, Environment, Vehicle Design, and Mobility. The subcommittees identified topics in need of study and recommended to the full committee those deemed most important for evaluation.

The full committee then ranked the topics and identified 12 for further exploration. Technical papers on these topics were then commissioned from 12 experts in the field. The chief criteria for selection of topics were (a) potential for a large beneficial impact on mobility or safety, or both; (b) cost-effectiveness; (c) freedom from legal or administrative barriers; (d) strong support from research data; and (e) minimum adverse effects on the younger driving population.

An international colloquium on Improving the Mobility and Safety of Older Persons was convened by TRB in October 1987. The commissioned papers were sent in advance to the 75 invited participants—committee members, allied liaison members, and recognized authorities on the topics covered. The basic purposes of the colloquium were to (a) help the authors of the technical papers clarify and modify their text and recommendations

and (b) assist the committee in creating its recommendations. The colloquium was planned so that authors, moderator-facilitators, and discussants would interact toward these ends.

Deliberations were recorded in full and were useful to the committee in preparing its recommendations. The committee emphasized the idea of a *workable* plan, and concentrated on what can and should be done now. It also pointed out what still needs to be determined before a program can be implemented. Although recommendations were based on fact, when it could be found, in some cases the lack of data led the committee to rely on a consensus of the best judgments of its members for conclusions and recommendations.

The products of the study are organized into two volumes. The first contains an overview of the issues and the committee's recommendations; the second contains the technical papers prepared for the study.

Exercising what I hope is a chairman's privilege, I call special attention to the recommendation that, in my view, touches but goes beyond all others—the creation of an organization to follow up on the recommendations of this report and to encourage and guide whatever research may be required to address the transportation needs of an aging society.

Serious groups have in the past tried to deal with the mobility and safety needs of older persons, but their efforts have fallen short. Their recommendations have, even as have those in this report, cut across different federal agencies and all levels of government and national associations, but unfortunately there was no central direction to influence implementation of programs and research. The committee wishes to avoid that deplorable outcome. The recommendations in Volume 1 of this report were created only after the investment of considerable time and great effort by many authorities and organizations. They deserve a better fate than to spark briefly and then be allowed to expire. A follow-up organization would, we believe, encourage a persistent effort toward our goal of improving mobility and safety for older persons.

In all phases of this project, the TRB staff could not have been more helpful to the committee. The study was conducted under the overall supervision of Robert E. Skinner, Jr., Director of Special Projects. Stephen R. Godwin, Senior Program Officer, was responsible for day-to-day management and drafted most of Volume 1 under the guidance of the committee. Malcolm Quint, Research Associate, drafted Chapter 2. Darlene Yee

was most helpful in organizing the colloquium, and Peter G. Koltnow provided valuable guidance to both staff and committee.

Special appreciation is expressed to Nancy A. Ackerman, TRB Director of Publications; to Naomi Kassabian, Associate Editor, for editing the report; and to Frances E. Holland for providing word processing support.

The liaison representatives of other organizations also made numerous contributions. Special thanks are in order for the extra efforts of Glenn Crawford, American Association of Motor Vehicle Administrators; Elaine Petrucelli, American Association of Automotive Medicine; and Michael Smith, National Highway Traffic Safety Administration.

Many other persons assisted the committee. Anthony DeLorenzo of the Oregon Department of Motor Vehicles made many thoughtful comments at the colloquium, as did Hugh McGee of the firm of Bellomo-McGee, Robert Dewar of the University of Calgary, Robert Henderson, and Frank Kenel of the American Automobile Association. Grace Hazzard of the National Highway Traffic Safety Administration provided special data on traffic injuries and fatalities.

These persons, along with friendly and spirited committee members, displayed so much interest and contributed so generously that chairing the committee turned out to be both a privilege and a pleasure.

James L. Malfetti
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Significance of Mobility for the Well-Being of the Elderly

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The goal of this paper is to integrate information about the mobility of older adults with that on their well-being and the quality of their lives. Toward that end, the literature on human adaptation and the gerontological literature on emotional and social well-being are reviewed, and a conceptual model is derived from knowledge about the meaning, determinants, and dynamics of well-being among the elderly. Then studies on their mobility are reviewed within the framework of the model. Social and emotional well-being is defined by the presence of such variables as positive self-esteem, feeling of usefulness, and happiness and the absence of loneliness, anxiety, and depression. Well-being depends on the individual's success in meeting his or her own needs, and this is largely determined by the degree of congruence, or fit, between needs and community resources. Mobility is discussed as a key element in the congruence term. Qualities of mobility that influence its effects on well-being are presented: feasibility, safety, and personal control. Studies of each major transportation mode are reviewed in terms of these qualities, and modes are compared on them. Other variables affect the qualities of mobility: the person's socioeconomic status, physical characteristics of the site, and transportation technology. These are discussed as moderators in the model. The final section comprises conclusions and recommendations for research.

Throughout the paper it is essential to keep in mind the heterogeneity of older Americans today and the future changes that will alter relationships of

age to other variables. Generalizations are presented, but this does not imply homogeneity. Older persons are more different from each other than are persons in any other age group. However defined, the old have a wide age range. For example, retired groups include parents and their children. With regard to any characteristic, diversity may be as great within as between age groups. Changes in older persons accompany alterations in the population's age structure.

Mobility as a major determinant of well-being among older persons has recently become a prominent issue. Several lines of evidence have attracted public attention, including perceptions by older persons, a closer look at housing for the elderly, and research showing decreases in both mobility and well-being with age.

Transportation was the "sleeper" issue at the 1971 White House Conference on Aging (1). Conference planners did not expect it to be a major issue, but delegates ranked transportation third in importance, preceded by income and health. Research confirms that, in general, older persons are not satisfied with their ability to get around in the community (2-5).

Housing for the elderly has been a focus of attention since the late 1950s, and its relevance to their well-being has been documented. "Housing for the elderly" is defined broadly to include the entire living environment. Thus, mobility plays a vital role in this domain by determining accessibility of community resources. Siting studies have shown that residents of retirement housing may sit home and look across an expressway at services and facilities accessible only to those with automobiles (6). In another study, some applicants who were offered apartments in a fine, new public housing facility for the elderly decided not to move in after a tour of inspection because, although the project offered a tremendous improvement in housing, it was surrounded by a slum (7). Most tenants considered the location undesirable, and ratings became more negative over the first 8 years of occupancy. Tenants complained about the scarcity of stores, churches, and eating places, and they feared going out on the street in that part of town to those that existed. The only "convenient" characteristics of the housing project were those that enabled them to meet their needs elsewhere: buses that stopped at the front door and being within walking distance (0.7 mile) from the central shopping district. "The quality of later life depends upon the quality of housing and environment, *made dynamic by transportation*" (7, p. 128).

Older persons make fewer and shorter trips than younger persons (4, 8). Reductions in rate and territorial range of mobility may reflect preferences. A third of all trips and about 40 percent of all vehicle mileage are related to work, and retirement may bring a welcome cessation of that travel (5). However, subtraction of work trips does not equalize travel totals between age groups. Moreover, reduced mobility among older persons is accompanied by

lower self-esteem, feelings of uselessness, loneliness, unhappiness, and depression (9). The fact that decreases occur simultaneously in mobility and well-being does not guarantee that one causes the other. However, such coincidence does suggest that the relationship merits investigation.

Thus, three lines of evidence point to the relevance of mobility to well-being in later life: the views of older people about its importance in their lives and their dissatisfaction with it, recognition that the quality of housing for the elderly depends in part on siting that provides safe access to services and facilities, and research showing diminutions in both mobility and well-being with age. In order to improve the effects of mobility on well-being, it is necessary to understand how these effects occur. The following section outlines a conceptual model of the determinants and dynamics of emotional and social well-being to provide the context for reviewing mobility studies.

A CONCEPTUAL MODEL

It has long been axiomatic that well-being depends on the individual's success in meeting her or his own needs (10–13). The Ecological Model of Aging (14) deals with the interaction between abilities of older people (with regard to health, sensory-motor functions, etc.) and environmental characteristics in the performance of tasks of daily living. Congruence models (15, 16) focus on the degree of fit between needs and environment. Each of these models is partial. The ecological model seems relevant primarily to the frail elderly, who are the minority, and to their maintenance of independent living, which is supportive of but not sufficient for well-being. The congruence models were developed to fit institutionalized groups and reflect their needs and special environments.

The model that provides the framework for this paper is based on general adaptation theory and includes the concepts of the ecological model and the congruence models. It incorporates the needs, abilities, and community environments of the majority of older persons (17, 18). The relationship between needs and environmental resources that determines how well needs will be met is that of congruence. Today, people must go into the community for almost everything they need. The existence of facilities and services is meaningless without access to them. Mobility is a key function in determining the degree of fit between need and resource for meeting it.

The qualities of mobility that facilitate the meeting of needs and thereby support well-being are (a) its feasibility for the person, which includes his or her abilities to perform the activities involved; (b) its safety; and (c) the sense of personal control it provides, that is, the degree to which it enables individuals to meet their needs independently. The feasibility, safety, and personal control of mobility are affected by (a) the socioeconomic status of the person (income may limit the type of transportation available); (b) physical characteristics of the site (severe weather or steep hills, or both, are barriers for older

drivers and pedestrians); and (c) transportation technology (power steering may compensate for loss of upper-body muscle strength; hand controls may allow paraplegics to drive their own automobiles). Figure 1 outlines the model. Its components are explained more fully below.

HUMAN NEEDS AND COMMUNITY RESOURCES

Well-being, as contrasted with mere existence, depends on satisfaction of two categories of needs: those whose satisfaction is requisite to independent living and those whose satisfaction is necessary to give life an acceptable and positive quality. Life-maintenance needs include nourishment, clothing, medical care, pharmaceuticals, and banking. Community resources for meeting them are food stores and other stores, physicians' offices, pharmacies, and banks. Unless, safely and through their own efforts, people are able to gain access to these resources, they cannot live independently. Institutionalization is strongly undesirable to older persons and negatively affects their well-being (9).

Other needs, sometimes labeled "higher-order," include those for social interaction, usefulness, recreation, and religious experience. There is a tendency to downplay this category. In one study (4) the most common trip purpose among older persons was "shopping/personal business"; few trips were work related, and other frequently mentioned trip purposes were "relaxation/enjoyment" and "religious activities." The investigators considered the latter trip purposes "unessential." Work (during employed years), shopping, getting medical care and medicines, and banking are requisite to independent living, but when well-being is at issue—that is, if life is to have an acceptable quality—higher-order needs such as those expressed in trips for relaxation and enjoyment and religious activities are also "essential."

The need for social interaction continues in later life. Although only 5.5 percent of the population under 65 lives in single-person households, this figure rises to 29.4 percent of those 65 and older (19). Older people are therefore more dependent on mobility to meet this common human need. The high incidence of loneliness among the elderly (9) suggests that, for many, affiliative needs are not met. Among two samples of older adults, loneliness (measured by a standard scale) was related to poor emotional and social well-being (20). Unlike the lonely young, the lonely old behaved in ways likely to inhibit restoration of social networks following a personal loss. They did not make plans or learn about available community health and social services. They tended to be anxious and depressed and to have low self-esteem.

During employed years, work not only provides opportunities to be with others, it also demonstrates usefulness. With retirement, customary bases for both aspects of well-being are lost. The prevalence of feelings of uselessness

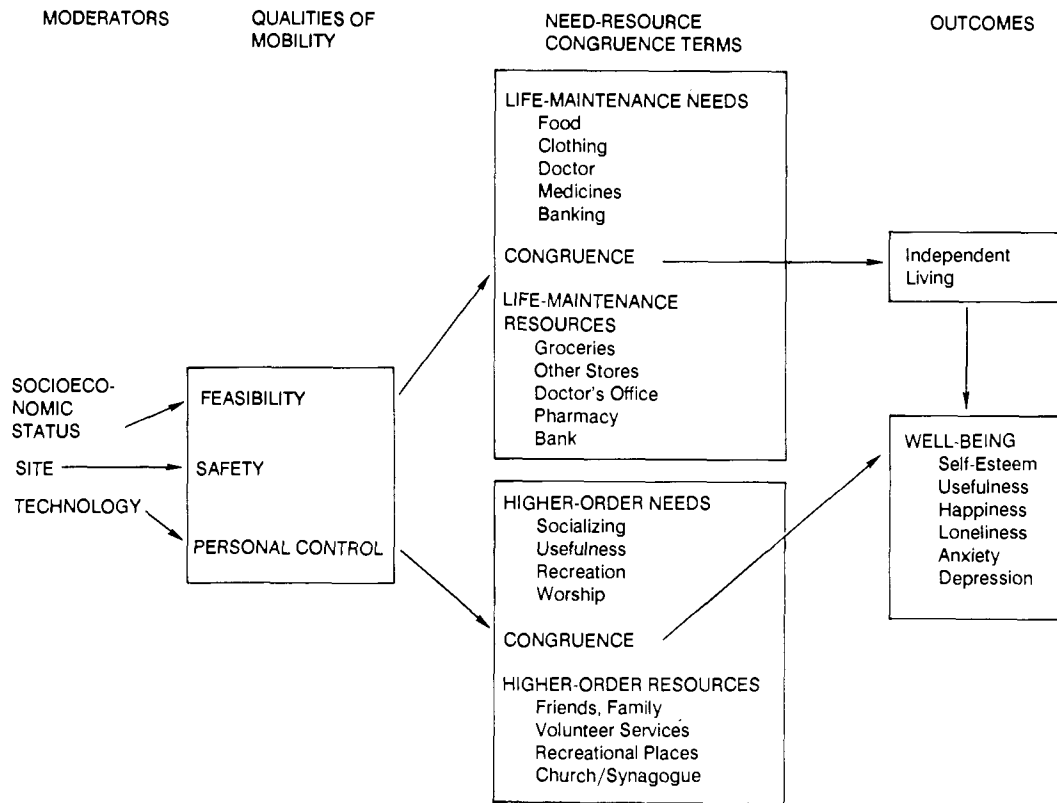


FIGURE 1 Conceptual model.

among older people (9) suggests that new bases are not found. Feeling useless is tied to lack of societally valued activities and is associated with diminutions in happiness and self-esteem (21).

QUALITIES OF MOBILITY

Satisfaction of both life-maintenance and higher-order needs requires going out into the community. Meeting basic needs depends not only on the presence of food stores and other stores, physicians' offices, pharmacies, and banks but also on the person's access to them. Resources for meeting higher-order needs are defined not only by the location of providers (e.g., churches and synagogues, places of entertainment, relatives and friends) but also by their accessibility.

Mobility is a key influence on the congruence term in the model. It largely determines the fit between a person's need and resources in the community by which it can be met. The qualities of mobility that influence its effects on social and emotional well-being include its feasibility, its safety, and the personal control experienced by the traveler. All three factors vary according to mode of transportation; thus, in the following sections each mode is discussed separately.

Feasibility for Meeting Needs

Other papers in this volume deal with specifics of age-related health problems, decrements in sensory-motor functions, and details of transportation design and management that may be problematic for persons with various impairments. Here, primary concern is with older people's perceptions of their limitations in traveling, and of travel conditions that create difficulties for them.

Automobile Driving

As Drivers People are aware of changes in their abilities and of driving situations that become more difficult as age advances. In one metropolitan area survey, problems for older drivers listed by the majority of respondents included visual problems (82 percent); slowing of motor response (75 percent); stiffness and crippling, especially by arthritis (62 percent); and difficulty adjusting to new situations (55 percent). Statistically significant proportions also mentioned decreased alertness and slowing of thinking (22). A survey in a different metropolitan area confirmed these results (23). In both, driving conditions perceived as especially problematic were speed, traffic congestion, complex and confusing signs, unfamiliar streets, and freeway interchanges.

Respondents generally considered speed an inevitable evil about which little could be done. Traffic congestion was thought to be controllable by improved street and highway design and more efficient traffic control. Respondents found no excuse for the proliferating and sometimes seemingly contradictory signs and signals at urban intersections, and most believed that they could deal with unfamiliar streets and freeway interchanges if these were more adequately marked. Street names are inconsistently located, often hidden by trees or other obstacles, and may be difficult to read. On unfamiliar freeways signs may not provide enough information for maneuvering into the proper lane to transfer to another freeway or exit.

Respondents perceived visual problems as the most serious. Losses in night vision were accommodated by reducing night driving to short trips in familiar territory or by eliminating it. Many believed that better printing, placement, and lighting of street signs would enable them to drive safely after dark without becoming lost. The temporary blinding effect of oncoming cars could be reduced by proper installation of headlights and drivers' switching them to low. The driver in a hurry to pass should not tailgate with lights turned up high in an attempt to force another driver to the right when it is impossible to change lanes safely.

Older drivers are extremely apprehensive about losing their licenses (24). The loss would mean inability to go where they needed to go and therefore meet their needs independently. It would mean inability to provide rides to others and so to feel useful. It would make them "feel old," which is negatively related to social and emotional well-being (25). Ex-drivers reported much more difficulty in getting places they needed to go than did drivers, and even somewhat more than persons who had never driven (24). They felt ineffectual, dependent, and demeaned.

Driving is the only mode of transport whose feasibility is determined by official decree. Just as receipt of the first driver's license is an important rite of passage to adulthood and independence, license loss formally identifies one as "over the hill." Age is sometimes used in studies as a stand-in for mobility competence. This is convenient but not accurate. "Age-related" changes are statistically defined: at a given time, older groups tend to score lower on some mobility-related efficiencies. Scores are not uniform across persons in any age group. Correlations with age may change over time. Levels of efficiency relevant to driving, not age, should determine licensure.

Those older individuals whose driving is greater than average for their age, thus resembling that of younger drivers, have accident rates similar to those of other age groups with similar mileage (26). Deterioration of driving skills through disuse among less frequent drivers may affect group rates. Self-assessment inventories (27) and courses of instruction (28, 29) may help older drivers identify and deal more effectively with their problems. Medical advances are reducing the correlations between age and some driving abilities.

For example, improvements in cataract removal and lens implantation enable some persons in their eighties to have restrictions removed from their licenses.

As Passengers Those without automobiles who have physical problems using public transit and walking are most likely to depend on rides (30). Rides are important in providing access to places they need to go, which otherwise would be difficult or impossible to reach. The main problem in feasibility, that is, provision of mobility adequate for meeting one's needs, is insufficiency. Requesting additional rides is inhibited because the riders generally are unable to reciprocate and thereby maintain the give-and-take that is requisite to healthy interpersonal relationships. Consequently, the passenger not only feels dependent but also suffers loss of social equity and therefore self-esteem.

Public Transportation

A major dissatisfaction with public transit is that it frequently does not provide access to the places and at the times older people need to go (22, 31). Transit systems are designed primarily for work commuters, and routes and schedules often do not meet the travel needs of retired persons. Proximity to the stop for "the bus that takes me where I want to go" is critically important; location of "any other bus stop" is irrelevant (32).

The match of abilities with activities involved in using public transit varies with the type and design of transit and the physical condition of the individual. A study in Great Britain compared bus use between retired persons who had physical difficulties in walking and retired persons without such difficulties (33). Interestingly, "the 44 percent of the sample who had physical difficulties with walking, walked more and used buses less than those without such difficulty" (p. 3-23). The physical conditions identified with difficulty in walking obviously made transit use even more difficult than they made walking. The majority (56 percent) of those with walking difficulties and 39 percent of those without such difficulties reported problems in using a bus. Getting to the bus stop and waiting there were about equally problematic to those with and without walking difficulties. However, getting on and off the bus was difficult for more of the former (27 percent) than the latter (11 percent). The validity of the "walking difficulty" measure is questionable in view of the fact that those with difficulties walked more than those without. "Bus-use difficulty" measures should include valid items on walking and on additional factors such as mounting and dismounting steps.

In a bus-use study in this country that did not include walking, ability-activity incongruences were observed at each trip segment studied (34). The wait for the bus was tiring, a drain on the lower energy of older riders. Entering the vehicle was a problem because of the greater agility, strength, and speed of other passengers, which made it difficult to negotiate steps and

enter vehicles before the doors closed. The ride was tiring, especially if one had to stand. In walking to seats or standing in a moving bus, older users had trouble keeping their balance. In alighting they perceived their disadvantages relative to younger passengers—10 percent volunteered that they needed help.

The consensus in this study was that engineers should be able to design steps more easily negotiable by older persons that would not create problems for the young, and sensors that would detect persons in the entry or exit and prevent vehicle doors from closing or drivers from moving the vehicle. Transit aides could ease older persons' problems in entering and leaving vehicles, especially with packages, and would be looked on as extenders of older users' independence (34).

Walking

Older residents of San Antonio (35) and San Francisco (36) reported that too many of their destinations are too far away for them to walk. In describing the ideal situation, older women living alone in Oakland would have most of the 37 listed services and facilities "within walking distance" (37). A major source of dissatisfaction with their existing situations was that many of these resources were beyond walking range.

Food is a basic need, and grocery shopping is an almost universal trip purpose among community-resident elderly. In San Antonio, food stores were beyond walking distance for most (35). In San Francisco, a high percentage walked to the grocery (36). In that hilly city, they could carry only light loads, which often necessitated an undesirably high frequency of trips for food. Moreover, adequacy of diet (on a food diary scored by a dietitian) was negatively related to the slope of the street on which the respondent lived. In neither city did walking provide satisfactory access to facilities for meeting basic nutritional and other needs. Ratings of walking were most favorable among persons who drove everywhere and least favorable among the most foot dependent.

Safety

Automobile

As Drivers There are two separate concerns associated with safety in driving: risk of accidents and danger from crime. Older persons rate the automobile high on "worry about accidents" and equally high on "feel protected from crime" (38).

In terms of rate per vehicle mile, the total elderly age group has more accidents than any other age group except the youngest (26, 29). When involved in accidents, older drivers are much more likely to suffer injury or

death (29). They are five times as likely to be killed in an accident involving another driver under the age of 20, and two and one-half times as likely to be killed when the other driver is aged 50 to 55 (26). Older drivers of small cars are more likely than are younger drivers to be killed when colliding with another small car or a larger one (26). These findings point to the greater physical vulnerability of older persons generally in the driving situation.

Awareness of danger may be a factor in the reduced driving of older drivers and their worry about accidents and may be reflected in reports of "nervousness" (75 percent in one sample and 80 percent in another) and "lack of confidence" (58 percent and 63 percent) (22, 23). However, the automobile insulates travelers against hazards of personal assault such as purse snatching to which walking and using public transit would expose them. Thus, persons who can drive prefer to do so, rather than riding as passengers, because they feel safer when they are in the driver's seat (24). Sitting at the controls of a powerful vehicle that can be locked from the inside seems the safest way to travel.

As Passengers The greatest drawback to feeling safe is distrust in the driver's skill (30). Fears must be suppressed because alternatives are not available. Showing nervousness might jeopardize future rides. Most who offer rides are relatives or friends, and the value of the personal relationship prohibits derogation of the driver's competence. Hence: "I close my eyes and hope for the best" or "I just pray." Fear for safety is prevalent among passengers and they must endure it in silence. The emotional cost may be high.

Public Transportation

Older persons fear being injured in falls or struck by doors when entering and leaving public transit vehicles, and falling by losing their balance during the ride (34). They do not worry about vehicular accidents in bus travel, but perceive the bus as leaving them extremely "unprotected from crime" (38).

Official records probably underestimate crime and fear of crime as deterrents to use of public transit by older persons. The Uniform Crime Reporting (UCR) system does not record the activity under way during commission of a crime or the location, and most police departments do not categorize crime by transit use. Transit providers are responsible for crimes committed on property under their jurisdiction, and this is reflected in their record keeping. Both police and transit systems depend on the public to report crimes. From the viewpoint of an older person considering use of a community resource that involves a trip via public transit, the trip also includes the walk to the vehicle stop and the wait there, plus the walk back home. Fear of criminal victimization during any segment of the trip may inhibit use of transit, and incentives

for reporting incidents experienced or witnessed may be weak. In Los Angeles, police officials considered bus crime to be a small fraction of total crime, but researchers found that 25 to 30 percent of crime reported in home interviews was related to bus travel (39). Interview-reported crime on buses and at or near bus stops was 20 to 30 times higher than that recorded by the transit agency. Over half the crimes reported in interviews occurred before victims entered or after they left the vehicle.

The elderly were more vulnerable to bus crime than any other age group; the more frequently they rode a bus the more likely they were to be victimized (40). More than one in four older people who took a bus daily were victimized between 1982 and early 1984. This is poignant in view of data from two different cities (22, 23): older people who drove automobiles rated public transit very favorably; those who rode the bus gave it low marks—the more frequently they took a bus, the lower the rating. Most victimization during bus use occurred at a few sites at certain hours. Intervention at those places and times should be effective and economical in reducing the overall victimization rate (39).

Is the fear that inhibits use of public transit rational? In the Los Angeles data, fear of transit crime was a function of the same variables as was actual crime. Direct assessment of the effects of fear on bus use was impossible, “primarily because so many of our respondents had no alternative” (40, p. 29).

Wachs (5) objects to stereotyping the elderly as “transit dependent” because only about a third do not have access to automobiles. However, research documents the hazards to older persons who use the bus as well as the fact that many have no option in attempting to meet their needs. It is inappropriate to label the entire elderly population with any tag; descriptors such as “transit dependent,” “poor,” or “frail” fit only some segments of that population. Nevertheless, the situations of those for whom the label is appropriate must not be ignored. Older persons who must rely on public transit are at risk of criminal victimization, regardless of whether they represent a majority of their age peers.

Walking

Fear for their safety while walking was expressed by about two-thirds of older persons in two metropolitan areas (35, 36). They were afraid of being attacked by people or dogs, being hit by a car, and falling. These fears are not unfounded. Elderly pedestrians are about twice as likely as younger walkers to be involved in accidents (41). Those involved in accidents are more likely than younger persons to be injured, and their injuries are more serious (42). Elderly pedestrians suffer five to seven times as many fatalities as do younger persons on foot (43).

In the view of older persons, "pedestrian territory" should be safe from invasion by vehicles (6). Where it is necessary for pedestrians and vehicles to share space, rights-of-way should be clearly indicated and enforced. Signs should be visible and unambiguous. Signals, especially when time intervals are involved, should allow for the rights of pedestrians as well as drivers.

Personal Control

The sense of mastery is basic to well-being. Experiencing loss of control over events leads to feelings of helplessness, dependence, incompetence, and depression (44–46), all of which are widespread in the older population (9). Among older persons, perceived control is negatively related to psychological distress (47) and positively related to emotional and social well-being (48).

Gonda (49) reviewed the literature showing that absence of driving one's own car and consequent dependence on public transit are associated with lower life satisfaction, poorer adjustment, loneliness, and lower activity levels, whereas driving, as compared to depending on others for rides, is linked to higher levels of satisfaction. She concluded that transportation modes affect well-being differentially through the degree of personal control they provide. She attributes the greater well-being among drivers to the fact that driving one's own car supports one's sense of personal control at a stage of life when other supports have been lost. "Driving may be one of the few areas in an older person's life where they can still 'call their own shots'" (p. 65). In a direct comparison of the automobile and public transit on the degree to which travel "makes one feel free and independent," older people rated the automobile much more favorably (38). Gonda did not include pedestrian studies in her review, and walking was not included in the comparison study. However, "independence" was perceived as an advantage of walking by 85 percent of a sample of persons 65 and older (36).

Summary of Mobility Qualities

A century ago, people could walk to work, shops, others' homes, religious services, and most other destinations. In this century "the city has been transformed by transportation technology" (5). Few destinations lie within walking distance for any person, and physical deficits that accompany aging may shorten distances traversable on foot. Walking is perceived to be, and is, unsafe. The walker may be said to have control over where and when to go, but this independence is seriously curtailed by problems with feasibility and safety. Walking earns low marks as a means of meeting one's needs—the more foot-dependent the person the less favorable the rating. The good of both old and young may lie in improving pedestrian conditions. In a study of

considerations that would be important in a prospective change of residence, San Francisco Bay Area residents 18 and older (to 98) rated 15 items (37). Although there was disagreement among age groups on the importance of automobile access to freeways and location of bus stops, "good walking conditions in the area" were "very important" to the majority of all ages.

Automobiles provide access to widely distributed services and facilities, and safety and independence, for those who can drive them. Drivers are the only elderly group satisfied with their ability to get around. Age may bring personal limitations on driving ability. Loss of license is a serious fear among drivers, a threat to their autonomy, usefulness, and self-esteem. Ex-drivers are the least able to meet their own needs. Relatively frail elderly find the supply of rides inadequate, have little control over when and where they are taken, and fear for their safety on many trips. Accepting rides reinforces loss of independence, and the necessity to suppress fears about safety is emotionally costly. Public transit routes and schedules often do not accommodate the needs of retired persons; physical deficits associated with aging make its use more difficult; it is realistically perceived as unsafe; and it does not engender a feeling of personal control. The more dependent the older person on public transit, the lower her or his ratings of that mode of travel.

The literature supports feasibility, safety, and personal control as qualities that influence the effects of mobility on well-being.

MODERATORS

Socioeconomic Status

The type of transportation available to a person—and therefore its feasibility, safety, and personal control—is influenced by factors such as income, education, ethnicity, sex, household composition, location of residence, and automobile ownership. Wachs' (50) "life-style," defined by clusters of such items, affects mobility. A "deprivation index" of such variables devised by Carp and Carp (48) accounts for significant variance in the well-being of older persons.

Automobile ownership has been identified in many studies as the most powerful correlate of mobility and satisfaction (4, 33, 50, 51). It varies according to income, sex, household composition, ethnicity, and location of residence, all of which are also related to mobility and satisfaction with one's ability to get about in order to meet one's needs (4, 33, 50, 51).

Location of residence is related to income, education, and ethnicity and affects the quality of transportation available (3, 50). The rural elderly have special problems in getting to where their needs can be met. Facilities and services are so far from home that walking is impossible; roads may be narrow and poorly paved, and public transit tends to be poor or absent (2). Most of the elderly live in urban areas. However, their numbers in the suburbs are

increasing because of both "aging in place" (52) and migration (53). Income is relatively high among suburbanites, which supports automobile ownership and driving safely and independently. Because of the distribution of community resources and the design of public transit for those who commute to work, older residents remain drivers for as long as possible (2). For the same reasons, when they become ex-drivers, their ability to meet their own needs is restricted (23). Central-city elderly were reported to make fewer trips than residents of other areas, in a study that did not include walking (50). However, in New York City (54) and in San Antonio and San Francisco (55), studies that included walking found high rates of trip taking by inner-city elderly as compared with others.

The effect of socioeconomic status on mobility is accentuated by the poor match between the transportation services and the socioeconomic status of residents in an area (50). On the basis of a 1979 study, those in Hispanic neighborhoods had very low incomes, and few had automobiles or licenses; yet bus service in those areas was poor, and taxi costs were high. Although residents of older suburbs had much greater access to automobiles, bus service was better in their areas and taxi rates were lower.

The socioeconomic status of older persons tends to be inferior to that of other age groups. Automobile ownership is lower (56). Financial resources are diminished (2). Women outnumber men; they are more likely to live alone, and older women living alone are the group with the lowest income (57). Older women are also less likely to drive automobiles (58).

Site

Differences in mobility between Houston and Miami (4) and between Ontario and Orange County (59) suggest the influence of characteristics of the data-collection site. The issue of site effects was addressed directly by testing hypotheses derived from differences between two additional areas, San Francisco and San Antonio (23). Total population size and socioeconomic status of respondents were the same between the two sites, thus removing the effects of these variables. San Antonio sprawls over the Texas plain. San Francisco is compacted into a small area, much of it hilly; residential lots are smaller and thus homes are closer together. Neighborhood groceries, other shops, and recreational facilities are more plentiful in San Francisco than in San Antonio, where stores and recreational services are clustered in major malls. San Francisco provides more complete transit coverage of residential areas and routing among them. In San Antonio public transit corridors radiate from the center, which necessitates transferring and involves greater distances and longer trip times than reaching the same destination by car. A lower rate of automobile use was predicted for San Francisco because of the deterrent effect of hills for older drivers. Walking was predicted to be more common because

of the proximity of homes to each other and to other facilities. It was expected that San Franciscans made greater use of public transit because of its proximity to their homes. The study data supported all three predictions.

Predictions on differences in frequency of trip types and mode of transportation used for them also were confirmed. San Franciscans made more trips to shop for food and other goods, to visit friends and neighbors, and to use places of recreation. Over two-thirds of San Franciscans but only one-fourth of San Antonians fetched groceries on foot. Many San Antonians (41 percent) but few San Franciscans (16 percent) did "other shopping" by automobile; transit was used for this purpose by three times as many San Franciscans (54 versus 18 percent).

The most impressive difference was in trips for recreation. Most San Franciscans (55 percent) went out for entertainment and recreation (to a club, play, movie, etc.) at least once a week, whereas only 3 percent of San Antonians went out that often. The distribution of transit was crucial. Over one-third (38 percent) of such trips in San Francisco, but only 2 percent of them in San Antonio, were by transit. The influence of neighborhood facilities is also obvious. Three times as many San Franciscans walked between home and the place of entertainment or recreation, despite the hills.

Evaluative perceptions were consistent with behavior. In San Francisco automobile driving received poorest marks (87 percent said it did not meet their needs "at all"), transit received the most favorable ratings (57 percent said it met their needs at least "fairly well"), and walking and riding as a passenger in a private car held the middle ground. In San Antonio all transportation modes received lower ratings in meeting respondents' needs. Transit and walking were given the poorest marks; driving and riding were rated relatively well.

Transportation Technology

In addition to the distribution of transportation facilities, technology moderates the fit between a person's abilities and the physical environment of travel. Studies demonstrate that age differences in performance attributed to "age-related" declines in abilities may disappear after certain technological alterations. For example, older drivers had to drive one-third to one-fourth the distance closer to a standard sign than did younger subjects to make a correct identification (60), but there was no age difference if the symbol appeared on a background having high luminescence contrast (61). For all transportation modes, such technological issues as readability of signs and timing of signals affect the feasibility, safety, and personal control of travel.

CONCLUSIONS AND SUGGESTED RESEARCH

Studies on the mobility of older persons fit well into a conceptual model based on general adaptation theory and gerontological literature on social and emotional well-being. In summary, well-being depends on success in meeting life-maintenance and higher-order needs. Satisfaction of any need depends on congruence between the need and the resources for meeting it. Mobility is a key factor in determining the degree of congruence, because community facilities and services are irrelevant if they are inaccessible. Characteristics of mobility that affect its contribution to well-being are feasibility, safety, and personal control. These properties are influenced by the socioeconomic status of the individual and characteristics of the broader environment in which she or he lives, including transportation technology.

This is a first-generation model that requires more explication and refinement. However, viewing the mobility literature within the model's framework suggests benefits from integrating what generally have been two separate lines of investigation. Understanding social and emotional well-being in the elderly may be furthered by inclusion of the mobility factor in theoretical models and study designs. Policymakers and planners may be better assisted by research that includes well-being as an outcome.

With regard to feasibility, distance to the needed destination lies within the province of urban planners and transportation providers, and research is needed to clarify the specifics of the fit between abilities of older persons and activities involved in use of each transportation mode. This requires identification of which of the many age-related changes in persons are relevant to each activity; then identification of how, in each case, feasibility of use can be improved by (a) compensations for personal deficits (e.g., cataract removal), (b) changes in transportation distribution and design (e.g., luminescence contrast of signs), and (c) education and training to enable the older person to recognize and deal more effectively with problematic situations (e.g., turning the head or using mirrors to see behind if peripheral vision is constricted).

With regard to safety, older people's fears seem realistic in view of accident and fatality rates. Efficiency and economy of attempts to improve travel safety can be improved by research. A few sites and times were identified as contributing disproportionately to bus crime in one city. Similar studies should be carried out at various sites and with all transportation modes; interventions should be evaluated. The sense of personal control experienced by the traveler needs further investigation. Such investigations should consider travelers' perceptions, which may not be obvious to planners. For example, although rides from family or friends threaten autonomy, transit aides are seen as supportive of independence.

Socioeconomic variables often are used as controls to eliminate their effects on study results. It may be preferable to interpret them as moderators and

assess their power relative to other variables. Attention should be paid to subgroups deprived on many socioeconomic variables (e.g., residents of minority-ethnic neighborhoods, older women living alone). Failure to consider site characteristics may produce discrepant results among studies and delay understanding of the role of mobility in well-being. Some site characteristics have been shown to affect mobility. Others probably should be included (e.g., climate). Site differences in transportation technology merit special consideration because they affect all qualities of mobility that underlie its effects on well-being. Research in transportation technology can dramatically improve the well-being of the elderly by increasing the congruence between abilities and activities.

In all areas of research certain considerations are important. One is the quality of the data for the study purpose. Official records are convenient and often valuable sources of data. However, care must be taken to ensure that the purpose and design of the records are consistent with those of the research. The UCR system was implemented to provide consistency of crime records throughout the nation. It was not intended to be a measure of resident experience and fear of victimization and is therefore of questionable value in drawing conclusions about the latter. In attempts to understand the roles of crime and fear of crime as deterrents to use of public transit by older persons, transit system records only give part of the story. Transit providers are no more responsible for criminal victimization during walks to and from a bus stop than are proprietors of grocery stores or providers of any other community facility or service. Transit crime records are designed for transit system needs, not to provide a full view of exposure to criminal victimization during the entire trip for the community involved.

The quality of data is affected also by the validity of instruments developed by researchers. The validity of a measure of "walking difficulty" that predicts more walking among those with difficulties is questionable. In understanding person-environment fit in bus use, an ability measure should include items relevant to performance of tasks in each segment of the trip. The same is true, of course, for other modes.

In all studies the central variable or variables of interest should be clearly identified and defined, and the appropriateness of the data should be assessed for relevance to study outcomes. For example, conclusions about overall mobility rates for residents of central cities contrasted with those of other urban areas differ between studies that do and do not include walking. Use of age as a stand-in for competence violates the basic assumption that competence-activity congruence underlies well-being. At any age, persons vary widely in mobility-related abilities; and the greater the age, the wider the variability. Correlations between age and abilities observed today may be reduced or eliminated by future changes in many areas, including medicine, socioeconomic conditions, and transportation technology.

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The Mobility Needs of the Elderly

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The ability to move about at will, to engage in social and recreational activities when desired, and to reach business and social services when needed—all are key components of the quality of life. Transportation services and facilities are part of a package that allows the elderly to perform these important functions.

Not surprisingly, many studies have noted the importance of transportation to the elderly; in 1971 the first White House Conference on Aging reported that transportation was one of the three greatest needs of the elderly. Since then a number of studies have made the same observation. Nevertheless, myths and misconceptions persist about the transportation patterns and problems of the elderly and how their mobility needs can be met. These myths act, in part, to obscure major deficiencies in assistance to the elderly—from dysfunctional land use patterns to inappropriately targeted human services. These deficiencies can reduce mobility or lower the use of needed services in ways that have little to do with transportation or that require heroic efforts on the part of transport providers.

In addition, the persistence of historical views of the elderly—either no longer valid or totally false—interferes with society's ability to increase access for the elderly to community activities.

The literature, both popular and scholarly, often represents the elderly as living at high densities in older, run-down parts of town and largely dependent on public transportation when not walking. The elderly are often portrayed as alone and lonely, without social support or resources, often lacking contact with kin and friends. When they do not use human or medical services seen as

necessary for their well-being, their behavior is often attributed to lack of transportation.

These views color societal response to the problems of the elderly. For many years commentators called for additional mass transit; today it is common to assume that specialized paratransit services run by the public sector can—and will—meet all the needs of the elderly. Few recognize the importance of supporting or augmenting the existing mechanisms used by the elderly: private cars, taxis, paid and unpaid carpools, volunteers, church groups, and so on.

The data and analysis presented in this paper effectively challenge many myths about the elderly. Although some older persons conform to every stereotype, there are far more who face different, equally problematic, situations. Failure to recognize their needs means a failure to address the mobility problems of the majority of the elderly.

Half of the elderly in this country live in the suburbs, at fairly low densities; 70 percent live in single-family homes. Another large portion of the elderly live in rural areas, where they make up a growing percentage of the total population. Most older persons drive their own cars; almost 100 percent will have driven by the turn of the century. Moreover, whether they drive or not, most of the elderly make an overwhelming percentage of their trips in private vehicles—not on transit or by walking.

Most of the elderly are not deserted by family and friends; they have frequent social contact. Thus, serious efforts should be made to strengthen those networks financially and socially, augmenting them when required. The elderly will not be well served by measures that break down their informal or family support mechanisms or destroy existing community transport options.

In spite of assertions to the contrary, there is strong evidence that the elderly do not use a variety of business and social services because they simply do not want to or cannot afford the activity in question—not because they lack transportation. The elderly who have objections to needed human services or who fail to recognize their usefulness will not begin to use such services simply because access becomes easier. Human service agencies must consider how and why they deliver services to the elderly and fashion more responsive alternatives.

Elderly people who have built a life in low-density areas on the basis of the freedom of the private car will not be well served by options that are designed for high-density communities or that do not recognize that the quality of life for the elderly depends on freedom of choice and flexibility. Planners must offer the elderly the freedom of the car as long as possible, using taxis and other paratransit options to approximate the car's flexibility.

The analyses in this paper suggest that the mobility problems of the elderly require both short-term and a long-term responses in three areas: transportation, land use planning, and human service delivery models. If deficiencies in

land use and human service planning are not addressed, the transport system will be unable to meet the mobility needs of the elderly now and in the future.

DATA SOURCES

The data in the following sections come from three categories of sources; the first is the published literature, which is always cited.

The second is the Nationwide Personal Transportation Study (NPTS), conducted by the Census Bureau for the U.S. Department of Transportation in 1977 and 1983. Although there are published documents from the NPTS, most of the data used here are directly from the computer tapes of the original 1977 and 1983 studies. Thus, NPTS data mentioned without citation were obtained from the tapes and are otherwise unpublished.

The third major data source is the national Health Interview Survey (HIS), which is undertaken yearly by the National Center for Health Statistics (NCHS). In addition to the regular annual survey, special surveys were undertaken in 1977 on car driving and in 1983 on the health of the elderly. Where otherwise not specifically cited, HIS data were obtained from the tapes and are otherwise unpublished.

All of the data used in this paper are cross-sectional, snapshots of what people are doing or experiencing at one given moment. There is always a strong incentive to draw longitudinal messages from such data—to assume that one can tell what happens to people as they age from 40 to 70 because differences between the two groups are apparent today. However, those who are now 40 are different in many ways from those who were 40 during the 1950s; there is no way of knowing whether they will have the same preferences, attitudes, and needs as they age. In fact, there is strong evidence of generational effects—such as the almost universal holding of driver's licenses by 40-year-old women today—that lead to the assumption that their behavior may be quite different when they reach 70.

REPORT ORGANIZATION

This paper has seven major sections. The next section focuses on demographic trends in society, especially the suburbanization of the elderly, and the transportation implications of those trends.

The following three sections examine how the elderly provide their own transportation—in private vehicles, walking and cycling, in taxis and on transit—outlining current use patterns and barriers facing the elderly in each mode.

The use of what has been called “socially provided” transportation—specialized transportation systems, human service agency programs, and volunteer networks—takes up the next section. Although often advanced as the

ultimate solution for the transport problems of the elderly, specialized transportation services face serious problems.

Last, the data and analyses presented here are summarized and a simplified model is described that predicts both the number who will lose their driving skill and the number of trips that will be lost.

DEMOGRAPHIC TRENDS

In 1986, 25.5 million Americans—approximately 11 percent of the U.S. population—were over 65 years of age. The Census Bureau estimates that as much as 18 percent of the population will be elderly by the year 2020, an increase of roughly 56 percent over 1980. Because of these major changes the median age of the entire society will rise from the current figure—just under 30 years—to just under 40 years by 2010.

A variety of social and demographic changes will accompany the aging of the population. On the positive side, people will live longer and in better health. They will more likely have their own homes, adequate incomes, and more material resources than previous generations. On the negative side, the need for specialized care and services will increase for the substantial number of very old people.

The aging of a society raises significant questions about mobility and transportation of the elderly. Strikingly, almost all of the “new” old will drive cars; the majority will live in suburban or relatively low-density urban settings. These people will have made a variety of decisions, and structured their social and economic lives, in response to their lifelong access to the private car.

The following section gives a brief overview of the elderly today and evaluates how current income, housing, and transportation trends will affect the needs of the elderly tomorrow. Overall, the data presented here strongly suggest that the future elderly will have different and more complex needs than the current elderly; society must understand these patterns in order to fashion effective and equitable transportation policies.

Population Patterns

The decade between 1970 and 1980 marked fundamental changes in American society and for the elderly in that society. Between 1970 and 1980, the number of Americans 60 and above increased 23 percent, both raising the percentage of elderly in society as a whole and pushing the median age of the population to 30. There was a far greater number of much older people in 1980 than in 1970, and the Census Bureau stopped using the category “75 and above” as the upper age limit in population breakdowns.

The percentage increase in the elderly population from 1950 to 1976 is shown in Table 1 (1, 2); in those 26 years, the entire elderly population increased 85 percent. The greatest growth was among the very old; those over 85 increased 233 percent. By 2020 those over 85 may well account for almost 15 percent of the elderly population.

TABLE 1 INCREASE IN U.S. ELDERLY POPULATION, 1950-1976 (1, 2)

	Percentage by Age Group			
	65+	65-74	75-84	85+
Total population	85	67	104	233
Men	60	51	69	159
Women	108	82	135	286

Substantial changes have also occurred in the economic attributes of older people and their households. From 1959 to 1981 the percentage of elderly people below the poverty level fell substantially, particularly those living in families; in 1981 only 8 percent of men and 16 percent of women over 65 in families lived in poverty.

As might be expected, there are important socioeconomic differences between the elderly living in the suburbs and those in the central cities. In both 1970 and 1980, the former were less likely to live below the poverty level than the latter. Between 1970 and 1980, the percentage of the poor who were elderly dropped in most states, but the change was far more significant for those living in suburban areas.

In general, the change in poverty status in the suburbs reflects two factors. The first is the overall improvement in the standard of living of the elderly; the second is that, from 1970 to 1980, the first cohort of more affluent postwar suburbanites became at least 60.

Unfortunately, although unrelated elderly individuals experienced a substantial drop in poverty rate, over 30 percent of elderly women and 23 percent of elderly men living alone in 1981 were below the poverty level. These data are disturbing, because the Census Bureau predicts a large increase in the number of elderly women living alone by 2020. By 2020, although roughly 91 percent of elderly men will live with others (a figure comparable to today's figures), 41 percent of elderly women will live alone. To make matters worse, the median age at which a woman is expected to experience widowhood will only increase from 64.5 in 1980 to 66.7 by 2010.

On the other hand, those who will turn 65 from now until roughly 2000 will have more children to help and support them than those who are now elderly, mainly because of the Baby Boom after World War II. Moreover, the current

elderly, whether living alone or not, often have strong family and social networks on which they can rely; the 1983 Special HIS study on the elderly found that many see their children frequently. Almost two-thirds of those who live alone see their children weekly; only one-fifth see them less than once a year. Nearly 75 percent of the elderly living alone have children who can reach them in a matter of minutes; almost every elderly person has a child only hours away (3).

Although all these older persons may occasionally or even frequently need assistance, it may not always need to be from some governmental source. Because they have personal resources, government programs should assist and strengthen these rather than break them down or neutralize them.

Housing Patterns and Mobility

There were also striking locational changes from 1950 to 1980 that sharply differentiate the previous generations of elderly from the current one. In the decades since World War II, America has experienced two migrational trends in which the elderly shared: the move out of rural areas into metropolitan areas and the move out of central cities into suburbs within metropolitan or urban areas.

Table 2 shows that in both 1970 and 1980 almost three-fourths of those over 60 lived in urban¹ areas—either in the central city or in the suburbs of those cities. However, in 1970 the majority of the elderly lived in the central city, and less than 40 percent of any elderly age group lived in what could be called suburbs. In contrast, by 1980 a majority of all urban elderly lived in the suburbs, with the youngest old cohorts showing the highest percentages of suburban living.²

The “new” suburban elderly are, in fact, the parents of baby-boomers. After the war, aided by federal mortgage assistance programs and the accessibility offered by the car, they moved away from the central city homes of their own parents and bought homes in the suburbs. The parents of the baby-boomers left their parents to age in the central cities; they are now, in their turn, aging in the suburbs. In spite of widespread belief to the contrary, all evidence is that the postwar suburbanites will stay where they are, “graying in place” and changing the character of the suburb—and the nature of their transportation needs.

Figure 1 shows that housing mobility rates have dropped sharply for all age groups since 1960, and probably will continue to do so.³ Today people are less likely to move as they age. By 1960 almost 80 percent of those 20 to 29 had moved, whereas only 60 percent of that same cohort had done so by 1970

TABLE 2 ELDERLY POPULATION, 1970 AND 1980

Age Group	Percentage by Location			Urbanized Area	
	Rural	Urban	Total	Central City	Suburb ^a
60-64					
1970	27.6	72.4	56.8	59.2	40.8
1980	27.0	—	73.0	41.0	59.0
65-69					
1970	27.8	72.2	55.8	61.2	38.8
1980	28.9	—	71.0	42.6	57.4
70-74					
1970	26.8	73.2	56.0	61.8	38.2
1980	29.5	—	70.5	44.0	56.0
75+					
1970	26.5	73.5	54.6	62.0	38.0
1980	—	—	—	—	—
75-79,					
1980	29.0	70.1	—	45.6	54.4
80-84,					
1980	29.0	71.1	—	46.3	53.7
85+,					
1980	29.8	70.2	—	46.2	53.8

NOTE: Generally in 1970, "urbanized area" included the central city and the urban fringe, and "urban" was urbanized area plus places of 10,000 and more plus places of 2,500 to 10,000. In 1980 "rural" meant outside Standard Metropolitan Statistical Areas plus places of 10,000 and more plus places of 2,500 to 10,000; "not in central city" meant urban fringe or suburb.

^aSuburb = urban fringe.

(when they were 30 to 39) and only 32 percent by 1980. Figure 1 also reveals a second trend—each successive generation since the war has been less likely to move at a comparable age than earlier generations: 43 percent of those who were 40 to 49 in 1960 moved compared with 34 percent of the same cohort in 1980.

A 1978 Census Special Study on the elderly commented (*1*, p. 35):

[Elderly] migration rates are relatively low both in an "absolute" sense and in comparison with those for younger age groups; with increasing age people migrate less. If the elderly do migrate, they generally go to various retirement areas within the United States, particularly Florida, to rural places or small towns (moving off farms), the country of origin (if foreign-born), or other areas abroad (e.g. Mexico) to retire. More commonly, many remain stuck in rural hinterlands or large urban centers . . . where they spent much of their adult lives.

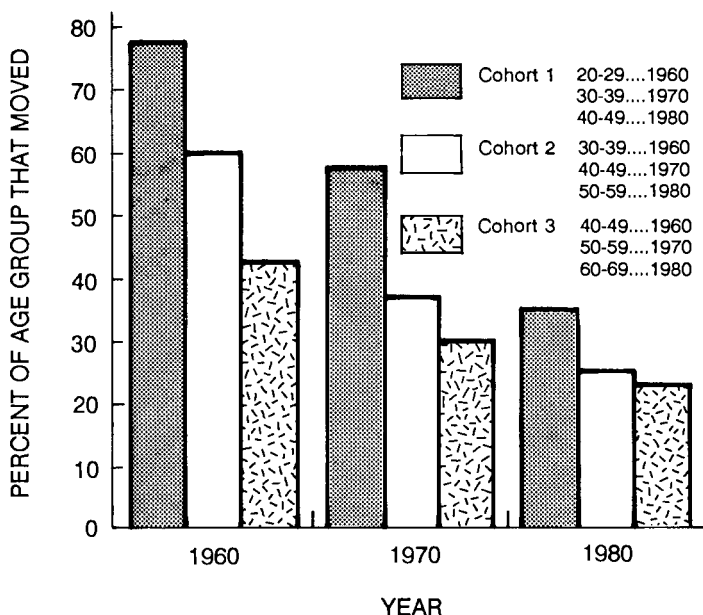


FIGURE 1 Housing mobility of people as they age (4).

Transportation Trends

The impact of increasing suburbanization and increasing income can be clearly seen in the travel patterns of the elderly. Table 3 shows that the elderly rely heavily on the private car, whether or not they drive. Several messages stand out in the data.

First, the elderly have come to rely even more on the car than in the past; in every age group more trips were taken in private vehicles (including vans, recreational vehicles, trucks, and station wagons) in 1983 than in 1977. Second, the elderly actually rely on private vehicles for more of their trips than do those 16 to 60; in fact, the importance of the private car actually declined between 1977 and 1983 for those under 60. Only those over 76 make a smaller percentage of their trips in cars than do those under 60. Third, elderly people in rural areas make more of their trips in cars than those in urban areas and more than younger people in rural areas; close to 90 percent of the trips of all rural elderly under 80 are taken in private vehicles.

Given the freedom offered by the car and the need to travel longer distances in low-density areas, it is not surprising that even those elderly who do not drive rely heavily on the private car. In fact, the elderly rely more on the car—or the taxi, a mode with the convenience of the car—for their highest-priority trips.

TABLE 3 ALL TRIPS TAKEN IN PRIVATE VEHICLES IN URBAN AND RURAL AREAS, 1977 AND 1983

	Percentage by Age Group						
	16-60	61-65	66-70	71-75	76-80	81-85	85+
Urban							
1977	90.0	85.2	79.4	80.1	70.8	63.7	67.4
1983	81.3	87.1	82.2	83.3	81.8	75.7	74.6
Rural							
1977	87.7	93.5	91.4	86.3	83.1	84.8	94.2
1983	85.0	91.6	89.7	87.5	88.7	82.2	80.2

NOTE: Private vehicles = automobiles, trucks, passenger and other vans, station wagons, and recreational vehicles.

SOURCE: Calculated from unpublished data from the 1977 and 1983 Nationwide Personal Transportation Study.

Table 4 shows that most of the medical trips of the elderly are made in the private car—over 80 percent for almost all cohorts. The taxi, however, also assumes an important, and even major, role for some: 6 percent of the medical trips made by those 66 to 70, 8.5 percent of the trips made by those 76 to 80, and 50 percent of the trips made by those 81 to 85 are by taxi.

TABLE 4 MODE USED FOR URBAN MEDICAL TRIPS, 1983

Mode	Percentage by Age Group						
	16-60	61-65	66-70	71-75	76-80	81-85	85+
Private vehicle	90.5	95.3	94.0	82.9	—	49.7	100.0
Walk	0.3	4.7	—	12.7	—	—	—
Transit	4.6	—	—	—	—	—	—
Taxi	0.6	—	6.0	—	8.5	50.3	—
Bike	—	—	—	—	—	—	—
Other	0.7	—	—	—	—	—	—
Unknown	0.4	—	—	4.4	—	—	—

SOURCE: Calculated from unpublished 1983 Nationwide Personal Transportation Study data.

Comparable analyses of unpublished NPTS data show that although private vehicles also form the dominant mode for shopping—over 80 percent for those under 80—a small percentage of such trips are made by walking. Between 12 and 15 percent of all shopping trips by those between 65 and 80 are made by that mode. In fact, the tendency to walk increases significantly with age; more than 50 percent of those 85 and over walk to shopping. Few urban shopping trips by any age group are made using mass transit—less than 5 percent of the trips of groups under 85 and 16 percent of the trips of those over 85.

Unpublished NPTS data also show that the car is the dominant mode of all groups of the elderly for a combination of closely related trip purposes: social, visiting, recreational, vacation, and school or church. The car is used for 80 percent or more of all these trips for those over 65 and becomes more important for those over 80; the highest percentage of automobile use by the elderly over 80 for any purpose is for these combined social trips.

Policy Implications

By the turn of the century the majority of the elderly will live in low-density communities in either the suburbs or rural areas. Over 90 percent of both men and women will have been licensed to drive for 20 years or more, and their whole pattern of life will depend on the accessibility offered by the car and the low-density delivery of public and private services.

The quarter of the population who lives in the central city will be less well off economically, but the suburbanites will suffer a larger absolute drop in mobility when they can no longer drive. The rural elderly, often seriously economically disadvantaged, will also suffer a large absolute drop in mobility when driving is no longer possible. Moreover, even if they can continue to drive, they will have to go further because both public and private services are being withdrawn from rural areas.

Each of these groups of travelers will require different transportation and other resources when they can no longer drive. One simple solution will not serve most of the needs of a society with a larger and larger elderly component.

THE ELDERLY ON THEIR OWN

Private Vehicles

American society depends on the private car; at all ages Americans make more trips in private vehicles than do travelers in any other developed country. The elderly make the majority of their trips in cars whether they drive or not.

There has been an explosion in the use of the automobile since the end of World War II. In 1978 the United States had almost twice the numbers of cars per capita as the next leading contender, Sweden, and 10 times the per-capita rate of Great Britain (5). Although rates of car ownership are not uniform, over 70 percent of U.S. households in central cities and 90 percent in suburbs and rural areas owned cars in 1978.

Traditionally the elderly have not had such high rates of car ownership or use; currently elderly Americans travel roughly one-third as many vehicle miles as those under 65. What is not clear is how much the current differential between those over and under 65 is a result of decreases in mobility that come

inevitably with age—for a variety of reasons yet to be grappled with—and how much is a generational effect, a historical artifact of the lower use and dependency on the car among those who were middle-aged two decades ago.

For example, there has been a significant increase in the number of both men and women with driver's licenses since the 1950s. Figure 2 shows that in the first half of the 1950s only 40 percent of all men over 70 had licenses; in 1984 that percentage had more than doubled to almost 90 percent.

Although women's licensing rates have traditionally lagged behind men's, the percentage increase has been roughly the same; in 1951–1956 only 8 percent of women over 70 were licensed to drive. By 1984, 43 percent of women over 70 had driver's licenses. Today, as Figure 2 shows, 94 percent of all adults 60 to 69 and almost 90 percent of men 70 and over have licenses.

Of equal importance, the traditional gap in licensing rates for men and women has largely disappeared for younger age groups. In 1984, 92 percent of women 30 to 39 drove (although male licensing was almost universal); this means that in the first decade of the 21st century, roughly 90 percent of women 60 to 69 will have been licensed and driving for over 30 years.⁴

In the following sections the use of the private car by elderly drivers and nondrivers is analyzed. The conclusion is that the private car is the dominant mode for today's elderly and will be for the elderly in the future. Those who are today over 40 will make a number of life-style decisions that will affect them three decades from now, decisions based on the accessibility offered by the car that range from where to shop to where friends live and that will not be easy to change after retirement.

However, the analyses also show that it is difficult to gauge the extent to which the elderly of the future will require additional transportation services when they cannot drive and the kind and quality of services required. Although there are currently great disparities in trip making between those elderly with and without licenses, it is not known how much of the difference reflects a genuine need for additional travel. The barriers to greater vehicle use, as well as driving, are composed of a complex mixture of individual and environmental barriers that often reduce the desire to travel more than the ability to do so.

Moreover, many individuals who continue to maintain a license may seriously restrict their driving, perhaps more than is necessary. Thus there is a hidden loss of mobility that is not recognized by those concerned only with licensing criteria.

Current Automobile Patterns

U.S. data show two clear patterns among all elderly, both those who drive and those who do not. First, they travel significantly fewer miles than younger

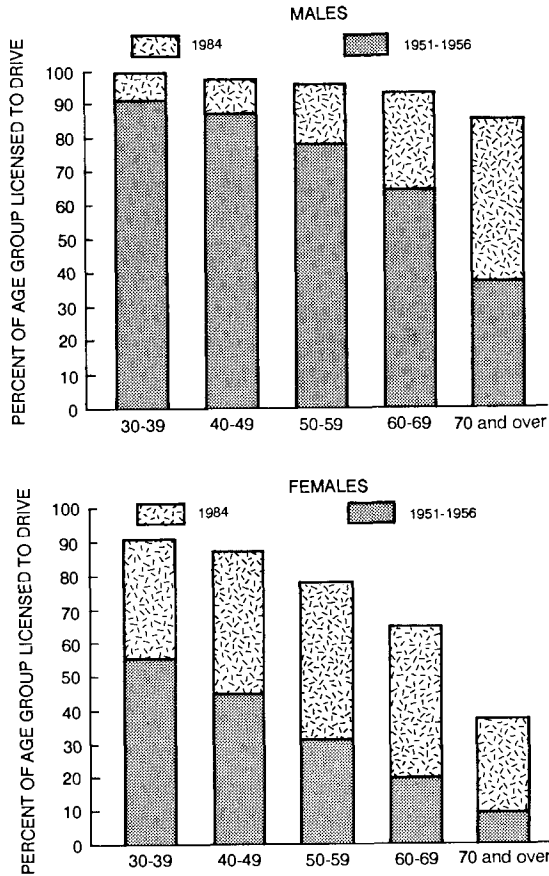


FIGURE 2 Licensed drivers by age and sex, 1951-1956 and 1984 (6, Table DL).

persons, but, second, they have come to rely as heavily on the private car. The first pattern can be seen in detail in Figure 3, which shows vehicle miles of travel (VMT) for those in urban areas, whether or not they drive (and including all forms of public and private vehicles).

Three trends are obvious: people of all ages traveled more in 1983 than they did in 1977, at all ages women travel fewer miles than men, and—the most important here—as people age they drive fewer miles. The drop in VMT seems greatest when people reach 60. However, the gap between men and women is much smaller for younger groups, and it may remain smaller for future groups of elderly. Unpublished NPTS data show similar patterns in rural areas.

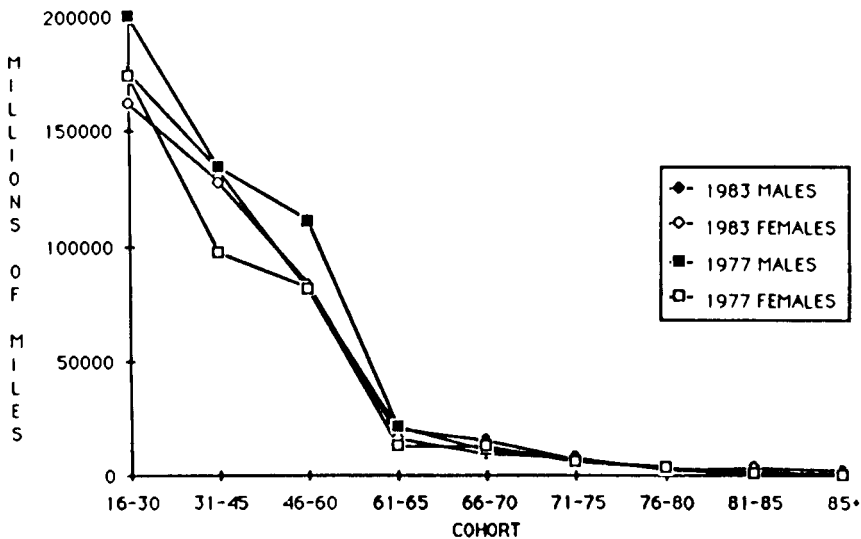


FIGURE 3 Annual urban VMT by age and sex, 1977 and 1983. (Calculated from unpublished Nationwide Personal Transportation Study data.)

Although the elderly travel less distance than younger drivers, this may not represent a corresponding—or any—decrease in the frequency of trip making. A major European study found that when home-to-work travel is eliminated from the pattern for both young and old, the elderly make more reasonably frequent but short trips than younger travelers (7).

U.S. patterns are similar. In Table 5 all work trips were removed from the vehicle trip distribution patterns of drivers and nondrivers to see whether the elderly substitute other trips for work trips. The data suggest that the elderly indeed make more shopping trips than younger employed persons, a finding consistent with common observations. Surprisingly, however, the elderly make fewer visits and other social trips than younger people. They may also attend church less than younger people, although this finding may be an artifact of the inclusion of school activities with church activities for younger people.

In the following sections the travel patterns of elderly drivers and non-drivers are discussed and the kind and frequency of trips made by both groups are evaluated.

Elderly Drivers U.S. data above suggest that all older persons may make shorter, more frequent trips than younger travelers; the data show this to be especially true of elderly drivers versus all others. A 1987 Dutch study found no significant difference in the frequency of driving among age categories for social or shopping trips (8). Kobayashi (9) found that, although elderly

TABLE 5 URBAN VEHICLE TRIP PURPOSES WITHOUT WORK TRIPS, 1983

Main Purpose	Percentage by Age Group						
	All Ages	61-65	66-70	71-75	76-80	81-85	85+
To or from work							
Business							
Shopping	26	35	32	33	36	29	19
Personal	23	22	23	22	15	12	7
School or church	11	7	7	10	7	17	11
Medical	2	3	3	4	8	2	7
Vacation	<1	<1	<1	<1	—	<1	—
Visit	15	14	12	10	11	16	17
Pleasure	<1	<1	2	<1	<1	4	15
Other social	20	18	17	18	20	15	26
Other	3	2	5	2	2	2	—
Unknown	<1	—	—	—	—	—	—

SOURCE: Calculated from unpublished 1983 Nationwide Personal Transportation Study data.

Japanese car owners drove less distance, their trip frequency was not much different than that of younger drivers: over half of those over 60 drove every day.

A 1976 study of drivers in Sweden found that older drivers did make fewer trips than younger drivers, but that over 55 percent of male drivers and 49 percent of female drivers used their car every day; an additional 28 percent of both sexes used their car two to three times a week (10).

U.S. data are comparable. NPTS data suggest that the elderly (to the age of 80) make more nonwork trips per capita than younger people. Thus, if work trips are removed from total trip patterns, the elderly travel more frequently than do travelers under 65.

Published NPTS data (11, pp. E-17-E-19) suggest that certain kinds of trips, not long in themselves, are made frequently by elderly drivers. Shopping and family and personal business trips each average less than 5 mi, but together they account for over 50 percent of all trips and almost 40 percent of all VMT. Conversely, although medical trips are among the longest taken (discounting vacations and short pleasure trips), they account for only 7 percent of all trips taken and 5 percent of all VMT by those over 65. This suggests that these trips are taken infrequently, as are vacation and pleasure trips.

Nondrivers Although it is clear that most travelers make extensive use of the private car, it is reasonable to assume that nondrivers—those unable or unwilling to drive—may have different, perhaps remarkably different, travel

patterns than those who drive. The data here show that nondrivers make far fewer trips with any mode than do drivers.

Figure 4 shows the annual trip patterns of elderly travelers with and without driver's licenses. It is immediately clear that those without licenses make far fewer trips than those with licenses, although the relative decline with aging is greater for those with licenses. Unpublished 1983 NPTS data reveal that in both urban and rural areas those over 65 with licenses make between 50 and 100 percent more trips in a year than those without licenses. Overall the older the traveler the greater the disparity in trips taken between those with and without licenses. Those over 85 without licenses make roughly 70 percent of their trips in a car compared with 40 percent of those 66 to 70 without licenses. Moreover, the differential is still greater in rural areas (NPTS data include walking, transit, and taxi trips also—modes that have little to do with the presence of a driver's license). In spite of these differences, 1983 NPTS data also show that the car is still the most frequent mode for those without licenses as well as for those with them.

Most elderly travelers without licenses make a significant percentage of their trips by walking—between 20 and 40 percent of all trips. Transit is a distant third choice for most urban travelers; no more than one-fourth of any group's trips is made on transit, and most age groups depend on mass transit

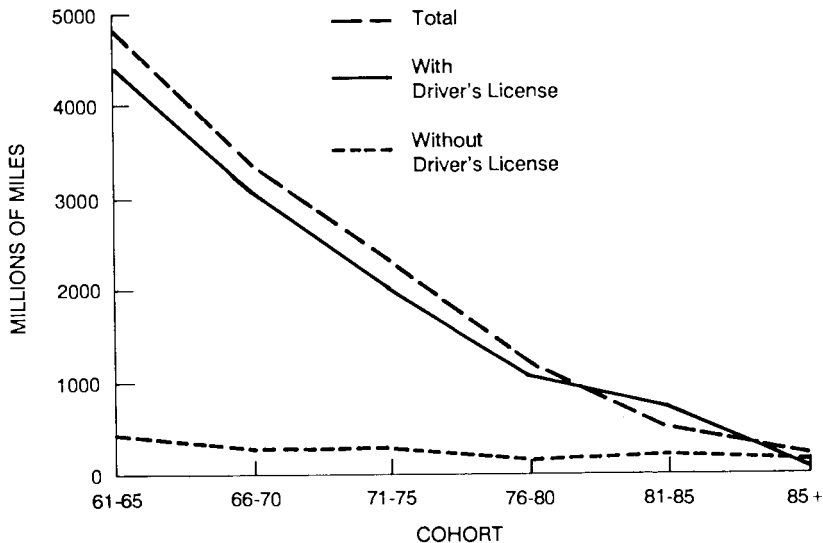


FIGURE 4 Annual urban trips (weighted in millions) by age and presence of driver's license, 1983. (Calculated from unpublished Nationwide Personal Transportation Study data.)

far less. There is also small but significant taxi use by older travelers without licenses.

Although the private vehicle is a major travel mode for all the elderly, those without driver's licenses are nowhere near as mobile as those with licenses. The data suggest that some of those who cannot drive do not have acceptable substitutes for the private car, at least not ones they can afford or physically manage, and their trip destinations may require the flexibility and convenience of the private car, so that transit and walking cannot be easily substituted.

Barriers to Automobile Use

The elderly face a number of barriers to initial or continued automobile travel. First, there are a variety of individual or personal physical problems that might interfere with the ability to travel; to these are added the financial problems of maintaining a car. Second, there are a broad class of environmental problems; among these are the way land uses and the road system are organized, and the kind, quality, and cost of activities offered to the elderly in a community.

There is significant evidence that the elderly often suffer a reduced desire to travel as they age (12, 13); it cannot be assumed that all differences between the young and the old and between the driver and the nondriver are due to lack of access to a car. Those without cars or licenses may face a variety of environmental and personal barriers that translate into reduced desire for all activities long before they translate into the loss of license or ability to drive.

Both environmental and individual barriers have complicated impacts; it is important to understand both the barriers that reduce the older person's desire to travel and those that reduce their ability to travel when they still wish to do so. Such a separation is not easy; the same physical problems that cause the elderly to reduce their driving could rob them of the ability to engage in activities at their destination.

However, the data below have a striking message; physical problems seem to create few of the barriers that keep the elderly from leading a more active life or from driving. It initially appears that environmental problems may pose greater barriers to the elderly, first reducing their desire and then their ability to travel.

Declining Desire to Travel Although it is known that those with driver's licenses make more trips than those without driver's licenses, how many more trips nondrivers (or elderly drivers, for that matter) might wish to make is unknown. Converting the gap between the two groups into needed trips is very difficult, because some of the differential is due to a lost desire for activity and travel.

One method is to analyze the number and kind of additional trips made by the elderly when provided with specialized transportation services. The U.S.

Department of Transportation (DOT) analyzed a number of specialized services for the elderly and found little evidence of additional trip making. For example, the DOT study of a New York system concluded (14), "These data suggest that most persons who made essential trips probably would have found an alternative mode if EASYRIDE did not exist."

In 1978 DOT examined five additional systems and found very similar patterns (15). At each site, only small numbers of people (between 5 and 24 percent) said that they would not make their trip without the special service in question. It was noted that there had been some small impact by the special service on user travel patterns, but it was concluded that, overall:

There is no definitive evidence from the demonstration projects that any of the transportation service improvements for the elderly and handicapped have had an impact on their overall rates of trip-making.

Data from an Austin study of Medicaid clients (16) show this pattern even more clearly. Sixty-eight percent of elderly users reported that the same trip (or a similar one) had been made before the establishment of the subsidized service; most of the remainder had not needed to travel previously. Only 14 percent of the remaining respondents said that their reason for not making the trip was lack of transportation.

Medical researchers studying why the elderly did not use medical services found that transportation was rarely the cause (although it was often assumed to be so by professionals). Evashwick et al. (17) concluded that when respondents report transportation difficulties, they are reporting a functional problem and not a barrier to use of either transportation or medical services (17, p. 378):

Despite the fact that transportation is reported as a problem, the high service use by these respondents indicates that transportation does not present an insurmountable barrier to obtaining care.

These data indicate not that these older persons never have transportation problems, but that lack of transportation does not explain their low use of key services or their overall lower rates of activity. Although it is difficult to identify all the problems that create barriers for the elderly, finances and lack of interest in social and other services seem to explain a great deal.

In 1979 a Congressional Budget Office study noted that (12, pp. 18, 19) "travel behavior is . . . closely related to income; severely disabled persons with high incomes tended to travel almost as much as able-bodied individuals." The Senate Special Committee on Aging made a similar observation (13, p. 12):

Amount of income appears to be very important in the degree of [transportation] difficulty experienced. Very small amounts of income added to that of persons living at the poverty line appear to result in considerable alleviation of transportation problems. Indeed the most striking aspect . . . is the substantial improvements in transportation which are indicated just at the point of the poverty line. . . . The percentage of those reporting difficulties rarely rises appreciably for either couples or individuals with incomes over the poverty line.

A number of studies have found that the elderly, particularly those who are poor, are not interested in many community activities and services (18, p. 271; 19, p. N-5; 20, p. 12). The California Department of Social Welfare concluded (21):

Old people—particularly those who are poor—have been less than enthusiastic. . . . In fact, few community service programs have been successful in reaching any sizeable portion of the aged population. . . . Most older people avoid most service programs for the aged.

Declining Ability to Travel Physical problems only explain some of the drop in travel by both drivers and nondrivers. Table 6 shows that the extent of driving, regardless of disability, lessens with age; at the same time, driving lessens for every cohort of the elderly as activity limitations increase. However, in every case, the decrease in driving is greatest with increasing age and not with increasing disability. For those 60 to 69, for example, the difference between those with no limitations and those unable to conduct a major activity (the most severe limitation) is only 12 percent. The difference between those 60 to 69 with no activity limitations and those over 80 with no limitations is almost 50 percent. In short, age alone is a greater predictor of amount of driving than activity limitations.

TABLE 6 RESPONDENTS WHO DRIVE CARS BY AGE AND CATEGORY OF DISABILITY, 1977

	Percentage by Age Group			
	All Ages	60-69	70-79	80+
Total	81.2	70.3	52.9	25.0
No activity limitations	85.3	74.4	59.8	33.8
Limited but not in major activity	74.7	66.9	45.4	20.5
Limited in major activity	63.2	61.2	41.0	18.3
Unable to conduct major activity	52.7	62.4	47.4	17.3

NOTE: Data include unknown responses.

SOURCE: Calculated from unpublished 1977 national Health Interview Survey data.

Table 7 analyzes further the impact of disability on extent of driving using HIS data. Overall, less than one-third of all elderly who do not drive are prevented from doing so by disabilities; even those over 80 do not explain much of their unwillingness or inability to drive in terms of their health or physical problems.

TABLE 7 CAUSE OF DRIVING BEHAVIOR BY AGE AND ACTIVITY LIMITATION, 1977

Category	Nondrivers in Category (%)	Nondrivers Prevented from Driving by Health or Disability (%)	
		Yes	No
All ages	18.8	19.2	81.8
60-69	29.7	18.7	81.3
No activity limitation	35.6	3.7	96.3
Not limited in major activity	33.1	21.4	78.6
Limited in kind/amount of major activity	38.8	27.4	72.6
Unable to conduct major activity	37.6	57.1	42.9
70-79	47.1	22.8	77.2
No activity limitation	40.2	7.4	92.6
Not limited in major activity	54.6	19.9	80.1
Limited in kind/amount of major activity	59.0	16.1	73.9
Unable to conduct major activity	52.6	57.9	42.1
80+	75.0	34.2	65.8
No activity limitation	66.2	14.8	85.5
Not limited in major activity	79.5	36.4	63.6
Limited in kind/amount of major activity	81.7	33.8	66.2
Unable to conduct major activity	82.7	61.2	38.8

SOURCE: Unpublished data from the 1977 special national Health Interview Survey by the National Center for Health Statistics.

When each group is disaggregated by activity limitation, a greater relationship between disability and driving is seen. However, the impact is very strong only for the most severe level of activity limitation. Less than one-third of the nondriving behavior of all other respondents is explained by their health or disability, regardless of age.

Loss of Driving Skills Actual physical disability may not explain why the elderly do not drive more, but it is a real issue. The data and published studies indicate that declining skills have two impacts on the elderly driver. First, they eventually leave elderly drivers unable to drive safely; some skill losses can be compensated for—through training—and others cannot. Once unable to drive, elderly drivers and members of their household dependent on them may suffer drastic losses in mobility.

Second, elderly drivers, cognizant of their declining skills, may elect to restrict their driving or stop driving entirely. They may, in fact, constrain themselves more than is necessary or fail to take advantage of programs that can compensate for some skill losses. Thus there is a hidden loss of mobility that might be unnecessary and that is effectively obscured from policy makers concerned only with licensing as a criterion.

The aging process is generally held to affect driving by reducing major cognitive functions; these cognitive reductions are often accompanied by both the loss of certain physical functions and the onset of dysfunctional medical conditions. These factors, when combined, affect skilled performance and result in degradation of perceptual ability, especially visual capacity, and slowing of performance and reaction times (22).

What are the measurable impacts of reduced performance skills among the elderly? Numerous studies show similar patterns: the elderly have far fewer accidents per capita than younger drivers and the accident rate declines with age. However, when exposure factors are added, societal accident patterns tend to display the classic U-shaped curve; accident rates are highest per exposure for the youngest and oldest members of society. When involved in an accident, those 65 and over are more likely to be injured or killed than younger persons.

One reason that the elderly have a lower per-capita accident rate is their choice to curtail their own driving significantly in response to problems. Several major U.S. studies found that older drivers restrict their driving more and more as they age, beginning at 60 for men (23). The studies also found that older drivers tend to avoid high-risk driving situations, for example, night and peak-period driving. A 1977 Canadian study concluded that, although medical conditions among elderly drivers did increase driver risk, it was more than offset by their adoption of new, less risky driving patterns (24).

Austrian researchers recently reported that there was no overall quality decrease in the driving behavior of the elderly in comparison with that of younger drivers because older drivers had increased regard for other traffic participants and reduced risk taking and aggressive behavior (25).

Two U.S. researchers, commenting on measures designed to restrict the driving behavior of the elderly, noted (26, p. 247):

It seems likely that restricting the licensing of older drivers to daytime driving and low stress environments will not significantly reduce their accident rates. Older drivers already avoid such situations voluntarily. . . . Thus restricting driving licenses cannot simply be accomplished on the basis of chronological age.

Two Dutch researchers recently noted, however, that the avoidance behavior of the elderly could be dysfunctional and cyclical (27):

Less frequent road use leads to a loss of functions, thus leading to an extra loss of functions and of routine. The feeling of the elderly that they are no longer able to function in traffic which is tailored to the "average" road user, and fear of their own vulnerability, have the effect that old people become even less frequent road users. A vicious circle supervenes.

Policy Implications

A number of issues have been raised. First, the elderly, both drivers and nondrivers, face an array of barriers both to traveling and to driving. All evidence is that the environmental barriers are more significant than the physical barriers. To address environmental problems, transportation planners must consider how the roadway network acts to discourage elderly drivers, land use planners should consider how both the cost and the location of activities affect the older person's desire to travel to them, and service providers must consider how to restructure the delivery of services designed for the elderly to encourage their use.

Without significant outreach services clearly targeted for those most at risk or in need, and some—perhaps major—alterations in the way these services are delivered to the elderly, it is not realistic to expect transportation to have a significant effect on their use.

In terms of licensing, it is important to remember that there are two separate issues in need of resolution. The first is whether elderly drivers pose a risk to themselves and others and should be either retrained or kept off the road. The second is whether elderly drivers, who pose no greater danger than younger drivers, are in fact suffering significant losses of mobility because they so constrain their own driving.

Walking and Cycling

Walking is not a common travel mode in the United States; although U.S. travelers each cover up to 10 times more vehicle miles per year than their counterparts in other developed countries, they cover less than one-sixth as much distance by walking. Walking is relatively more important to the elderly, especially in other countries. Those over 65 in the United States annually walk an average of 28 mi, compared with almost 300 mi per year in Denmark and 250 mi per year in Germany (7).

Cycling is clearly not a major mode for any age group in the United States and less so for the elderly; in 1980 those 65 and over traveled only 2 mi per capita on bikes. Cycling is, however, a much more important travel mode for the elderly in Europe; in Germany the average older person travels roughly 100 mi a year by bike, and in Holland the average is over 500 mi a year (7). A recent Finnish study found that those over 65 made up to 70 percent of all trips on bikes.

In this section the focus is on walking—how and when those over 65 walk to meet their mobility needs. Overall, the data show that walking is not nearly as important a travel mode for elderly people as was commonly thought; it rarely accounts for more than one-tenth of all trips taken by those 65 to 80. Moreover, the importance of walking has declined—substantially for younger cohorts of the elderly—since 1977.

At the same time, most data analyses probably underestimate the importance of walking for the elderly, because this mode serves more than one purpose. Besides being an individual's sole travel mode, walking can serve as an adjunct to mass transit and as a form of recreation. Current travel data tend to undercount walking as access to other modes and simply do not count recreational walking. Data on walking, therefore, are valuable for understanding specific kinds of trips but less so for evaluating the importance of walking in the life of the elderly or the need for pedestrian improvements.

The following analyses suggest that the elderly have both personal and environmental problems that prevent them from walking more. Only a small percentage of the elderly actually have physical difficulties in walking any distance. Most do not walk more because their communities are not designed for, or conducive to, pedestrian travel—trip lengths are too long, and streets and intersections pose hazards to elderly pedestrians.

In the short run, alternative transportation options must be found for those unable to drive or ride in a car or to walk for needed trips. In the long run some mobility problems, as well as some recreational needs, can be addressed by paying serious attention to structuring some land uses in ways that facilitate walking as a purposeful travel mode and that create a more effective pedestrian environment for all types of walking trips.

Current Walking Patterns

NPTS data show three patterns common to those over 65. First, in 1983 walking was a measurable but not very large component of the total travel pattern of most elderly travelers, accounting for less than 12 percent of all trips for those under 80 in either urban or rural areas. Only travelers over 80 made more than one-fifth of all trips by walking.

Second, walking as a percentage of all trips taken decreased, sometimes markedly, from 1977 to 1983. The older the traveler in urban areas the more noticeable was the drop in the importance of walking in the total travel picture. The percentage of trips taken by walking decreased from almost 25 percent to only 12 percent for those 76 to 80 and dropped from almost 29 percent to 17 percent for those over 85.

Third, although not a major travel mode, walking does increase in importance as people age for all but the oldest. However, as with all of the cross-

sectional data described in this paper, it is not known whether this increase is a function of age or of generational differences. The decline in the importance of walking between 1977 and 1983 suggests the latter; that is, younger cohorts, unused to walking for many trips, do not begin to do so simply because they have aged.

Table 8 gives trip purposes for 1983 walking trips in urban areas by age and sex. The three major purposes named were shopping, personal business, and social visits, although the relative distribution of these trips changed with age and sex. It is clear that as travelers age they use walking to serve fewer and fewer kinds of trips; by 76 most travelers are walking for significantly fewer kinds of trips than younger cohorts.

Barriers to Walking

Do the elderly want to walk more but are prevented from doing so? The data below suggest, but do not prove, that personal handicaps do not explain why the elderly do not walk more—the impediments appear to be the result of effective barriers in the built environment.

Individual Barriers HIS data show that in 1983 less than 10 percent of the elderly 65 to 74 reported that they could not walk $\frac{1}{4}$ mi; the differences between the sexes were not great. The differences between age groups of the elderly were not great either: 7.9 percent of men 60 to 64 reported being unable to walk a quarter of a mile compared with only slightly more, 8.7 percent, of men 70 to 74 (28).

Additional HIS data show that reported difficulties in walking, getting around outside, and shopping rise significantly after 80; almost 40 percent of all respondents over 85 had difficulty in walking, whereas over 30 percent had difficulty with the other two tasks. Women over 80 were more likely to experience difficulty than men; the greatest differential was in shopping—almost 42 percent of women over 85 had difficulty compared with 27 percent of men (29).

There are two striking points in these data. First, there is a large number of elderly people who report no difficulty with walking or related tasks—from 50 to 70 percent of respondents over 65. Moreover, at most only 10 percent of any age group over 65 report being completely unable to walk, shop, or get around outside. Second, of the 20 to 40 percent who reported walking or shopping problems, most were in fact faithful walkers who were more likely to take a majority of trips by walking than were those who reported no problems.

Overall, the data on self-reported walking difficulties do not explain why the majority of elderly do not take more walking trips. Environmental factors, such as pedestrian safety problems and land use patterns, may give more of an explanation.

Environmental Barriers: Pedestrian Safety It is thought that the elderly significantly reduce their driving in response to their recognition of loss of driving skills. It is also possible that the elderly significantly reduce their walking in response to real and imagined safety and security problems along urban streets.

Accident rates for elderly pedestrians resemble those of elderly drivers; the older person is less likely to have an accident on a per-capita basis but more likely on a risk-exposure basis. When involved in accidents, the elderly are more likely than younger persons to receive serious or fatal injuries.

There are a number of common patterns in studies of these pedestrian accidents: elderly pedestrians are often hit in crosswalks or when crossing intersections, they are generally hit on the far side of the street, they are usually observing the law and not behaving dangerously, they often do not see the vehicle that hit them, and when they do see a vehicle, they usually believe that the driver has seen them and will take evasive action.

The lack of forewarning of an accident on the part of the elderly is a common research finding. A 1972 British study found that 70 percent of elderly pedestrians involved in accidents in a 6-month period did not see the vehicle before it hit them. Although the elderly were more likely than other pedestrians to look before crossing, they were also less likely to see the striking vehicle (30, p. 332).

Given the number of accidents occurring in crosswalks, experts have questioned the role of traffic signal timing in accidents involving elderly pedestrians (31, p. 15). Because older persons usually walk more slowly than younger ones, current signal times may contribute to such pedestrian accidents and create understandable hesitation on the part of the elderly to walk in signalized as well as unsignalized areas.

The Australian Office of Road Safety recently commented (31, p. 15):

Older people generally *know* the right thing to do. But their ability to cope with the unexpected—especially if their minds are on something else—is reduced by their inability to take quick evasive action.

Moreover, the elderly are often victims of bad drivers whose unsafe driving behavior or illegal parking forces pedestrians into dangerous maneuvers. A recent British study cited by the Australian Office of Road Safety (31, p. 13) found

that in almost all cases of potential conflicts between vehicles and pedestrians, it is the pedestrian who takes evasive action. Moreover, drivers frequently fail to take evasive action until it is almost certainly too late to avoid a collision.

In addition to worrying about safety, elderly pedestrians may have to be concerned about their personal security as well, especially if they are walking

TABLE 8 URBAN WALKING TRIP PURPOSES, 1983

Main Trip Purpose	Percentage by Age and Sex													
	16-60		61-65		66-70		71-75		76-80		81-85		85+	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Work	14.2	9.5	17.2	6.2	—	3.1	—	10.5	—	—	—	—	—	—
Business	2.6	1.5	—	—	6.3	—	—	2.3	—	—	—	—	—	—
Shopping	14.0	16.4	12.1	38.1	37.0	28.7	41.4	39.8	39.2	54.4	24.4	59.8	100.0	57.9
Personal business	14.1	12.5	41.4	14.8	9.4	13.7	8.1	9.4	12.2	27.2	26.8	25.5	—	—
School/church	19.4	29.3	—	6.9	—	9.7	—	5.3	—	—	48.8	—	—	42.4
Medical	0.3	0.4	—	1.7	—	—	8.1	2.3	6.8	—	—	—	—	—
Recreation	—	0.5	—	—	—	—	—	—	—	—	—	—	—	—
Visit	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Other social	34.4	16.7	22.2	25.4	47.4	23.7	42.3	30.4	41.9	19.7	—	14.7	—	—
Other and unknown	—	—	—	10.0	—	—	—	—	—	—	—	—	—	—

NOTE: Totals may not add to 100 because of rounding errors.

SOURCE: Calculated from unpublished 1983 Nationwide Personal Transportation Study data.

to transit services. The street is the site of a large portion of bus transit crimes; a 1982 study found that 60 percent of all known bus crimes occurred at bus stops (32). A larger study in Los Angeles in 1983 found that 54 percent of all bus-related crimes occurred outside elsewhere than on buses when victims were either walking to or waiting at bus stops (33).

Elderly travelers who choose to walk must take that mode very seriously and learn to avoid all but the most harmless situations, altering, and perhaps lengthening, travel patterns to avoid difficult intersections. They must understand that they will find little support or help in the traffic environment.

Surely such concerns negatively affect the willingness of the elderly to walk to meet their needs or for social or recreational purposes. Fear of personal safety must also play some role; a 1984 study in Southampton, England, found that 22 percent of elderly women felt unsafe walking along streets during the day, and the percentage rose to 50 percent at night (34).

Environmental Barriers: Land Use Patterns There can be little doubt that the low-density development of many of the U.S. suburbs where the elderly reside contributes to the declining use of walking as a trip mode. As pointed out earlier, Europeans over 65, who generally live in denser cities, walk between 200 and 300 mi a year (7).

Most of the elderly could not easily change their current vehicle trips into walking trips, because the widely scattered places to which they travel cannot easily be accommodated by other modes. In Table 9 the mileage of the older person's average 1983 vehicle trips for various purposes is converted into the time each trip would actually take if the elderly walked or took transit instead

TABLE 9 AVERAGE ONE-WAY TRIP TIME BY MODE OTHER THAN CAR (11, p. E-18)

Main Trip Purpose	Time (min) by Mode and Age					
	Car		Walking		Public Transit	
	60-64	65+	60-64	65+	60-64	65+
Work	11	10	128	116	31	29
Work-related	23	16	268	184	55	41
Shopping	8	8	90	88	25	25
Family/personal	17	7	198	86	43	24
Doctor/dentist	37	14	436	158	83	36
School/church	6	8	74	90	22	25
Vacation	151	48	1,764	562	304	104
Visit friends	17	16	202	182	44	40
Social/recreational	16	14	190	166	42	38
Other	53	9	616	108	113	28

NOTE: Computed assuming automobile speed of 35 mph, walking speed of 3 mph, and average transit speed of 18 mph plus 10 min walking and waiting time per trip.

of riding in a car. Not one trip that the elderly currently make in a car can be made by walking in less than 1 hr, one way, not even those to current church activities or friends. Table 9 also shows that mass transit could effectively be substituted for some current automobile trips, although there are few existing trips that can be made in under $\frac{1}{2}$ hr, and then only if transit services actually existed within four blocks of where the person lived.

Moreover, transit use can be limited by the need to walk to and from bus stops. As noted in a West German study, cited by the Australian Office of Road Safety (31, p. 12), "the inherent safety of public transport modes may be cancelled out unless pedestrian protection receives a high priority."

Given current urban land use patterns, the elderly can only walk to meet their needs by making drastic alterations in their most fundamental decisions about medical care, social and religious contacts, and personal business. Even then, some of those needs could not be served by walking, because medical and human services are not equally distributed across communities.

Policy Implications

The elderly are victims of traffic environments that were not designed with the pedestrian in mind, particularly not the elderly pedestrian. They are faced with a network of roads designed to maximize convenience for the automobile driver: traffic signals are set much too fast for their effective use and roads are too wide to cross in one signal cycle.

Moreover, although elderly drivers are causing a great deal of public concern, elderly pedestrians, whose problems are often caused by careless younger drivers, do not receive the same attention.

Given the dispersed and still dispersing nature of the American city, many elderly simply cannot walk to meet their current needs. It is unrealistic to expect that cities will—or should—be drastically reconfigured, but it is important to question the basis for the location of needed business and social services in a community. Furthermore, both site-specific and general urban design decisions about all public and private developments in suburban areas should be based on recognition of the problems facing elderly pedestrians and should attempt to incorporate appropriate modifications into the planning process.

Suggested modifications include requiring sidewalks in new neighborhoods as well as retrofitting existing neighborhoods with sidewalks, separating pedestrian travel from automobile travel where appropriate, lengthening signal cycles in areas with high concentrations of the elderly, building islands in the middle of streets which allow the elderly to cross in two cycles, and providing useful street furniture.

Mass Transit and Taxis

Previous analyses show that the elderly use both transit and taxis infrequently, even when they lack other options. It is crucial to examine exactly why the elderly do not use these resources more and to determine whether it is possible to make them more useful for elderly travelers now and in the future.

Taxi and transit ridership, as with other modes, is constrained by both individual and environmental barriers. Data in this section show that taxi ridership by the elderly is largely constrained by financial concerns; most barriers could be reduced by effectively lowering the cost of this service.

However, neither personal financial nor physical barriers account for the low use of transit by the elderly; removing such barriers will make transit better only for those who already use it. It is the environmental barriers that need to be addressed: transit systems should reorient traditional routes, restructure service, and attend to the safety and security concerns of the elderly.

Such responses may permit the elimination of many barriers to taxi and transit use without development of extremely expensive alternatives, which could be saved for those who cannot use public transit or traditional taxis under any circumstances—the feeble and handicapped elderly.

Current Taxi and Transit Patterns

Three taxi and transit trends stand out in the unpublished NPTS data from 1977 and 1983. First, transit and taxis account for a relatively small percentage of the total trips taken by all age groups. Less than 1 percent of all trips by those over 65 are made in a taxi; less than 6 percent of urban trips by the elderly are made using transit. Moreover, both modes were less important to all groups of the elderly in 1983 than they were in 1977. Second, elderly users are slightly more likely to use transit than those under 60 but slightly less likely to use taxis. Third, both taxi use and transit use as a percentage of total travel increase as people age, although there are anomalies.

Unpublished 1983 NPTS data also show that work trips accounted for the largest percentage of all transit trips for those 65 to 70. Less than 0.1 percent of those over 60 used transit to visit doctors or dentists.

These trends again raise the problem of using cross-sectional data. Older cohorts of the elderly, particularly those who do not drive, may use transit now because they were transit riders when they were younger. This does not mean that nontransit users under 65 will suddenly become transit users when they age. Given the demographic trends and the automobile-licensing figures discussed in previous sections, transit use may continue to drop among future generations of elderly.

Conversely, younger drivers, used to the flexibility of the car, may find the taxi a more compatible option when they age. Even now, in contrast to

aggregate national trends just mentioned, elderly travelers in low-density communities and those in which there has never been high transit ridership frequently use taxis. A 1980 study for the Administration on Aging (AoA) (35) found that in six small urban and rural areas, between 10 and 30 percent of elderly people used traditional (i.e., full fare) taxi service regularly or occasionally. Wachs (36) found that well over one-fourth of the taxi business in the County of Los Angeles consisted of elderly passengers. Rosenbloom, in a 1974 unpublished study, found that between 40 and 60 percent of daytime taxi passengers in a large suburban area of Los Angeles were elderly.

Barriers to Taxi and Transit Use

Financial Barriers A major study done in 1976 of the travel needs of the elderly and disabled by the Urban Mass Transportation Administration (UMTA) found that the principal barrier to taxi use was affordability. Although a small number of elderly respondents had trouble getting in and out of the vehicle or getting a taxi to respond to phone calls, the study concluded that subsidized taxis would overcome between 37 and 60 percent of all barriers to taxi use for both the elderly and nonelderly handicapped traveler (37, pp. 14–15).

Conversely, financial barriers to transit use are relatively small, although it is common to assume that economic issues create significant transit problems for the elderly. For example, a 1977 Los Angeles study found that over 50 percent of public officials believed that cost was a major part of the transportation problem of the elderly (38).

Yet the elderly rarely report cost as a major problem; less than one-fourth of all respondents in the Los Angeles study reported transit difficulties based on cost. The study concluded that (38, p. 66) "it is obvious that reducing fares alone will not satisfy all the problems experienced by elderly bus riders."

The belief that low fares can increase ridership is not only ineffective, it can be dangerous. Requiring transit systems to offer very low fares reduces their willingness to make any of the service changes really required to meet the needs of the elderly. Wachs has noted (36, pp. 20, 21):

Low fares for serving elderly passengers might even discourage transit companies from making special efforts to improve services which are tailored to meeting the needs of the elderly. . . . If a transit company must charge its elderly riders only half the normal fare, it faces the prospect only of increasing deficits if it spends money to program improvements which will bring additional elderly riders. . . . [R]educd fares . . . clearly discourage transit managers from being creative in trying to serve larger markets of elderly patrons.

Physical Barriers to Transit Use Several studies have estimated that between 20 and 50 percent of the elderly (both drivers and nondrivers) have

physical or mental disabilities that might interfere with their use of transit (12). These studies usually infer a causal relationship between the presence of these handicaps and low transit use.

For example, in the 1976 UMTA study cited earlier (37) 7.5 million people were identified as "transportation handicapped" because they had such physical problems as the inability to walk $\frac{1}{4}$ mi or up three steps or to stand for a brief period; 47 percent of these were elderly—approximately 23 percent of the 1976 elderly population.

However, there are two major difficulties with studies that infer a direct relationship between handicaps and transit problems. First, a large number of those identified as facing transit barriers drive cars, for example, over 40 percent of those identified by the UMTA study as transportation handicapped. Second, inferring that the presence of a disability creates a barrier to using transit implies that the removal of that barrier will increase transit use. However, there is little empirical support for this widely held view.

For example, Table 10 gives unpublished 1977 HIS data on the effect of activity limitations on transit use. Consistent with NPTS data, the majority of the elderly did not use transit, but very few of the nonusers reported that this was because they faced physical or psychological barriers. Less than 11 percent of elderly nonusers under 80 reported that they would need assistance to use transit; the percentage rose to one-fourth of those over 80.

TABLE 10 USE OF TRANSIT AND NEED FOR HELP IN TRANSIT USE, 1977

Age Group ^a	Percentage by Use of Transit and Need for Help ^b					
	Uses Transit			Does Not Use Transit		
	Total	Needs Help	Does Not Need Help	Total	Would Need Help	Would Not Need Help
All ages (20+)	35.0	7.9	92.1	65.0	0.6	99.4
60-69	39.8	11.3	88.7	61.2	6.3	93.7
70-79	44.5	23.8	76.2	55.5	10.3	89.7
80+	52.8	54.5	45.5	47.2	22.9	77.1

SOURCE: Unpublished data from the 1977 special national Health Interview Survey.

^aWith and without disabilities.

^bExcludes unknown responses.

What is more striking about the data in Table 10 is that far more of those who used transit reported needing, and apparently obtaining, assistance in their use of transit—over 50 percent of those over 80 and almost one-fourth of those 70 to 79.

The data in Table 10 do not take into account differences in disabilities among the elderly, which might change these findings. Unpublished 1977 HIS

data show a weak positive relationship between the degree of activity limitation and the need for transit assistance. Less than one-third of those under 80 who had severe physical limitations (i.e., were unable to perform major activities as defined by the NCHS) reported difficulty with transit, and between 11 and 18 percent of those drove their own cars. Only those over 80 showed the expected relationship between severe activity limitation and the need for transit assistance; half of those respondents reported the need for help (but almost 6 percent of those needing help still drove).

These data suggest that there are more disabled people among those who use transit than among those who do not. There is no strong reason to attribute a great deal of the low transit ridership by the elderly to the presence of physical barriers within the transit system. Clearly, addressing these barriers would make transit better for existing transit riders, but it would do little to increase the mobility of those not currently riding.

Policy Implications

Environmental barriers to transit use are obviously significant. Traditional line-haul transit services—designed to serve work trips and often focused on historic downtowns—do not meet the needs of most elderly travelers. These systems are less likely to do so in the future when more of the elderly (a) live at fairly low densities and make extensive suburban-suburban trips and (b) are used to the convenience and flexibility offered by the private car.

There are three classes of options to meet the mobility needs of a population increasingly unable to use conventional transit and taxis even when other options are lacking. First, traditional transit service can be identified as inappropriate for most of the elderly; instead public agencies and transit operators can organize and provide alternative, or paratransit, services for all travelers.

Second, public agencies can directly subsidize some or all elderly travelers in their use of conventional taxis. Given the convenience of the taxi, and its presence in thousands of communities lacking conventional transit systems, this is an important option.

Third, transit operators can reorient some of their services and routes to meet the needs of the elderly; in so doing they may well serve the needs of other nondriving members of society, such as the young and the disabled. Public transit systems, alone or in conjunction with other agencies, can provide a variety of services geared to growing suburban concentrations of elderly as well as to those still living at higher density in central cities.

First, transit systems could reorient some routes to better match the origin and destination patterns of the elderly. This option may be appropriate for recurring activities and large trip attractors, such as shopping malls, hospitals,

senior centers, adult day care facilities, and so on. For example, for many years the Parks Department in Austin, Texas, paid the local transit system to run fixed-route service for attendees at a senior activity center; funding cuts forced cancellation of the otherwise successful program. A regional human service agency in Southern California identified concentrations of their elderly and handicapped clients traveling to daily programs and designed fixed-route service to match their origins and destinations.

Second, community-based systems with either flexible routes or a combination of fixed and demand-responsive services could be instituted. Such systems are common in Canada and Europe and have been tried with some success in the United States. Many neighborhoods in London and Paris have small community-based transit systems designed largely for the elderly, which also feed the larger rail and bus networks.

These new services will not be cheap, and they will continue to require significant subsidies, which, however, may be no more than the current ones required by peak-period fixed-route services. For example, communities like Memphis, San Diego, and Tucson have each contracted with private operators to provide flexibly routed or demand-responsive services in low-density areas; in all cases these cities have reduced the actual or expected subsidy required by traditional services in the area (39, pp. 181–214). In all these cities, the elderly are the largest group of riders.

None of these options is entirely satisfactory; each can only be part of a package designed to meet the needs of elderly travelers. In the short term such responses may serve a number of people; in the long term the package of responses must include land use and community planning changes that reduce the need for travel and promote other modes such as walking and cycling.

SOCIALLY PROVIDED TRANSPORTATION

Society provides a wide range of services and facilities to meet the needs of elderly travelers who cannot drive, use transit, or pay for taxis. For convenience, they can be grouped into four categories:

1. Those provided by private individuals informally through church and volunteer networks;
2. Those provided by agency staff and human service workers, generally informally, often in staff cars;
3. Those provided more formally by public or nonprofit human service agencies; and
4. Those provided formally by public transit systems.

Far more is known about the last two categories than about the first two. Human service agencies and transit operate both fixed-route and demand-

responsive services and a range of options in between. Many special systems also run charter services and specialize in group trips and outings. Overall, these services are more flexible than conventional transit even when routed or scheduled. They are often called specialized transportation or paratransit, because, in the best case, they approximate the convenience of the private car or taxi while still serving a transportation function.

There are as many myths about specialized transportation or paratransit for the elderly as there are about the other travel needs of older persons. Specialized transportation for the elderly now has the cachet—and the presumed curative powers—once reserved for mass transit.

It is important to understand that specialized transportation is far more limited and limiting in actual operation than it is in theory. It is expensive and difficult to operate well; moreover, the elderly do not seem to find such services more than a marginal addition to their existing transportation resources.

The data show, first, that few people find these services useful or satisfactory for many of their needs; even the most handicapped individual rarely takes many trips using specialized transportation. Second, elderly travelers show a pronounced desire for flexibility and choice in meeting their travel needs; specialized services usually form only part of a package of responses put together by these travelers or their families. Third, such systems are extremely expensive. Their high cost makes them an impractical way to meet the needs of the 18 percent of the population who will be 65 or older at the turn of the century.

In the short term, such services can meet the needs of handicapped travelers who have no other options. In the long term, other planning and land use options should also be considered to minimize the need for the handicapped elderly to travel long distances to take care of their human service and social needs.

In the following sections, federal programs and policies that support these more organized responses to the needs of the elderly are discussed; the kinds of services provided by human service agencies and transit systems are highlighted. Finally, the messages that can be found in the ridership patterns of such systems are considered.

Programs and Policies

Many federal, state, and local programs support specialized transportation for the elderly as well as for other disadvantaged travelers. In 1977 the General Accounting Office estimated that 114 federal programs expended money on transport services to disadvantaged and vulnerable client groups; the U.S. Department of Health and Human Services (HHS) is responsible for half of these programs, and DOT is responsible for only three.

Governmental policy and supporting programs have had two focuses—the regular transit system and services provided by human service agencies. DOT has been largely responsible for programs provided by transit systems, over time requiring that transit systems have special fares for the elderly and handicapped, that buses be accessible to the handicapped, and, most recently, that transit agencies make special provisions for the handicapped, including the handicapped elderly.

DOT has also played a major role in the development of paratransit services at the local level. Many transit systems provide specialized or paratransit services in response to DOT regulations. Also, the DOT program under Section 16(b)(2) of the Urban Mass Transportation Act of 1964, as amended, grants vehicles to private nonprofit providers to operate human service systems.

HHS agencies, as well as other federal agencies, also support a myriad of services and systems at the local level. The major funding programs in each federal agency and their estimated 1987 appropriations are listed in Table 11.

HHS Programs

Policy Mandates HHS, within which the AoA is located, spends a considerable portion of its annual budget on transportation services for eligible clients of its many programs. Because of the fragmented nature of these programs at the local level, and because transportation costs are often not itemized separately at either the federal or the local level, it is difficult to calculate the amount spent for transportation; in 1985 an HHS administrator estimated that the department spent \$800 million on transport services (41, p. 231).

The 1985 HHS figure, although striking, is debatable, because a 1980 study done for the AoA estimated that Title III of the Older Americans Act alone spent between \$500 million and \$800 million annually for transportation services (35).

Local Responses Most of the programs and agencies shown in Table 11 do not provide services specifically for the elderly. The exception is Title III, which funds services for any person 60 or over; Title III programs are not need or income tested. All the other programs have eligibility criteria that screen out elderly travelers unless they have the requisite physical, racial or ethnic, financial, or geographic handicap.

HHS-funded agencies provide transportation services locally by

- Reimbursing clients, volunteers, or staff for travel—so-called user-side subsidies;
- Contracting with or purchasing service from existing public, private, or nonprofit providers; or

TABLE 11 SEVEN MAJOR DOT-HHS PROGRAMS THAT DIRECTLY OR INDIRECTLY FUND TRANSPORTATION SERVICES (40)

Federal Program or Administrative Agency	Estimated 1987 Appropriation ^a	Beneficiaries
DOT Programs		
Section 9: Urban Mass Transportation Capital and Operating Assistance formula grants, Urban Mass Transportation Administration	\$2,224,989,000 (formula grants)	Individuals residing in urbanized areas benefit from these grants to public and private operators of mass transportation services (some diversion to rural areas possible)
Section 16(b) (2): Urban Mass Transportation Capital Improvement grants, Urban Mass Transportation Administration	\$35,000,000 (project grants)	Elderly and handicapped individuals receive transportation services through funded nonprofit organizations or private operators contracting with the nonprofit organizations
Section 18: Public Transportation for Nonurbanized Areas, Urban Mass Transportation Administration	\$75,011,000 (formula grants)	Individuals residing in rural or small urban areas receive transportation services from public transportation providers funded with these grants or private operators contracting with the public providers
HHS Programs		
Title XIX: Medical Assistance Program (Medicaid), Health Care Financing Administration	\$26,700,000,000 (formula grants)	Individuals meeting income and resource requirements and requiring medical services receive transportation services to medical facilities
Title III, Parts A & B: Special Programs for the Aging (grants for supportive services and senior centers), Office of Human Development Services, Administration on Aging	\$270,000,000 (formula grants)	Persons 60 and over, especially those with the greatest social and economic needs, receive transportation services to and from senior multipurpose centers, medical services, shopping, and other locations
Title III, Part C: (congregate nutrition services), Office of Human Development Services, Administration on Aging	\$348,000,000 (formula grants)	Persons 60 and over and their spouses, especially those with the greatest social and economic needs, receive transportation services to and from nutrition sites
Social services block grant, Office of Human Development Services	\$2,700,000,000 (formula grants)	Depending on the services provided by the grant, eligible individuals receive transportation to support program services

^aTotal amount appropriated, which includes the amount spent for transportation.

- Directly providing transportation services by buying vehicles and operating their own systems.

Although HHS programs vary in the extent to which they allow funded agencies to choose among these three major options, there is considerable evidence that many agencies ultimately do operate their own systems. For example, in 1985 Title III-B of the Older Americans Act funded 4,000 individual transportation systems. In 1985 HHS reported to Congress that approximately half of their transport expenditures went for direct provision; the remaining funds were evenly divided between user-side subsidies and purchase of service (41).

AoA-sponsored systems are typical of those choosing direct service provision; the number of local systems grew from an estimated 1,000 in 1974 to 3,200 in 1980 (35) to over 4,000 in 1985. This profusion of HHS-funded services has been severely criticized because it confuses eligible recipients, creates narrow categories of eligibility for any given service, and leads to expensive inefficiency.

There is a very wide range of costs for individual trips delivered by these systems—from \$4 to \$31, although system-reported costs are suspect. Systems that carry only the ambulatory elderly tend to have the lowest costs, ranging from \$5 to \$14 for a one-way trip, because they serve limited destinations like congregate meal sites and because they do not include the time required to assist nonambulatory riders.

A 1987 survey of 10 states found that only 7 could itemize the transportation component of their aging-program (Title III) expenditures. Only 2 states of the 10 surveyed—Pennsylvania and North Carolina (where the computation was done by the state department of transportation)—knew what an average client trip cost. The range is impressive: an average one-way trip cost \$5.30 in North Carolina and \$15.41 in Pennsylvania (42).

DOT Programs

Policy Mandates DOT funds services to the elderly in two key ways. First, there are two special programs that often serve special groups like the elderly: the Section 16(b)(2) program (discussed above) and the Section 18 program of the same act, which spends \$76 million annually for nonurbanized areas. Second, through its funding of capital and operating expenses at the local level, DOT assists transit operators in reducing fares and in providing specialized services for elderly and handicapped travelers who have difficulty with fixed-route transit. Section 9 of the Urban Transportation Assistance Act of 1970 is the major federal funding source for urban transit systems. In urban areas, Section 9 funds, and sometimes local funds, are used to provide the specialized transportation services for the elderly and handicapped that are required or encouraged by federal legislation.

Active federal concern with how local transit systems treat elderly and other disadvantaged travelers began in 1970 with the so-called Biaggi Amendments to the Urban Mass Transportation Administration Act of 1964, which required federally aided transit systems to make "special efforts" for the elderly and handicapped. These special efforts included requirements that elderly and handicapped citizens be involved in regional transportation planning efforts and that aided transit systems actually provide special services targeted toward these citizens.

In 1974 Congress specifically decreed that all elderly and handicapped citizens of a community receiving federal operating assistance were to receive half-fare reductions when they traveled in the off-peak period.

In order to pursue "special efforts," DOT suggested, but did not require, that local transit companies spend an amount equal to 5 percent of all money received under Section 5 of the Urban Mass Transportation Act of 1964, the predecessor to Section 9, on services for the elderly and handicapped. Recent DOT regulations relax the formal requirements on local transit systems but still require attention to the special needs of the elderly and handicapped.

Local Responses In response to these DOT requirements many cities began active programs for their elderly and handicapped riders; responses include user-side subsidies, contracting with a public or private provider, or directly operating services. Like HHS-funded agencies, most transit agencies also directly deliver transport services to the elderly, although contracting options have become a larger component of system operations. Teal (43) found that approximately one-third of all transit agencies contracted with the private sector to deliver specialized transportation services.

It is not unusual for an agency to separate services for the ambulatory and the nonambulatory. In some communities, the public agency contracts for one type of special service, usually for ambulatory travelers, and itself provides service for those in wheelchairs; Austin and San Antonio in Texas are examples. Some communities both contract for and directly provide all types of special services (Minneapolis and St. Paul, Minnesota).

The majority of transit systems restrict either ridership or financial subsidy to those elderly persons who have some permanent physical handicap that prevents them from using fixed-route transit. Simply reaching a certain age, lacking access to transit, or being unable to drive does not qualify an elderly person for such services in communities such as Chicago, Dallas, Houston, Miami, Milwaukee, Minneapolis-St. Paul, Philadelphia, San Diego, or Toronto (44).

Data from almost 70 systems for which comprehensive information was available, collected over 10 years and adjusted to 1986 dollars and reconstructed to include accounting, monitoring, and administrative expenses, give the following costs per trip for specialized transportation services:

	<i>Private Delivery (\$)</i>	<i>Public Delivery (\$)</i>
Ambulatory, congregate	4.20–11.00	3.80–6.90
Ambulatory, independent	6.30–11.00	12.00–18.00
Nonambulatory, congregate	9.90–17.90	11.50–29.00
Nonambulatory, independent	11.10–27.10	14.00–31.40
User-side	1.71–8.40	n.a.

A 1987 study found that a number of major systems were incurring comparable costs; the transit systems in Boston and Miami averaged over \$20 apiece for nonambulatory client trips, and six major cities were spending well in excess of \$10 for such trips (44).

Costs for ambulatory clients were also comparable, although in systems that contracted with taxi operators for some or all services, costs were lower. Houston, Dallas, and Milwaukee, all of which use taxis, averaged less than \$7 per one-way client trip. The cities with the highest average trip costs in the survey for ambulatory riders were Boston (\$25.75) and Toronto (US\$16.77), where the transit system directly provided almost all service (44).

Taxis are often cost-effective contract operators for transit systems, but it is important to note that most transit systems that use them in this manner change the nature of the services offered by the traditional taxi operator in ways that reduce their utility to the elderly. They impose scheduling and trip restrictions on users and often force group riding. Only user-side subsidy programs allow elderly travelers most of the choice and convenience of the conventional taxi.

HHS and DOT Coordination

Because both DOT and HHS sponsor so many services for elderly (and other) travelers, there have been attempts to coordinate among HHS programs and between HHS and DOT programs at both the national policy and local operational level.

At the national level in 1978, in the amendments to the Older Americans Act of 1965, Congress mandated that all services delivered to the elderly, including transportation, be provided in a coordinated and comprehensive manner. At roughly the same time DOT began to stress the brokerage concept as a mechanism to aid in coordinating the myriad of local service providers. Later, DOT augmented that approach with even more emphasis on privatization, as a complement to coordination.

In October 1986, Otis Bowen, Secretary of HHS, and Elizabeth Dole, Secretary of DOT, signed a joint agreement on the coordination of the transportation services funded by the two agencies. Among other activities, this agreement established a coordinating council at the federal level to conduct research and monitor coordination at the local level.

At the local level, HHS-funded agencies have increasingly worked with one another and with the local transit operator. Many large systems run and organized by area administrations on aging currently contract with other human service providers or are active participants in coordinated services organized by local transit authorities; Houston and Pittsburgh are two examples.

In other communities, smaller human service agencies routinely contract for services from either the transit operator's special system or other human service agencies. Several dozen agencies buy services for either individual client or group trips from the transit systems in Portland, Oregon; Lancaster, Pennsylvania; San Francisco and Sacramento, California; and Seattle, Washington.

Several states have also taken an active role in encouraging or requiring coordination of resources or services at the local level. Florida, Iowa, Maine, and North Carolina have mandatory coordination requirements. Each has established substate regions with a designated transportation provider, the only eligible recipient for DOT and most HHS transportation funds. All local agencies receiving key federal or state funds must either purchase service from this provider or prove that they can do it more cheaply.

Current Specialized Transportation Patterns

In analyzing the travel behavior of those elderly or other disadvantaged travelers who use specialized transportation, it is necessary to rely on ridership data from such systems; there is little information comparable with the NPTS data discussed earlier.

Using system-specific data creates several problems. First, the systems for which there are data do not constitute a random or even a representative sample; it is conceivable that the most atypical systems are the most studied. Second, most systems serve a variety of travelers; it is not always possible to differentiate the elderly ones from the others. Third, because of the restrictions imposed by these systems, it is difficult to tell whether the data reveal what people want to do or what the system has forced them to do. Last, it is important not to generalize from the ridership patterns of these systems to the universe of elderly; system riders are a very disadvantaged group. Most are elderly and poor, and suffer from multiple handicaps. The data in the following discussion show that between 50 and 90 percent of special system ridership is elderly and one-third to two-thirds have incomes below the poverty level.

Nevertheless, most elderly do not ride special systems and do not suffer from multiple handicaps. For example, special 1983 HIS data on the elderly

show that those under 75 were more likely to use special services than those over 75; at most no more than 16 percent of the elderly ever used such services and most never used them (45).

Table 12 presents data from the 1983 special HIS survey, which disaggregates specialized transportation and other service use by degree of activity limitation; these are the only nonsystem data available. Those living alone are more likely to use special services, as are those who are moderately to severely disabled.

The combination of those two variables yields the highest number of users; 15.4 percent of those with moderate to severe activity limitations who also

TABLE 12 USE OF SPECIAL SERVICES FOR THE ELDERLY BY THE ELDERLY, 1983 (45)

Special Service	Percentage by Living Status and Activity Limitation					
	Lives Alone			Lives With Others		
	All	Moderately to Severely Limited	Not Limited to Slightly Limited	All	Moderately to Severely Limited	Not Limited to Slightly Limited
Senior center	20.3	18.8	20.8	12.4	7.5	13.1
Senior center meals	11.9	11.6	12.0	6.4	4.4	6.7
Specialized transportation	10.5	15.4	8.4	2.4	2.7	2.2
Home-delivered meals	3.8	10.3	1.7	1.2	2.4	0.7
Homemaker services	3.0	10.4	0.5	0.9	1.7	0.5
Home health services	4.2	13.2	1.4	3.1	8.6	1.2

NOTE: "Moderately limited" means that one is limited in the kind or amount of one's major activity. "Severely limited" means that one is unable to perform one's major activity. "Slightly limited" means that one is limited in outside activity only.

live alone use specialized transportation. However, all other groups of elderly users are far less likely to use transportation, or any services, designed for the elderly. In contrast, note that conventional transit use was higher among similar groups.

Other studies show similar patterns. A 1981 review of 202 systems providing specialized transportation for the disadvantaged found that users tended to be elderly, without driver's licenses, without continuing access to a car, living alone, and with generally very low incomes (14).

Nevertheless, studies show that elderly users and nonusers of specialized services are also alike in several important ways. In 1980 an UMTA-sponsored study analyzed why some eligible users did not take advantage of

specialized transportation services in four cities. They found that users and nonusers made on average the same number of trips per month (46). The major difference between the two groups was that work trips constituted 10 percent or so of nonusers' trips; if work trips are removed from the analysis, the trip patterns are almost identical within each city. For both groups shopping was the major type of trip, followed by those for leisure and recreation. Medical trips were a distant third; in no city were more than 20 percent of trips taken for doctor's visits or therapy (46).

Elderly riders surveyed in five AoA-funded systems were making an even larger percentage of all their trips for shopping—ranging from 46 to 62 percent. Recreation trips were the second most common—accounting for between 12 and 26 percent. Club and religious activities accounted for between 5 and 15 percent of all trips, whereas medical visits accounted for the lowest number (47).

A 1979 study of all Medicaid recipients in Austin, Texas, found that elderly respondents had other travel resources besides subsidized services for some of their trips. In spite of having multiple handicaps and being eligible for special Medicaid transit, elderly respondents reported using that subsidized service for only half of their medical trips. Almost 30 percent of all medical trips were made in a car and almost 5 percent by regular city bus (in spite of the fact that ability to use mass transit technically made them ineligible for special services) (16, p. 111).

These analyses suggest three things. First, the elderly who use special services are usually nondrivers, but the distribution of their trip patterns resembles that of drivers. Users of special services make fewer trips than those that drive, but if they can, they try to retain flexibility and choice. If they do not have the freedom of those who drive, they find other ways to widen their transportation options.

Second, it is clear that although users of special services are often disadvantaged, some are drivers and most have access to cars. It is wrong to conceive of specialized transportation users as simply those with no other options.

Third, these data suggest that specialized systems may have to respond to the needs of drivers who do not always wish to drive. Apparently those who can drive occasionally use subsidized services, perhaps for a social event, perhaps to relieve themselves of the aggravation or cost of driving for any given trip.

Barriers to Specialized Transportation Use

Special services meet the needs of very few of the elderly; moreover, they appear to meet only some of the needs of those whom they do serve. The reasons for this situation are complex: as with other modes, these are both environmental and individual.

The environmental barriers to specialized transportation use are significant for many elderly travelers. First, most systems have rigid eligibility criteria: elderly users must have some physical or financial handicap. Such standards have both direct and indirect effects.

Directly, they select out elderly travelers who cannot drive but who are not living below the poverty level or facing serious physical ailments. This leaves a large number of elderly ineligible for service who still cannot travel without assistance from others. Moreover, many elderly travelers face different problems at different times of day or during different seasons but most eligibility criteria do not take into account seasonal or occasional problems such as driving at night or using transit during winter.

Indirectly, such standards act as deterrents because they create confusion among the elderly (and their advocates) about who is eligible for service and when. Some otherwise eligible travelers are no doubt discouraged by incorrect information about their eligibility (16).

The second major environmental reason why more of the elderly do not use specialized transportation services is that, once they are personally eligible for service, users find that, because of additional service and trip restrictions, the services do not match their needs. Many systems do not operate at night or on weekends. Some systems, particularly those with younger handicapped riders, give preference to work or school trips or to medical travel.

Third, most systems also restrict trips indirectly by having a very high number of prescheduled or reserved trips. Large sections of the day are blocked out during which these systems rarely have the capacity to accommodate the elderly traveler who wants a ride for social or recreational reasons—the kind of trip for which it is difficult to schedule a reservation.

A fourth major reason why the elderly do not use specialized transportation is its unreliability. Although there are often compelling reasons for such service problems, it makes little difference to the elderly person who will be late to an important appointment or to the traveler who is anxiously waiting to be picked up before the doctor's office closes.

Last, there is a major personal reason why the elderly do not use special services more; no matter how disadvantaged, elderly people want to keep their freedom and flexibility. Few people want to exchange the restriction of depending on friends and relatives for that of depending on a special service that requires significant advance reservation and questions the inherent value of each trip.

Moreover, it seems clear that even very disabled elderly people want to keep a variety of options, varying their mode choice with how they feel, the climate, and the availability of other options. No one wants to depend solely on one mode; several studies described earlier found that even those "objectively" judged unable to use conventional transit occasionally used the regular bus.

Policy Implications

It is dangerous to assume that specialized transport systems hold all, or even some, of the answers to the transportation problems of the elderly. Many current systems are at capacity and effectively limit demand by barring riders, restricting trip purposes, blocking out large windows of time for prescheduled trips, and even more simple mechanisms like not answering their phones. (A major system estimates that 40 percent of calls are never answered and an additional 30 percent are not answered in less than 6 min.)

Assuming that the important needs of the elderly can be met by any one service is simplistic; assuming that all their needs will be met by specialized systems is to doom the majority of the elderly to limited and often inferior service and for only those trips to which the provider has given priority.

Other alternative or paratransit responses are possible. One has been suggested earlier; public agencies could make better use of taxi and other private operators who already exist in many communities. Transit systems and human service agencies can do so first by supporting user-side subsidies and second by contracting with taxi operators for additional special services.

User-side subsidies, although not common, have a great deal to recommend them. A 1984 study of the public specialized transportation system in a large Midwestern city found that the agency could have saved between 15 and 30 percent if it had simply paid existing private taxi companies full fare for individual taxi trips rather than itself organizing and serving those trips through a special public agency (48).

SUMMARY AND POLICY IMPLICATIONS

Summary

Today two-thirds of the elderly live in the suburbs or in rural areas and over 90 percent of men and 40 percent of women are licensed to drive. The car is the dominant travel mode for all these travelers; even the most disadvantaged elderly make the majority of their trips by car.

The car is rapidly becoming even more important; from just 1977 to 1983 this mode increased in importance in the total travel pattern of the elderly, whereas walking and transit became even less important. Because of the accessibility offered by the car, the average older person travels more miles today than just a few years ago.

These trends will intensify into the next century. Almost one-fifth of the U.S. population will be over 65 by the turn of the century; almost three-fourths of the elderly will live in low-density areas and depend on the private car for the majority of their trips.

Given the inevitability that the elderly will lose their driving skills, it is important to consider how well the other modes can be made to serve their

travel needs when they can no longer drive. Unfortunately, even today the elderly do not walk or ride transit as much as their counterparts a few years ago, and only a fraction use specialized transportation services.

The elderly face a variety of personal and environmental barriers to their use of any mode: the data show that those who complain about transit or walking are those most likely to be walking or using transit. Physical handicaps explain only a small percentage of the lack of use, and these constraints seem small compared with the environmental ones.

Environmental barriers have complicated effects, often reducing the elderly's desire to travel before or while they reduce the ability to do so. Removing an obvious barrier to travel in a transit system or even providing door-to-door special service may not overcome the resistance of elderly people to utilizing the community and medical services they do not use today.

The most significant environmental barrier to transit and walking is clearly the spread-out nature of most American communities. The average elderly car driver could not easily convert an automobile trip into one or another mode; the average car trip to church, to the doctor's office, or just to visit friends could not be made one-way in less than an hour by walking or in less than 30 min by transit (even if transit were readily available).

The most significant environmental barrier to specialized transport use is the limitations in both services and choices. Even the most disadvantaged traveler rarely uses such systems for many trips because there are serious restrictions and operational problems. The costs of such services should give the policy analyst pause: they range from \$5 to \$30 for a one-way trip.

A driving-loss model was built for this study. It calculates the number of trips the public sector may need to provide at the turn of the century if it must bridge some or all of the transportation/travel gap between those who are still driving and those who have lost (or never had) the ability to drive. The numbers are staggering and stress that policy makers must actively consider a repertoire of options to meet the mobility needs of the elderly of the future.

The driving-loss model, which uses travel data presented in earlier sections, is shown in Figure 5. The model projects the year 2000 population by area (suburban, central city, and rural), groups the population by activity limitation, and projects the number of travelers in each group who will be unable to drive in 2000 (either because they have lost the skill or because they never drove).

Table 13 converts the number of elderly nondrivers in the year 2000 into the trips lost by each nondriver. The difference between the number of trips taken by drivers and nondrivers with comparable activity limitations is initially considered to be the number of trips lost by nondrivers simply because they cannot drive.

If the government felt obliged to provide all the missing trips, and could do so at \$7.00 a trip, a low-end average for current specialized transport systems,

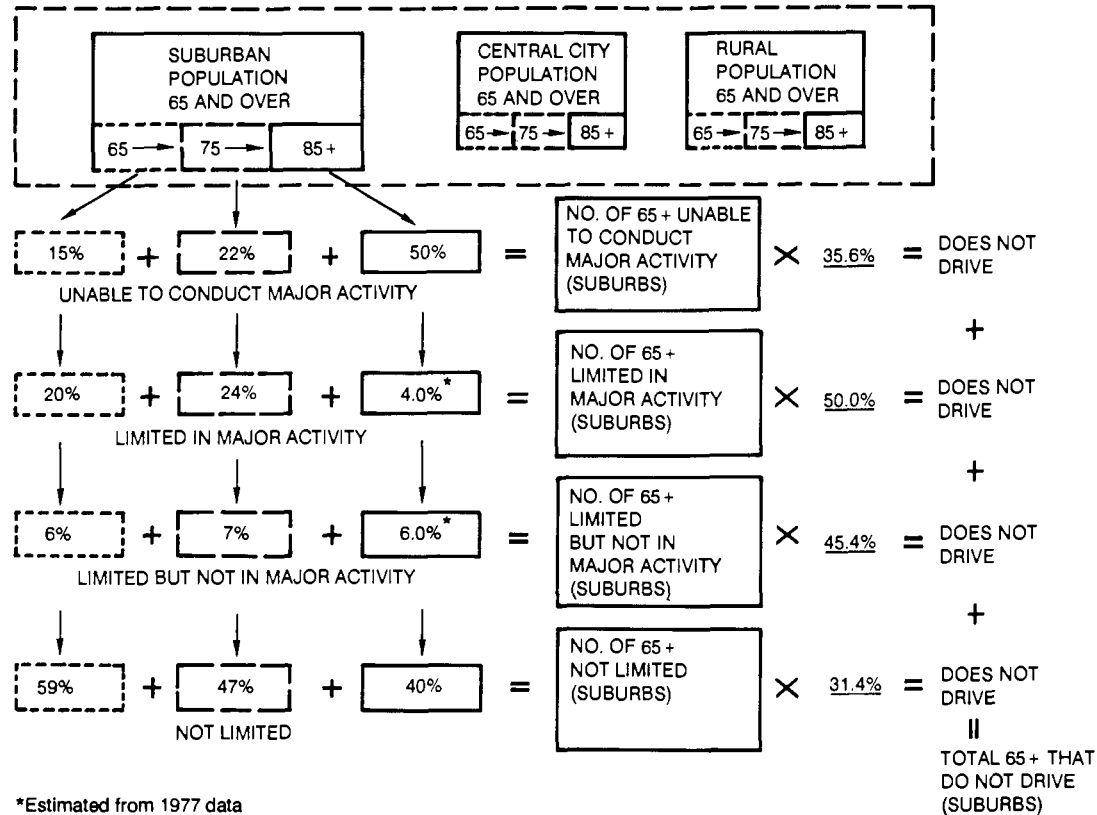


FIGURE 5 Activity-limitation model derived from cohort-specific activity limitation rates and age-specific HIS data [unpublished and described in *Developments in Aging: 1983* (50)].

the total annual cost would be in excess of \$174 trillion. It might be worthwhile to note that this figure is more than 10,000 times greater than the current AoA budget.

Even if society assumed responsibility only for the travel needs of those with severe physical limitations, 5.2 trillion trips would have to be provided each year. If only 1 of 10 of the trips needed by those severely physically limited were served, this would still amount to hundreds of billions of dollars a year.

TABLE 13 LATENT DEMAND FOR TRANSPORTATION SERVICES OF POPULATION 65 AND OVER IN 2000

	No. of Nondrivers	Trips per Capita per Year	Total Annual Trips
Urban		1,734.4	
Activity limitation			
Unable to conduct major activity	821,730		1,425,208,582
Limited in major activity	986,592		1,711,145,388
Limited but not in major activity	297,116		515,317,417
Unlimited	1,753,335		3,040,984,073
Suburban		1,734.4	
Activity limitation			
Unable to conduct major activity	1,211,704		2,101,578,756
Limited in major activity	1,454,805		2,523,214,312
Limited but not in major activity	438,120		759,874,835
Unlimited	2,585,426		4,484,162,956
Rural		1,679.3	
Activity limitation			
Unable to conduct major activity	1,058,500		1,777,538,568
Limited in major activity	1,270,864		2,134,162,587
Limited but not in major activity	382,725		642,710,544
Unlimited	2,258,533		3,792,754,649
Total no. of trips not taken because of lack of transportation			24,908,652,616

NOTE: Table is based on high population projections for 2000.

SOURCE: Calculated from the driving-loss model and derived from cohort-specific activity limitation rates and non-age-specific HIS data (49, 50), and mid-series population estimates (51). Also based on unpublished 1983 Nationwide Personal Transportation Study data.

It is clear that no one transportation option can meet even some more reasonable subset of these numbers. In fact, without extensive attention to the other societal decisions that affect the elderly's need to travel, it can easily be predicted that the travel problems of the elderly will become far more serious.

Policy Implications

Addressing the mobility problems of the elderly requires both short-term and long-term responses in three areas: transportation, land use planning, and human service delivery models. If deficiencies in land use and human service planning are not addressed, the transport system will be unable to meet all the mobility needs of the elderly in either the short or the long term. It is not only wrong but dangerous to place the burden for all of society's failures on the transport network.

Transportation planners, in conjunction with other planners, must fashion a variety of solutions appropriate to the clients and the community. Four major recommendations stand out. Transportation planners must

1. Offer the elderly a variety of transportation options, each geared to their needs and desires as well as to the increasingly limited funds available to meet their needs;
2. Consider how and whether current options can be improved or made more responsive to the needs of the elderly before offering alternatives;
3. Ensure that socially devised solutions support and rely on private and family options, in recognition of the web of potential support systems in which the elderly live, which could be strengthened both financially and socially (in part because the cost of duplicating them would be so extraordinary); and
4. Always recognize the importance of the automobile to the elderly, how pervasive it is in their lives, and the great potential of this mode and the advantages it offers when social solutions to the needs of the elderly are devised.

Among the most useful actions in support of these recommendations are

- Enhancing the pedestrian environment in both the short and the long term,
- Supporting volunteer and family networks,
- Training and retraining automobile drivers,
- Facilitating paid and unpaid carpool networks, and
- Developing community-based mass transit and appropriate paratransit systems (for those unable to use other modes when modified).

To support these actions, land use and community planners must

- Identify current and future concentrations of the elderly and services and facilities of particular interest to them,
- Target long-range service plans and capital expenditures (e.g., libraries, parks) on those elderly concentrations,

- Incorporate pedestrian-enhancing features into subdivision and zoning regulations, and
- Reduce the need for travel by facilitating small-scale mixed development in residential areas.

Human service planners must

- Develop effective outreach programs,
- Physically locate groups of needed services together near concentrations of clients,
- Match long-range land purchase and capital development programs to future concentrations of elderly, and
- Aim programs more clearly at clients who really need—and want—them.

The sheer size of the problem of transporting all those without cars and the complexity of fashioning appropriate responses for urban, suburban, and rural users will necessitate the use of all the resources currently available to the elderly as well as the development of additional resources.

ACKNOWLEDGMENTS

The author is indebted to many people who helped organize and digest the voluminous data in the two unpublished studies on which this paper relies so heavily. Jerry Hendershott of the National Center for Health Statistics made available the unpublished HIS data, and Rich Margiotta, and particularly Malcolm Quint, of the Transportation Research Board programmed the NPTS data tapes.

Shahrzad Amiri painstakingly organized the NPTS data from computer printouts, and James McCaine produced most of the graphics; Abi Lerner and Sarah Copp are responsible for the remaining graphics.

Last, Steve Godwin, Bernice Neugarten, Bill Bell, Doug Gurin, and Claire McKnight made helpful comments on earlier drafts. They are not, of course, responsible for any of the errors of fact or judgment that remain.

NOTES

1. The Census Bureau changed terminology in 1980: in Table 2 the data for 1970 were termed "urban" and in 1980 they were termed "urbanized area."
2. These figures actually significantly understate suburban living in high-growth areas and in the West, South, and Southwest in general. The Census Bureau defines "central city" as all areas within the corporate limits of a city, thus including all land in such spread-out cities as Tucson, Jacksonville, and Oklahoma City. Conversely, the figures may overstate suburban living in the built-up areas of the Northeast where high-density communities adjacent to what has been defined as the central city are considered suburbs. This "overcounting" is less common.

3. The Census Bureau defines as "mobile" those who have changed residence once or more during the 5 previous years. Cohorts are groups of people born in the same time period; thus, a cohort can only grow through in-migration and can only decrease through death or out-migration.
4. Possession of a license does not equal travel, of course; as the data make clear, there is still a sizeable gap between the miles driven by men and by women in all age groups in the United States.

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Renewal Licensing of Older Drivers

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Basically, the elderly are no different from the rest of us as far as the driver's license is concerned. How would any of us react to the loss of our right to drive? In our society, for the young beginning driver as well as the older driver and those in between, the driver's license represents a sense of freedom to come and go as we please. Its symbolic value is probably at least as great as its actual value. Just as the young person views the license as a rite of passage into the adult world of independence, so the elderly driver views its loss as a loss of independence and even identity. And indeed this view is based in large part on reality. The identity aspects can be dealt with through the issuance of an identification card that looks like a license and is used by many older persons in place of a license for the purpose of cashing checks. However, the independence aspect cannot be so easily addressed. The loss of the license is a very real loss that frequently places the older person in a position of dependence on those who previously depended on him or her. It is a difficult and often painful role reversal for all concerned.

At the same time, it is clear that the risk of crashes per mile driven increases for older drivers, and markedly so for those 75 and over. Furthermore, older persons are much less able to survive a crash of any given severity because of their vulnerability to injury and death. Consequently, they pose an increased safety risk to themselves and others, one that cannot be ignored. Their growing numbers simply underscore the increasing magnitude of the problem.

In the past, states have been almost lax in their recognition of and response to this problem. By and large, licensing programs have been designed to qualify young beginning drivers, and relatively little attention has been given

to the special needs and capabilities of the elderly. However, the growing size of the elderly driving population in combination with the increasing potential liability of states for failure to implement rational procedures for licensing high-risk drivers have led to increasing attention to what, if anything, can or should be done in renewal licensing of the elderly.

This paper will review what is known about this issue, and recommendations will be made regarding program modifications and research. The conclusions drawn should not be considered final in that the issue has not been sufficiently investigated to warrant definitive solutions. Nevertheless, an attempt is made to make interim recommendations based on the evidence available.

CURRENT STATUS OF RENEWAL LICENSING

U.S. Renewal Practices

The federal highway safety standard for driver licensing (1) includes the following requirements for the reexamination preceding renewal. The reexamination should

- Occur at least every 4 years before license renewal,
- Include testing for visual acuity at least and for knowledge of rules of the road,
- Be designed to identify driver deficiencies and limitations,
- Provide remedial measures for applicants with such deficiencies and limitations,
- Include provision for terminating the driving privilege of those who are unable to meet safe driving standards, and
- Provide remedial procedures for improving driver performance by refreshing the driver's knowledge and educating him in areas unknown to him.

Of course, if vision testing and overall evaluation by the license examiner are to occur, renewal licensing must require in-person application. The following review of current renewal practices is based on a report by the American Association of Motor Vehicle Administrators (AAMVA) on state and provincial licensing systems (2), a recent evaluation of Pennsylvania's reexamination program (3), and, to a lesser extent, an evaluation of the Nebraska driver licensing program (4). According to the AAMVA, 41 jurisdictions in the United States require periodic reexamination of all drivers.

Frequency

States vary in the length of time for which a driver's license is issued. The most frequent term is 4 years, but at least one state issues a license for only 1 year and two for 5 years.

Vision Screening

Most jurisdictions (39) require vision testing of all renewal applicants. Maine institutes vision testing at age 40 and Oregon at age 50. Pennsylvania requires random vision and medical examination for applicants 45 and older. (Presumably the knowledge that one may be required to undergo such an examination would motivate applicants to be examined before renewal.)

Standards for visual acuity generally require 20/40 vision with both eyes open for licensure without restriction to corrective lenses. Some states have somewhat less stringent standards for licensure with glasses or for licensure in the case of blindness in one eye, or for both. Other states require better vision in the remaining eye if one eye is nonfunctional. Most states do not report testing for visual field, dynamic visual acuity, color perception, depth perception, or other visual proficiency for a regular operator's license.

Knowledge Testing

Eight jurisdictions report routine knowledge and sign testing of all renewal applicants. One state requires it beginning at age 89 and three more institute it at 75. Most states do not have routine requirements for knowledge and sign testing at any age.

Road Testing

No jurisdiction includes road testing for routine renewal of license. One state requires road testing beginning at 69, and three other jurisdictions institute it at 75. In addition, one state reports that the road test and medical report are discretionary at 65, and one state requires it at 78.

Medical and Physical Evaluation

No jurisdiction requires a medical examination for applicants for routine renewal, although Pennsylvania requires it for original licensure. According to the AAMVA report (2), the District of Columbia requires a medical evaluation and reexamination at 70, and according to Freedman (3), Louisiana does likewise.

Most states have in place some kind of medical advisory board (MAB), which provides expertise to the licensing authority on medical questions relating to an applicant's ability to drive safely.

Effectiveness of Reexamination

It is difficult to evaluate the effectiveness of any licensing procedures because, by definition, applicants must pass in order to be licensed. Hence, it is not

possible to obtain a sample of those who failed and evaluate their subsequent records. Nevertheless, a number of studies shed some light on the effectiveness of driver's license examinations.

Vision Testing Although it is obvious that vision is essential to safe driving, it has been difficult to demonstrate strong relationships between performance on standard vision tests and driving records (5). More recent work shows promising findings, but there remains a need to develop the research in this area further (6, 7). The importance of routine vision testing for all applicants is shown by failure rates on standard tests of visual acuity reported at all ages (8).

Knowledge Testing The evidence for the effectiveness of knowledge testing is even more limited than that for vision testing. Much of the difficulty may arise from the fact that most knowledge tests in existence are not well constructed from a psychometric standpoint, so that if there are relationships between driving knowledge and subsequent driving performance, they would be difficult to detect through the use of these instruments.

In the early 1970s North Carolina enlisted the Educational Testing Service to construct psychometrically valid knowledge tests for driver's license examinations. A subsequent evaluation of these instruments showed that when reported mileage was taken into account, those applicants scoring at or below the median experienced a per-mile accident rate that was 62 percent higher than those applicants who scored above the median. Thus it appears that performance on a well-constructed knowledge test is related to driving performance, as indicated by official driving records (9).

Nevertheless, when a test waiver law eliminated routine knowledge testing for most renewal applicants who had no violation convictions within the preceding 4 years, no evidence could be discerned that there was any detrimental effect for applicants 25 and older. Younger drivers who were excused from knowledge testing showed worse subsequent performance than their counterparts who renewed before the new law and hence were required to take the knowledge test (10).

In summary, it appears that the elimination of routine knowledge testing for older license renewal applicants who have no convictions during the 4 years before renewal has no adverse effects on subsequent driving performance, as measured by crashes and convictions on the official driving records.

Road Testing Road testing is time-consuming and expensive and is generally avoided when possible by both licensing agencies and applicants. Performance on the road test for the original license has been shown to have some relationship to subsequent driving record. Campbell (11) compared the road test scores of 1,100 drivers involved in fatal crashes with 1,100 drivers selected at random. Three maneuvers (out of 88) revealed significant differences between the two driver groups, namely, parallel parking, second left-

turn signal, and third left-turn signal. Shortly after this study was conducted, the state legislature removed parallel parking from the state road test.

A subsequent study by McRae (12) also showed some relationship between road test performance and subsequent driving record. However, the relationships were not strong.

The test waiver law referred to earlier provided an opportunity to measure the impact of the removal of routine road testing from the renewal licensing process for drivers 65 and older. It was anticipated that this change would result in observable differences in the subsequent performance of the affected drivers. However, an exhaustive analysis of the driving records of this age group failed to reveal any effects of the removal of routine road testing for this or any driver age group.

Furthermore, the implementation of the test waiver law required for the first time that driver histories be reviewed before applicants were sent their renewal notices so that the notice could indicate whether the applicant was entitled to test exemption. At the same time it was decided that those applicants with exceptionally poor records should be flagged for more intensive evaluation, including a road test. In this way the manpower that had previously been used to test all older drivers could be redirected at those drivers most in need of evaluation, namely, those with the poorest records. Evaluation of subsequent records failed to find any beneficial effects of this procedure. On the contrary, the data showed a statistically significant deterioration in performance of the road-tested applicants compared with drivers with similar histories who had not been required to take the road test (those who renewed shortly before the law was implemented).

These findings were consistent with those from a California study (13) that evaluated out-of-state applicants transferring licensure to California. In a procedure with no apparent bias, some applicants were road tested and others were not. When data were analyzed by age and sex, it was found that middle-aged women (30 to 49 years) given the road test had significantly more crashes and significantly more fatal and injury crashes than those not given the road test. With the exception of the young drivers, the other driver groups showed results with the same trend, although they were not statistically significant.

Ratz (14) examined the effects of a traffic safety film along with a long written test emphasizing safe driving or a driving test used in combination with a counseling session for renewal applicants with poor records. He reported that applicants who took the road test had a significant increase in fatal or injury accidents. Thus, the evidence suggests that road testing as it is currently practiced is probably not useful in routine renewal testing, even for older drivers. This is not to say that, in the case of questions about a specific older driver's performance, road testing should not be used.

Finally, there is evidence that the measurement of skill per se is not a good predictor of on-road driving performance (15), and the evaluation of older drivers must particularly reflect these limitations.

Medical and Physical Evaluation In-person renewal allows the license examiner to observe the applicants and, with proper training, to detect potential medical problems that may interfere with safe driving performance. The National Highway Traffic Safety Administration (NHTSA), in cooperation with the AAMVA and the American Medical Association (AMA), has developed a training program for license examiners that is available to state licensing agencies (16). It should be noted that even though the NHTSA training program for examiners has been implemented, at least to a limited extent, in several states, it has not been evaluated for its effectiveness in detecting potential problems. Nevertheless, at this time it is the most rational tool available for overall evaluation of applicants by the examiner.

Although the license examiner should never attempt to diagnose medical problems, it is important that he or she be trained to recognize when an applicant should be referred for more extensive professional evaluation. *The examiner's personal contact with the applicant is the only routine opportunity to detect potential problems. This opportunity should not be lost because of inadequate training.*

Chronological age per se is usually not a criterion for referral for medical evaluation, but the probability of developing medical problems does increase with age. It should be noted, however, that in the absence of specific medical problems, age alone has not been shown to be associated with poorer driving performance (17). Nevertheless, it has been recommended that older drivers be subjected to more frequent evaluation (18). Presumably the increased risk of problems for older drivers would constitute a legally sound basis for more frequent reexamination, but there have been no legal cases to substantiate or refute this thesis.

Renewal Practices in Canada and Other Nations

According to the AAMVA (2), Canadian provinces generally do not require vision testing, knowledge and sign testing, road testing, or medical evaluation for routine license renewal. However, a complete retest, including medical evaluation, is required in Alberta beginning at 70, and Ontario requires a complete retest annually beginning at 80. Manitoba requires a medical report at 65.

A recent report from Australia (19) addresses the effectiveness of license retesting of older drivers. The state of Victoria and the Northern Territory are alone in Australia in having no special provisions for licensing of older

drivers. Other states vary in the age at which special requirements are imposed, as well as in the requirements placed on older applicants. New South Wales requires a medical report and vision test for renewal of applicants 80 to 84, and from 85 on a road test is added. In the case of motorcycle licenses, annual road tests are required beginning at 80.

South Australia renews licenses by mail until 70, when a road test is required every 3 years until 80. Medical and eyesight certificates are required for those years after 70 when there is no testing. Beginning at 80, annual road tests as well as medical and eyesight certificates are required.

Queensland reduces the period of license renewal from 5 years to 4 beginning at 62 and reduces it further to annual renewal at 66. Annual vision and medical tests are required from 70 on.

Tasmania allows renewal by mail until 75, at which time there is an annual requirement for a road test, medical report, and vision test.

In Western Australia road and vision tests are required at 75, 78, and 80, after which they must be administered annually.

In Australian Capital Territory applicants are tested at 70, and a physician determines whether a license is issued for 1 or 2 years. After 75, annual medical tests are required.

Torpey (19) also reviews the literature on retesting of older drivers and compares the experience of older drivers in Victoria, which has no age-related requirements, with that of older drivers in other Australian states with special requirements. Examining the rate of involvement in both fatal and injury accidents, based on total population as well as licensed population, Torpey found no detrimental effects associated with a lack of special licensing procedures for older applicants. Indeed, for injury accidents, Victoria experienced a substantially lower rate than that observed in states with special programs. Thus, the study concludes that implementation of a retesting program for older drivers would not be likely to improve the current situation. Additional analyses of accident costs versus estimated benefits further confirmed the conclusion that institution of a retesting program for older drivers would not be warranted.

It should be noted that the retesting considered in this study involved physicians and optometrists. No study has directly addressed the effectiveness of a well-defined inexpensive screening (as opposed to testing) program designed especially for elderly drivers.

CHARACTERISTICS OF OLDER DRIVERS

Although in many, if not most, ways older drivers are similar to their younger counterparts, there are certain characteristics that set them apart. These include a reduction in mileage driven, characteristic patterns of violations, and an increased vulnerability to injury in the event of a crash.

Changing Driving Patterns

Data from the most recent Nationwide Personal Transportation Study (NPTS) (20) indicate that although older drivers still average fewer miles than younger ones, a larger proportion of both men and women 65 and over hold licenses, and the increase for women is even more dramatic than that for men. However, older women are the only ones to show a decrease in average mileage driven since the last NPTS (20, 21). Although mileage per older female driver is lower, because the proportion of women licensed has almost doubled, total mileage driven by older women is much higher.

Whether this increase in the proportion of older persons licensed, as well as the overall increase in mileage driven by this group, is viewed as a problem depends on how their performance is viewed. Based on the number of licensed drivers, older drivers are no worse and possibly somewhat better than younger drivers. Traditionally, licensing agencies, as well as the insurance industry to some extent, have taken the position that drivers should be judged or assessed on the basis of the absolute number of crashes or violations incurred. Thus, the driver with one crash is a better risk than the driver with two crashes, even if the latter drives 10 times as far as the former. (An exception is the commercial driver, who in some states is allowed an increased number of violations in recognition of the greater exposure to risk.)

However, older drivers as a group drive fewer miles than younger drivers, and when their crashes are calculated on a mileage basis, their records may be the worst of any age group (22). However, there is a relationship between low-mileage and high-mileage crash rates that holds true across age groups (23), and mileage appears to be much more strongly related to crash rates than either age or sex. High-mileage drivers of any age have lower crash rates per mile driven, and older drivers who report high mileage have crash rates comparable with those of other age or sex groups with similar mileage. Of course, it is likely that there is an interaction here, in that drivers who, for whatever reason, are having difficulty with their driving are more likely to reduce their exposure and thus fall into the lower-mileage group. Older drivers who continue to accumulate high mileage are more likely to be physically and mentally fit.

Violation Patterns

When violations as well as crashes occur, those involving older drivers differ from those of younger drivers. Brainin (22) identified left turns at intersections, inattention, failure to yield right-of-way, and failure to obey stop signs and traffic lights as problems for older drivers, with the difficulty becoming significantly worse after 75. In an analysis taking into account exposure by age and sex, Waller et al. (24) found that older drivers (over 64) are overrepresented in failure to yield, failure to stop, and safe-movement violations, but

underrepresented in recklessness, following too closely, and alcohol violations. When sex is considered, the overall pattern indicates that older drivers and women are similar in their driving behavior, as are younger drivers and men.

Based on their exposure, older drivers of both sexes were overrepresented in at-fault crashes, and older female drivers were overrepresented in total crashes. The crashes of older drivers were more likely to be multivehicle, particularly in the case of women, with a higher proportion occurring during the daytime. They were likely to occur at somewhat lower speeds than crashes of other drivers, and they were somewhat more likely to occur in an older car. A higher proportion of crashes involving older drivers proved to be fatal, with this outcome much more marked in the case of single-vehicle crashes.

Likewise, in her analysis of fatal crashes Partyka (25) found that fully 25 percent of the drivers over 64 who survived a crash that was fatal to someone else were charged with failure to yield the right-of-way, compared with only 7 percent of similarly surviving drivers under 65. Failure to observe signs and inattention were also more characteristic of the older driver.

Interestingly, Brainin (22) identified alcohol as probably the single most important factor in fatal crashes for drivers 65 and older, with estimates that 25 percent of such drivers are legally intoxicated. However, he indicates that the alcohol involvement is greatly reduced after age 75. In contrast, Waller et al. (24), examining crashes of all kinds, and Partyka (25), examining two-car fatal crashes, found that older drivers were less likely to have been drinking.

Vulnerability to Motor Vehicle Injury

Although older drivers are not overinvolved in crashes on the basis of their presence in the licensed population, they are more vulnerable to injury. Analyses based on the Fatal Accident Reporting System (FARS) data show a much lower proportion of older drivers surviving with no injury and, conversely, a much higher proportion experiencing a fatal injury (22).

More recently, Partyka (25), using 1979–1981 FARS data, analyzed 15,336 fatal crashes, each involving two cars. She found that older drivers were much more likely to die, and that the probability of death increased with increasing age. Compared with drivers younger than 20, drivers over 64 were five times as likely to die. She also examined crash configuration. For all accident configurations combined, the older driver had a 77 percent higher risk of fatality. However, the older driver was more likely to be in the car that was struck as opposed to the striking car and thus was more vulnerable to injury. Nevertheless, when crash configuration was controlled, the older driver was still 43 percent more likely to be fatally injured than other drivers. Thus, she concludes that the higher risk of fatality for the older driver has more to do

with lower resistance to crashes than to the crash configuration *per se*. This conclusion is consistent with an earlier report by Baker and Spitz (26). Thus crash avoidance and occupant protection take on added significance for this age group.

TRENDS IN LICENSING FOR OLDER PERSONS

There have been two conflicting trends in licensing older drivers. The first concerns efforts to reduce costs associated with license examination; the second stems from the increased liability of states for licensure of high-risk persons.

Reducing Costs of License Examination

The first trend focuses not on the elderly driver but rather on all licensed drivers, with the elderly consequently affected. The aim is to reduce the burden on both the public and the licensing agency by reducing or limiting the amount of testing required for license renewal. California has evaluated the impact of allowing drivers who have no entries on their driving record for the previous 2 or 4 years to renew their licenses by mail. In the case of the 4-year extension, eligibility was limited to drivers under 70. Extensive evaluations of these procedures concluded that the 4-year extension may result in a slightly higher accident rate overall, but not for the older drivers (27, 28). The small increase in crash experience for those drivers receiving license extension by mail was not firmly established statistically, although the authors conclude that there is "at least a 76% chance that the extension program does not increase accidents" (28, p. 165). Because the estimated savings to the state are close to \$3,000,000 annually, California has enacted a renewal-by-mail pilot program through which renewal applicants with clean records for 2 years or more immediately before the generation of the renewal notice are eligible for mail renewal that is valid for 4 years. The legislation allows two consecutive renewals by mail if the applicant meets the criteria.

Earlier attempts in California to reward drivers with clean records by extending their license by mail failed to show beneficial effects (29). Nevertheless, the more recent studies strongly indicate that removal of routine in-person testing for older drivers with clean records does not result in detrimental effects that are apparent in the official driving record. This finding is consistent with the evaluation of the North Carolina test waiver law that showed no detrimental effects of eliminating knowledge and road testing for license renewal for drivers 65 and over (24). Likewise, Stoke (30) found no short-term evidence that successful completion of a written knowledge test was associated with better subsequent driving performance.

In contrast, Creech and Grandy (9) found that when reported mileage is taken into consideration, drivers who score well on the knowledge test have significantly fewer crashes than drivers who do poorly. It should be noted that the test they were evaluating was carefully constructed to meet psychometric criteria, a situation that does not hold in the case of most state knowledge tests. McKnight and Edwards (31) examined the effectiveness of using written manuals and tests that deal with safe driving practices. They conclude that "well-designed manuals and tests are a cost-effective accident counter-measure" (31, p. 187). However, they found effects only for their new-driver and renewal groups, whereas the older driver group showed no consistent effects. McKnight has pointed out that the older drivers were not given as much information as the standard renewals but rather were given only that information specifically related to problems of age. Had they been given the other information as well, it is likely that they would have shown the same improvement as did the standard renewals. Furthermore, the older driver group was much smaller in size, and hence it would have been more difficult to detect an effect.

At least two studies suggest that removal of knowledge testing may have detrimental effects on younger drivers (24, 32) but not on older ones. Thus the evidence on the value of knowledge tests for renewal applicants, and particularly the elderly driver license applicant, is unclear. On the whole it appears that removal of knowledge testing for the older driver is not associated with adverse consequences, at least not in the short run.

The elimination of vision testing for renewal licensing appears somewhat more problematic. A recent report by Zaidel and Hocherman (33) examines Israel's system of requiring vision and medical evaluations for license renewal applicants 65 and older. They found that 25 percent of the elderly applicants were required to wear corrective lenses. However, they estimated that only 7 percent of all elderly drivers actually started wearing glasses as a result of the required vision test. Because of the cost of the vision and medical evaluations, and because they report considerable self-restriction of driving among the elderly, the authors conclude that the evidence does not warrant singling out elderly applicants for more intensive evaluation.

On the other hand, other studies clearly document the increase in frequency of vision problems that occurs with advancing age (6-8, 34-36). Although there is evidence that many older drivers attempt to limit their driving as their faculties show evidence of failure, there is also evidence that older drivers as a group may fail to recognize certain important limitations. Planek et al. (37) compared older drivers' errors that led to crashes with the perceptions of older drivers of their problems with driving. Although failure to yield the right-of-way ranked first in causes of older driver crashes, older drivers themselves ranked it ninth out of ten maneuvers that posed problems. Likewise, running a

red light ranked third as an actual cause of crashes but was ranked tenth by the elderly drivers themselves. Certainly the evidence on crash rates based on mileage driven indicates that even though older drivers limit their driving to safer conditions, they are still greatly overrepresented in traffic crashes. Furthermore, although Zaidel and Hocherman (33) concluded that only 7 percent of the elderly applicants obtained corrective lenses as a result of the license requirement, that 7 percent would translate into many thousands of drivers in this country.

Increased State Liability

The second, and opposing, trend in driver licensing has been weaker but is gaining momentum. It is a response to the growing recognition that the driving population is aging and that with increasing age there is an increase in risk per mile driven. This growing interest in and concern about older drivers accompanies an increase in the liability of state administrators for the programs they oversee. States are increasingly losing their immunity to suit, and licensing administrators have found themselves the defendants in actions brought by victims of persons licensed by the state but whose qualifications were questionable. Thus far, most cases have involved alcohol problems, but there is recognition that states must be prepared to defend their practices of renewing licenses for persons about whom questions may legitimately be raised. For example, routine license renewal by mail for a 95-year-old driver could be questioned in court if that driver subsequently injures someone else and it is discovered that his vision is seriously impaired.

Administrators are finding themselves in a dilemma, because there are no clear guidelines on how to deal with elderly applicants. On one hand, it is clear that impairment associated with aging is not closely correlated with chronological age for individuals. Those charged with protecting the interests of the elderly rightly use this fact to oppose arbitrary cutoff points for driving. On the other hand, the clear evidence that the probability of problems that would affect driving increases with increasing age places a responsibility on the states that cannot simply be ignored. National television coverage of extreme cases has not eased the burden on states.

Thus licensing administrators are subjected to directly opposing forces; at the present time, whatever course of action they pursue may very possibly lead to criticism.

Limitations of Driver Licensing Programs

Driver licensing should not be viewed as a way of screening out all the bad drivers. The factors that contribute to good or poor driving performance are

many, and licensing cannot realistically test for all of them. For example, it is known that certain personality characteristics are associated with a higher probability of poor driving performance, but it is not politically feasible to include personality testing as part of the driver licensing process. Furthermore, even under the best of circumstances driver licensing programs can only modify rates of crashes for large groups. The driver licensing process cannot predict performance for individuals. For example, in North Carolina 16-year-old boys have an extraordinarily high crash rate in their first year of driving. Approximately 20 to 25 percent of them will experience a crash. Even so, the best prediction for any one such driver is that he will be crash-free in that first year, because three-fourths of this group have no reportable crashes. Nevertheless, the excessive crash rate of this group argues strongly for special licensing procedures, that is, a graduated licensing program, even though most of the drivers affected by such a program would be crash-free under the current system.

If licensing programs cannot test for all characteristics relevant to driving performance and cannot make accurate predictions for individual drivers, what can such programs accomplish? A sound program should be able to determine whether an applicant meets the established criteria for licensure. These criteria should be based on evidence of their relationship to safe driving, even though they are not adequate for individual predictions. Thus, the vision screening is based on some evidence that groups scoring more poorly are characterized by poorer driving performance when age, sex, and exposure are controlled for. Likewise, it has been shown that a well-developed knowledge test is associated with driving performance. There is some evidence that skill testing is associated with subsequent performance, at least in the case of motorcycle operation. There is also evidence that persons suffering from alcoholism or certain forms of mental illness have poorer driving records. In all these instances the associations are based on group performance, not individual; at best, driver licensing can only modify rates for groups.

Driver license testing is not really different from other criterion testing. Successful completion of the medical boards does not guarantee that one will be a good physician. However, most of us would be reluctant to seek medical care from someone who has failed the boards. Meeting the criteria for licensure is considered necessary but not sufficient for safe driving, just as passing the medical boards is considered necessary but not sufficient for effective medical practice. In neither case would it be wise to eliminate the criteria, even though the prediction is less than perfect. In both instances decisions have to be made on an individual basis, whereas prediction is probably valid only for groups.

PROPOSED CHANGES IN LICENSING PRACTICES

The literature clearly shows that older drivers (65 and older) as a group do not constitute an increased hazard to the public (22, 38). Their crash rate per driver is no greater than that of younger drivers and possibly lower. However, it is equally clear that on a per-mile basis older drivers increasingly are overrepresented in crashes (39, 40) and that drivers 75 and over *as a group* are greatly overrepresented. It is also clear that older drivers are more vulnerable to injury once a crash has occurred.

How can driver license programs operate to enable the older person to drive as long as possible under conditions that are reasonably safe for both the driver and other highway users?

Outside of a very few urban areas that have adequate public transportation systems, the private automobile is the major form of transportation in the United States today. There is little indication that this situation will change in the foreseeable future. Housing patterns and the location of shopping and work sites combine to ensure that the personal vehicle will continue to be the choice of transportation.

In the United States the driver's license is prized as almost no other personal possession, and recent surveys to identify anti-drunk driving measures that the public would view as harsh have placed license removal near the top of the list (41). Thus, the removal of licensure from an elderly person, particularly someone who has not been involved in a crash or incurred any violations, must be recognized as a measure that is likely to be viewed as harsh and punitive by the driver as well as by others.

Although states persist in referring to the driver's license as a privilege, rulings by the Supreme Court have made it clear that driver licensure may not be denied or removed without due process and just cause (42). The fact that chronological age is a poor indicator of functional age makes it more difficult to design a license renewal system that is cost-effective and at the same time fair to the elderly applicant, not to mention legally defensible. Ultimately, all licensing decisions must be made on an individual basis, although it is apparently possible to introduce modifications in licensing procedures on the basis of age.

Several states already have such practices. Most frequently, the only modification for the older driver is that the regular 4- or 5-year renewal cycle is reduced to 2 or 3 years, although at least one state requires annual renewal at ages 75 and older. Some of these states also require increased frequency of renewal for very young drivers as well. This shorter renewal cycle allows the examiner to evaluate the applicant in person, thus enabling earlier detection of developing problems.

Graduated Driving Reduction Program for Older Drivers

Possibly the most important modification that should be considered for older drivers is a graduated driving reduction program. Just as there is growing recognition that young beginning drivers should not be introduced into the driving population all at once but rather eased in gradually, it should be recognized that many, if not most, older drivers do not have to be abruptly removed from the driving population. All states have the authority to place restrictions on the driving of any applicant, but traditionally license examiners have been reluctant to impose them. MABs often assume this role, but the major portion of their cases involve alcohol problems. Even so, there is currently some experience with gradually reducing the amount and kinds of driving that older drivers may do.

It is not suggested that restrictions be imposed indiscriminately or in accordance with specific chronological ages. However, it is recommended that clearer guidelines be established for how and when, as well as what kind of, restrictions should be placed on some older applicants. The development and use of more relevant vision tests could be useful in defining and applying appropriate restrictions.

Because of the rapid increase in crash risk after 75 it appears warranted to increase the frequency of routine reexamination beginning at this age. With in-person renewal the examiner could determine whether a license should be issued for 1 or 2 years, but it appears reasonable to require renewal for this age group at least every 2 years. It should be recognized that any arbitrary cutoff age is likely to trigger opposition, but the available data suggest that 75 would be defensible. As indicated earlier, if states do not implement some special procedures, they may find themselves under attack or even liable for failure to act on the basis of evidence that crash risk increases dramatically at these upper ages.

Counseling for Driving Alternatives

At whatever age special procedures are incorporated as a part of routine testing, there needs to be some special program to assist drivers in making the transition from full-fledged driving to more restricted and eventual elimination of driving. Whether or not the licensing agency addresses this need, the society as a whole is going to be faced with it as more drivers reach the point at which they can no longer meet their own transportation needs.

There are no simple solutions to this problem. Nevertheless, it would be useful to begin to address it, and the licensing agency is a logical place to start. It is the licensing process itself that officially defines the boundaries within which one may legally operate a motor vehicle on the public roads. Therefore,

it is reasonable for any program designed to assist in identifying alternatives to driving to be affiliated with the licensing program. Whether the program is sponsored by the state or by private interests and coordinated with the state is irrelevant to its overall purpose and function. Its aim would be to work with drivers of any age, but most likely predominantly older ones, who are faced with the prospect of limitations on their driving and who must therefore identify alternative means of meeting their transportation needs. Ideally, such a program would be community based, so that there would be not only broad knowledge of local resources but also a local commitment to develop resources where needed.

Obviously, program for identifying alternatives to driving is based on the assumption that such alternatives either exist or could be developed. Where there are no such alternatives, it will be less feasible to restrict or deny licenses to elderly applicants. In other words, the decision to restrict will to some extent be based on the available choices rather than on an arbitrary standard that is applied in every instance. This approach is not different from what is already employed in vision standards. Although most states require 20/40 acuity in each eye, an applicant with only one eye may be licensed even though the standard cannot possibly be met. Even so, an applicant with 20/40 in one eye and 20/70 in the other may be required to use corrective lenses if by so doing the poorer eye may be improved to 20/40. The decision is based on what can potentially be accomplished by imposing a requirement for corrective lenses. By the same token, if there are driving alternatives available, restrictions are more likely to be imposed than if there are no such alternatives. The ultimate goal is to fulfill the necessary transportation needs in as safe a manner as possible.

Initially, there will be a need for developing overall guidelines for how to establish and operate such a program. It may be that organizations such as the American Association of Retired Persons (AARP) or the American Automobile Association (AAA) could assist in this endeavor, beginning with exploration of existing efforts, however informal they may be.

It should be emphasized that the development of this kind of assistance will not be creating a need but rather organizing a response to an existing and growing need. It will enable a more fruitful approach to the problem because it will identify and capitalize on whatever ingenuity has already been brought to bear on the issue. Older drivers and their relatives and friends can share what they have already learned, often through trial and error and difficult experience.

BENEFITS OF CHANGE

Because the driver's license holds such symbolic, as well as real, value to the older applicant (as it does to all of us), it is important to assess carefully the

trade-offs involved in the imposition of special license renewal procedures. A graduated driving reduction program, if widely applied, may assist older drivers in becoming used to the idea of limited driving. Indeed, the early stages of such a system would probably not be imposing many restrictions that are not already self-imposed by most elderly drivers. Nevertheless, the official sanctioning would clearly communicate to the older driver that he or she must begin to limit the circumstances of driving. Just as young beginning drivers accept restrictions in those states that have provisional licensing or curfew laws, or both, older drivers may be expected to gradually recognize that it is accepted practice to progress through a series of stages of driving reduction before total restriction.

Although any such system would need to be carefully implemented and evaluated, it may be anticipated that benefits would accrue not just to the older driver but also to the older driver's family. The older driver would benefit because the system would remove him or her from the more hazardous driving situations, if self-restriction has not already done so. At the same time, it would help prepare the older driver for the possibility that the driver's license may eventually be completely denied. The family of the older driver would experience some alleviation of anxiety in knowing that driving has been restricted to those circumstances in which it may most safely occur. Presumably, the public would likewise benefit because the driving that does occur is under the safest conditions. It is in the best interests of all concerned—the elderly, the family of the elderly, and the greater society—for older drivers to continue to drive as long as it can be accomplished in relative safety. Such a program, based on the best available evidence, should also provide licensing administrators with some security in knowing that their procedures for licensing elderly drivers are defensible.

COST OF CHANGE

The cost of change would of course depend on the practices adopted. The available evidence indicates that special procedures beyond those already in use in most states would not be warranted until about age 75. Routine in-person renewal that includes vision screening, medical questions, and overall evaluation by a trained examiner should be sufficient to detect most of those applicants who should be referred for further evaluation. In addition, states should establish routine procedures for reviewing crash reports to identify instances in which medical problems may have contributed to the crash. It is also recommended that physicians be provided immunity for referring to licensing authorities persons considered a hazard on the road but who will not respond to medical advice to cease driving. (The North Carolina Medical Society requested such legislation, but the state legislature rejected it.)

The increase in crash risk before age 70 or 75 is probably not sufficient to warrant across-the-board requirements for all applicants. Nevertheless, the state should carefully review current policies and practices to ensure that when problems do arise at earlier ages, they are likely to be detected before they translate into serious injury.

The proposed components of a graduated driving reduction program are discussed in the following sections.

Medical Questions

Most states already include such questions on renewal application forms, and they should incur no additional cost.

Vision Screening

Most states already include vision screening for routine renewal; in those states there would be no additional cost unless additional skills were included. Current testing procedures can measure static visual acuity under reduced illumination, but no vision-testing equipment currently in routine use for licensing includes a measure of dynamic visual acuity. Tests of both these skills should be included, but it is recommended that they be used with applicants of all ages, not just the elderly. Problems with night vision begin long before age 60 or 70. If these skills are incorporated into the licensing procedures, there would be no additional costs as far as the elderly are concerned.

Medical Advisory Board

Most states already have in place a medical advisory board (MAB), but special licensing procedures for the elderly may be anticipated to increase the load on this program. Even without a special licensing program for the elderly, it may be anticipated that the demands on MABs will increase, simply because of the increase in the elderly driving population and the corresponding increase in medical problems of all kinds. Thus, whatever additional cost is incurred as a result of a special program for the elderly will probably simply reflect cases that should have been referred but were not being detected before the special procedures.

Advisory Board for Licensing Elderly Drivers

Because of the special and growing needs of elderly applicants for licenses, it is recommended that each state establish a special advisory board to deal with

problems of the elderly driver. Such a board should work in collaboration with the MAB but be separate from it in that its focus would be somewhat different. Its membership should include not only medical experts but also legal experts and groups representing the interests of the elderly. The ultimate purpose of such a board would be to establish and interpret guidelines to enable as many elderly drivers as possible to drive as long as possible under as broad circumstances as possible while protecting the health and safety of the older drivers as well as of the public.

The cost of such a board could be minimal. The out-of-pocket expenses of participants should be covered, but it is probable that service on the board could be secured without remuneration or at most with token remuneration. It is assumed, of course, that once guidelines were established, the board would not have to meet more frequently than once a month and perhaps as infrequently as quarterly. There would, however, need to be funds to staff such a board.

Counseling Program for Driving Alternatives

Related to the advisory board for licensing elderly drivers would be a network of counselors to assist elderly applicants, as well as others, in identifying alternatives to driving. The advisory board should provide guidance to this counseling program, but there may also be a need for a state-supported system of supervisors or administrators to work with the counselors. From a cost standpoint, it would be ideal if the counselors themselves were volunteers, but it may not be realistic to anticipate obtaining sufficient assistance in this manner. Obviously, the cost to the state will depend on how much of the program is supported by state funds. This component of the program cannot be clearly described until there is sufficient investigation of existing programs and resources. It may well be that whether and to what extent state funds are required will vary from one area of the country to another.

Increased Frequency of Testing

Special licensing provisions for the elderly would likely be accompanied by a need for more frequent license examination; that is, greater attention to the possibility of developing problems could result in shorter renewal periods before the age at which all applicants would be required to appear more frequently. Until there is better evidence substantiating the effectiveness of road testing, reexamination should not routinely include this component. (It should be pointed out, however, that from the standpoint of face validity, administration of the road test would probably provide the strongest defense

to the state in the event that problems arise later. Nevertheless, the high cost of routine road testing plus the lack of clear evidence for its effectiveness make it a low-priority component of reexamination.) There is no basis for including routine knowledge testing either. The elderly as a group perform worse on knowledge tests than do younger applicants, and there is no empirical evidence to support routinely subjecting older drivers to this experience. However, appropriate medical questions and vision screening should definitely be included. Furthermore, examiners should be trained to recognize the more obvious signs and symptoms of impairment.

Thus, the more frequent evaluation would not ordinarily result in more extensive testing than that which usually occurs. Because neither road testing nor knowledge testing would ordinarily be included, the amount of time required from both examiner and applicant would be minimal. Nevertheless, because the number of applicants appearing at the licensing station would increase, there would probably be a need for additional examiners, at least in some stations.

Records System

The imposition of a graduated driving reduction program will require accurate documentation on the driver's record of when and what restrictions were imposed. Without this information it will not be possible to evaluate the effectiveness of any program. There will be some cost associated with implementing such a system, but once in place it should not require any increased funding.

In summary, the costs of a graduated driving reduction program for older drivers will be those associated with enhancing the vision test, which should be applied to all applicants; increasing the work load of the MAB, which is likely to occur in any event; increasing the frequency of testing based on more careful evaluation of applicants and more frequent reexamination for applicants beyond a certain age; the establishment of an advisory board for licensing of elderly drivers; and development and implementation of a counseling program to identify driving alternatives.

POTENTIAL SOURCES OF REVENUE

The costs of special programs should be shouldered by the total driving population. Thus a graduated driving reduction program for the elderly would be financed in the same way as the graduated licensing system for young beginning drivers. Included in this approach would be the stipulation that the elderly driver not be required to pay for any additional examinations beyond the schedule routinely applied to all drivers.

A strong argument can be made for spreading the costs of such a program among all drivers. First, a larger proportion of the elderly fall below the poverty level than of the population in general. Furthermore, the medical costs paid by the elderly are on the whole higher. For some, but not all, money is a problem. If a graduated driving reduction program is aimed at enabling drivers to continue driving as long as is safely possible, it should not impose an additional financial burden on the applicant. Furthermore, it is in the best interests of other drivers that the elderly be allowed to continue driving as long as is safely possible because once they can no longer drive, their transportation needs must be met in other ways.

Finally, the distribution of the costs across the total driving population will result in only a very small increment in the cost of any one person. An increase of 25 cents per driver per year in North Carolina would create a \$1,000,000 fund to finance the additional costs. As noted earlier, the type of program recommended should not require large sums.

IMPLEMENTATION ISSUES

Legal, Administrative, and Institutional Barriers

Perhaps the major potential barrier to the implementation of special licensing procedures for elderly drivers is opposition from groups representing the interests of the elderly. Any program that is viewed as arbitrary and discriminatory will be opposed, and rightly so. It is important that the procedures adopted be developed with input from groups such as the AARP. The program must be viewed as fair by those who are most affected by it. Although states do not want to risk liability for licensing persons who should not be on the road, neither do they want to find themselves the object of discrimination suits. Even short of legal action, the appearance of discrimination against the elderly would not be welcomed by most licensing administrators. Thus, any proposed renewal licensing program must include careful scrutiny by experts on the constitutional aspects of driver licensing, as well as by representatives of the elderly themselves.

Administrative barriers include inherent resistance to change of any sort. Those responsible for the administration of the program, including the license examiners themselves, must be involved from the beginning and be given sufficient opportunity to understand and digest the reasons for change. Thus it would be useful to give examiners the opportunity to make suggestions before all procedures have been firmly established.

Institutional barriers include the traditional compartmentalization of governmental functions. Licensing authorities have not always worked closely with medical experts and, even where MABs exist, there is sometimes a somewhat adversarial relationship between the MAB and the licensing authority. It is important to obtain broad-based opinion in the planning of any

program so that disagreements are resolved at an early stage. Licensing administrators and the advisory board for licensing of elderly drivers should be in accord before new practices are implemented for elderly applicants.

In spite of potential barriers, it is possible for the various interests to work together to develop a program for renewal licensing of older applicants. Although it is unlikely that every state will be comfortable with the same program, variations could prove beneficial in that evaluation of different programs might identify those approaches that appear most promising.

Time Frame for Implementation

Although some portions of the proposed program would require additional research, most could be readily implemented in any state that is receptive to new ideas. The steps required are as follows:

1. A decision on the age at which special procedures will be routinely imposed. This age need not be below 70 or 75, but, in any event, its specification should be based on the collective thinking of all relevant groups. The time frame for this decision should be no more than 1 year. Of course, whatever decision is made could conceivably be modified later in light of new information.

2. A decision on procedures to be used to identify problems emerging before age 75 (or whatever age is selected). These procedures should be in place for all applicants, and many of them already exist in at least some states. These include, but are not limited to, the following:

- a. Routine medical questions on license application;
- b. Vision screening, including acuity under reduced illumination and dynamic visual acuity;
- c. Overall evaluation by a trained examiner (16);
- d. Routine review of crash reports to identify possible medical problems;
- e. System for reporting drivers identified as having special problems; and
- f. Greater use of restrictions on driving, for example, restrictions on speed, roadway system, hours or days of driving (or both), distance from home, light conditions, and weather conditions.

Determination of Special Procedures

For applicants the age selected and older, the examiner would still employ all procedures in use with other drivers. In addition, there may be more extensive medical questions and vision testing. If any medical evaluation is required routinely, for example, blood pressure, ideally it could be obtained through the

local health department. In other words, extensive and expensive medical evaluation should be avoided to the extent possible.

J. A. Waller (43) has recommended repeated examination of older applicants on successive days because of the large variation in performance that may be observed in this group. However, it is unlikely that such a requirement would be imposed at this time as part of routine procedures. Nevertheless, the major change beginning at the age selected would be the requirement for more frequent examination, and in certain cases it may be appropriate to require repeated evaluation on successive days. Ordinarily, the length of renewal for this age group could be as short as 6 months or as long as 2 years but probably no longer.

Initially, the procedures to be used in this system should be tested at a single major station so that problems can be detected and resolved before statewide implementation. Once the procedures have been clearly defined and the implementation practices determined, examiners will need training in their use. The time from when the system is designed until it is implemented statewide should be no more than 1 year. However, examiners should know well in advance that the new system is being developed.

PUBLIC POLICY AND OTHER ISSUES

It should be clearly stressed that although the data can only define the level of risk, they clearly show that with increasing age every mile driven by an older driver entails an increasing risk of crash. The data alone cannot determine what level of risk is acceptable. That decision must be made by those who make public policy.

The availability of acceptable alternative means of transportation would facilitate the selection of a lower level of risk; the absence of such alternatives may dictate the acceptance of higher-risk drivers on the public roads.

For a graduated driving reduction program to be successful, it must be acceptable to the public. This may require broad-based educational efforts to inform the public of the extent and characteristics of the problem. The current TRB effort should provide the basis for such an education program. If the public understands the nature of the problem as well as the overall goal of enabling mobility of the elderly within the constraints of safety for both themselves and the rest of the population, it is unlikely that serious opposition will be encountered. Nevertheless, those responsible for a program in any given state must be familiar with the data for that state and prepared to answer questions as well as respond to opposition.

RESEARCH NEEDS

The major research needs fall into five areas: review of the legal basis for special licensing procedures for the elderly, further development of vision and

other testing, special education programs for the elderly driver, state programs to counsel elderly drivers on alternatives to driving, and evaluation of any new programs implemented.

Legal Basis for Special Licensing of Elderly

There is a need at the outset for a careful review of the constitutional issues affecting special licensing programs for the elderly. Because some opposition is almost inevitable, there must be a clear-cut legal basis for whatever programs are implemented. Although legal authority is not sufficient for implementing a program, it is certainly necessary. Absent such authority, no program can be given serious consideration.

Development of Vision and Other Testing

A second research need is the further elaboration and investigation of special vision testing with particular emphasis on its practical application for elderly drivers. Much of the work in this area has already been accomplished, but there remains a need to define clearly those vision skills most relevant to license examination for the elderly and how they may be incorporated into routine licensing procedures at minimal cost. To the extent that visual skills may be improved through training—for example, learning how better to scan the roadway—methods for instruction of the elderly should be developed.

In addition, there remains a need in most states for knowledge and performance tests that are developed on the basis of psychometric principles. There is a science of test construction that has rarely been used in the development of driver's license tests. Unless the instruments used are scientifically constructed, they cannot be expected to reflect valid measures of the knowledge and skills of interest, nor can they be successfully defended in the face of criticism.

Education Programs for Older Drivers

A third research area concerns the extent to which older drivers can benefit from education concerning their driving habits, including how they choose when to drive or not to drive. This research should include the kinds of information elderly drivers can benefit from and how receptive they are to it.

It should be noted that the driver's license program offers an ideal point of contact for such educational interventions. If it can be demonstrated that older drivers can benefit from training or retraining, it may be possible to coordinate these programs with licensing to extend the period of driver licensure for those renewal applicants who successfully complete such instruction.

It may also be worthwhile to explore other opportunities for contacting elderly drivers about educational and service programs relevant to their needs. The driver's license program is the only state program that has the potential for reaching all drivers on a routine basis, and we have not begun to capitalize on the possibilities this contact offers. Educational and other information of all kinds could readily be made available through this contact, which is already being paid for by the taxpayer. Not all information provided would have to be aimed directly at older license applicants, but rather may be made available to those responsible for them. Thus the grown children of older drivers may be informed of alternatives available to reduce the necessity of driving for their elderly parents.

Counseling for Driving Alternatives

There needs to be research into the usefulness of assistance to elderly drivers in exploring alternatives to driving within their own particular circumstances. Most elderly persons, as well as their younger counterparts, do not have readily accessible public transportation. Nevertheless, there may be other alternatives, which would vary for different people. For example, it may be possible to arrange to go with a neighbor for groceries once a week with or without compensation. Or it may be possible to demonstrate to an older person how much less expensive it would be to use taxi service for transportation rather than maintain an automobile when it is used very little. What the possible alternatives may be and how the elderly could utilize them need to be further explored.

Most states have some type of driver improvement analyst who meets individually with drivers who have repeated convictions and attempts to assist them in solving their driving problems. This concept could be extended so that specially trained older-driver counselors could meet individually or in small groups to assist these drivers in identifying driving alternatives.

It may be that volunteers trained by the AARP, AAA, or state agencies could assume this function, at least in some states.

Evaluation of New Programs

Finally, as special programs for licensing older drivers are designed and implemented, it is essential that they include from the outset an evaluation component. It is highly unlikely that the ideal program will emerge immediately. Rather, it is more realistic to anticipate a bootstrap operation in which programs of varying sorts are implemented, and over time the better components of each are identified and incorporated by other states.

CONCLUSIONS AND RECOMMENDATIONS

The growing population of older drivers and the increasing use of motor vehicles by this segment of the population, along with their demonstrated increase in risk per mile traveled, combine to identify license renewal of elderly drivers as an area of growing interest and concern. There are conflicting values at stake. Our society is sensitive to any taint of discrimination against the elderly, and there is clear evidence that deficiencies attributable to aging do not neatly correspond to chronological age for any given individual. At the same time, the increased probability that deficiencies of some sort will occur with age places states under pressure to develop and implement some kind of special procedures for monitoring the performance of older drivers. Although it can be argued, and often is, that aging effects on performance can occur as early as the thirties, and that any special procedures to detect problems should therefore apply to all applicants, the fact remains that from a cost-benefit basis it would not be worthwhile to engage in elaborate interventions for all license renewals. Indeed, the data indicate that although increase in overall risk apparently begins in the late fifties, it is probably not great enough to warrant special interventions on a routine basis until the age of 70 or 75. Nevertheless, before that age there should be in place for all applicants procedures designed to detect the emergence of special problems, such as deterioration of vision or special medical problems that may affect driving.

Although there are no clear-cut indications for procedures that should be applied to all elderly applicants as opposed to younger ones, it appears that vision testing of all applicants should be expanded to include visual acuity under reduced illumination and dynamic visual acuity. In the case of applicants beyond a specified age (e.g., 70 or 75), the major modification should be to increase the frequency of renewal to at least every 2 years. In addition, greater use should be made of license restrictions so that the norm for older drivers would be a graduated driving reduction program. Just as young beginning drivers would ideally be introduced into the driving population gradually on the basis of demonstrated skill and experience, so the elderly should be gradually removed from the driving population as performance becomes less proficient. Such a procedure should be less traumatic for the elderly applicant, enabling driving to continue for as long as it can safely be done. Of course, there will still be some instances in which the license will need to be discontinued abruptly as a result of precipitous changes in ability.

It is also recommended that states create an advisory board for licensing of elderly drivers. This board would be charged with establishing and updating guidelines for the state licensing authority in the licensing of elderly applicants both before and after the age at which frequency of renewal increases. It

would also work with licensing and other relevant groups to develop innovative alternatives to driving that may be considered by individual applicants. Obviously, what some of these alternatives would be would depend not only on the circumstances of the individual applicant but also on the resources available in the community and the state.

Because so little is now known about the effectiveness of licensing modifications for the elderly, it is essential that programs be carefully evaluated and the results be made available to other states. In this way, states can benefit from each other's experiences and be better able to tailor a program that best meets the needs of their own citizens.

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Driver and Pedestrian Training

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This paper provides a discussion of current efforts to train older drivers and pedestrians, identifies ways of improving training and the best prospects for change, and outlines needs for further research.

RELEVANCE OF DRIVER AND PEDESTRIAN RETRAINING

Magnitude of the Problem

Older drivers and pedestrians face accident risks that differ substantially from those of their younger counterparts.

The Driving Problem

The nature and magnitude of losses in physical and mental functioning that make driving more difficult and less safe for drivers of advanced years have been well and completely described in other papers in this volume. Because they tend to drive less than their younger counterparts, older drivers have fewer accidents as a group (1) and on an individual per-driver basis (2-5). However, they have more accidents on a per-mile basis (6) and their fatal accident rate, both on a per-driver and per-mile basis, greatly exceeds that of other age groups except teenagers (7, 8). Moreover, older drivers tend to be more often responsible for those accidents in which they are involved (9, 2). Last, they are more likely to be injured or killed in any given accident than younger drivers (10, 11).

The solution often advanced—getting older drivers “off the road”—overlooks the extent to which older drivers already limit their exposure by driving less often and under less hazardous circumstances (12–14). It also overlooks the enormous dependence of older drivers on an automobile as a means of maintaining independent mobility.

The Pedestrian Problem

On a per-individual basis, pedestrians over age 75 have over twice the pedestrian fatality rate of any other age group (15). A major contributor to older-pedestrian fatalities is the greater vulnerability of the older accident victim to injury or death. Compared with children in the 5- to 14-year age group, a pedestrian 65 to 74 years old is four times more likely to die if struck by an automobile; those in the 75-plus age group are six times as likely to die. According to Evans (16), increased susceptibility begins at about age 20, increases steadily to about age 80, and then accelerates. Men are at greater risk than women throughout the age span and the difference increases sharply after age 75 (17, 18). However, elderly pedestrians appear to be at no greater risk of having an accident than are adults of other ages (19, 17).

It is of interest to note that the fatality rate for pedestrians over age 64 in the United States has declined by 32.5 percent during the decade 1975–1984, whereas that for ages up to 64 has remained unchanged (20). To what extent this reduction is due to a reduction in pedestrian travel within this age group as compared with changes in the characteristics of the highways and population itself (e.g., greater fitness) cannot be determined from available data. However, it is apparent that the involvement of older people in pedestrian accidents has been declining.

The Role of Training

Although safer cars and highways can help bring down the accident rate among older drivers and pedestrians, as such improvements have for other highway users, they will not necessarily lessen the apparent overrepresentation of older people in highway accidents. This is best achieved by measures that will help older drivers and pedestrians overcome those specific problems that lead to highway accidents and injuries. That is a role that training attempts to play.

Training can make highways safer for older drivers and pedestrians in two ways. One is by ameliorating the problems that lead to accidents and injuries. One such problem is simple lack of information. The highway transportation system has changed a great deal since most older drivers first learned how to

drive. It is evident that many have not kept abreast of the changes, as shown by the number of older drivers who come to a complete stop at the end of a freeway acceleration lane. Similarly, many older pedestrians are unfamiliar with Walk cycles and do not know what to do when the signal changes to Don't Walk when they are halfway across the street. Training can attempt to ameliorate these problems by providing up-to-date information.

Unfortunately, not all of the problems that affect the safety of older drivers and pedestrians can be overcome through training. A second role of training is that of helping older people to recognize and compensate for the effects of their deficiencies. For example, drivers who recognize that they have trouble finding their way in unfamiliar areas can allow someone else to act as navigator and avoid blazing new trails during heavily traveled times of the day.

Learning Requirements of the Elderly

Research fails to disclose any substantial differences between the elderly and other adults in what is required for effective learning. Outside of the need to accommodate the visual and hearing impairments of some students, the general principles of adult learning are as applicable to the elderly as to younger adults. Adult learning principles applicable to the training of older drivers and pedestrians can be succinctly summarized as follows:

1. *Instructional method:* Adults are much more responsive to instruction that allows them to interact with one another than they are to lecture. Not only are they less familiar with the lecture format than their younger counterparts, but they generally have more relevant experience to share with one another.
2. *Outside study:* The availability of reading material to permit outside study helps not only to reduce the burden on classroom instruction but also to accommodate the wide variation in learning rates that characterize older populations. Highly interactive classroom instruction provides an incentive for outside preparation.
3. *Familiar referents:* Adult instruction is made more interesting and more understandable by use of familiar referents. For example, right-of-way rules can be discussed in the context of a well-known local intersection; the problems of rush-hour traffic can be discussed in relation to local arteries.
4. *Physical arrangements:* The visual, hearing, and other impairments of some older students can be accommodated by (a) keeping class size relatively small, (b) prescreening films and slides to make sure that important material is legible, (c) seating impaired students where they can see and be heard, (d) using large print for all textual materials, and (e) providing frequent breaks.

CURRENT STATE OF THE ART

A variety of training programs have been offered to older drivers and pedestrians to help them overcome and compensate for age-related problems. Any attempt to assess the state of the art in driver and pedestrian training requires some prior determination of what such training can be reasonably expected to do. Therefore, this discussion will start with a summary of age-related problems that need to be overcome or compensated for, which of these problems are being addressed by existing driver and pedestrian training programs, and new developments in the training area.

Problems To Be Addressed by Training

Those problems of older drivers and pedestrians that affect traffic safety and are appropriately attacked through training are addressed here on two different levels. The first includes mental and physical problems that have been known to be related to both age and safety, such as vision, memory, knowledge, strength, and frustration. These are both problems that are the direct result of the aging process and those that result from age-related health conditions, such as cardiovascular disease or arthritis. The second level includes performance problems that are believed to relate to age and safety. Many of these result primarily from the mental and physical conditions related to the first set of problems.

It is important to emphasize that the problems to be addressed in this section, although age-related, are not universal concomitants of age. Only a small portion of the older population is significantly deficient in driving-related activities. The result is greatly increased variation across drivers rather than a general decline among all drivers. This variation is particularly great across age levels within what is considered the older population, with some functions showing no appreciable deficit until 70 or 80. Also, certain of the differences between older and younger drivers may not reflect changes in individuals themselves so much as differences that have existed in the age groups from the start. Younger age groups as a whole have the benefit of better nutrition and freedom from a variety of diseases, to say nothing of more information and experience relating specifically to driving. Many of the problems described in this section may lessen as younger age cohorts reach advanced years.

Mental and Physical Problems

A number of physical and mental functions have shown a relationship with both age and safety on the highway. For purposes of discussion, these functions will be subdivided into the sensory, perceptual, cognitive, motor,

and affective. Much of the information provided is drawn from recent reviews by Staplin et al. (21) and by Yanik (22). Although both of these reviews were concerned specifically with drivers, the problems discussed affect the safety of pedestrians as well.

Sensory Functions Vision is the sensory function most closely tied to age and safety. Although hearing is certainly age diminished and is believed to be important to the safety of both drivers and pedestrians, research shows little relationship between hearing loss and highway accidents.

Summaries of the relationship between vision and accidents have been provided by many studies (23–25) and the recent summary of age in relation to visual functions has been provided by Staplin et al. (21). From these sources, it is possible to piece together a picture of the impact on driving of diminished visual capacities such as static visual acuity, dynamic visual acuity, low-illumination acuity, visual field, contrast sensitivity, binocular depth perception, dark adaptation, glare resistance, and glare recovery. These problems are more fully discussed in the two papers in this volume by Schieber and by Bailey and Sheedy.

Obviously, the sensory problems noted cannot be directly overcome through training. However, through training, older drivers and pedestrians can be helped to recognize the nature and possible consequences of visual problems, as well as to seek ways of correcting them and compensating for them. Of the problems listed, only static acuity is open to correction, although improving static acuity will improve other aspects of visual performance. Many of the remaining deficiencies can be compensated for in driving. For example, compensatory behaviors include (a) avoiding driving under low illumination, which helps to offset deficiencies in visual acuity (particularly at low illumination), dark adaptation, and glare recovery; (b) increasing the frequency and speed of the scanning pattern to offset reductions in visual field; (c) wearing dark glasses during daytime; (d) avoiding substances that might degrade night vision (alcohol, poor diet); and (e) avoiding traffic and highway conditions that present heavy visual demands, for example, having to read street signs in fast-moving traffic.

Although sensory problems are not quite so debilitating to pedestrians as to drivers, they are still a threat to safety. Through instruction, pedestrians can be helped to recognize and compensate for lessened ability to hear approaching vehicles, to spot them in their periphery, or to judge the speed at which they are closing.

Perceptual and Cognitive Functions A number of perceptual and cognitive problems have been shown to relate to both age and traffic safety. These include the following:

1. *Knowledge:* McKnight and Green (26) found older drivers to be somewhat deficient relative to their younger counterparts in their knowledge of

many aspects of driving law and practice. These differences may result not so much from loss of information as from the lack of formal instruction at the time they first learned to drive and their failure to keep abreast of changes that have occurred since.

2. *General attention*: Hoyer and Plude (27) and Quilter et al. (28) found that ability to maintain general attention declined with advanced age, whereas Kahneman et al. (29) found performance on a test of attention to be related to accidents.

3. *Selective attention*: Older people tend to experience increasing difficulty in separating important from unimportant information (30–32). The decrement appears to be due in part to redundant processing of irrelevant information by older people (33). Deficiencies in selective attention have been found to be predictive of traffic accidents (34, 29).

4. *Attention sharing*: The ability to shift attention has been found to be age-related by Craik (35) and by Parkinson et al. (36). The relation of attention sharing to accidents has been demonstrated by Mihal and Barrett (34) and by Kahneman et al. (29).

5. *Information processing*: A decline in the speed and accuracy with which information is processed has been found among the elderly by Braune et al. (37), Welford (38), and Rackoff (39).

6. *Problem solving*: Although the solution of complex problems is not often required in driving, deficiencies in problem solving might manifest themselves in reduced ability to handle confusing signs and directions and to find destinations. Studies by Case et al. (40) and Arenberg (41) show a decline in problem-solving ability during later years. The study by Case et al. involved driving tasks performed in a simulator.

7. *Memory*: Short-term memory is a factor in the ability to recall signs and directions. Age-related declines in short-term memory are reported by Arenberg (42), Miller (43), and Welford (38). Craik (35) and Bacon et al. (44) found no such decline, but Rackoff (39) found it under conditions in which recall was interrupted by another task.

Of the various problems described, those dealing with knowledge are most readily overcome through training. Indeed, providing knowledge is one of the things that training does best. Research by McKnight and Edwards (45) shows that providing information to experienced drivers can improve their safety of operation provided there are means to ensure that the information is learned in the first place.

There is little evidence that any of the other perceptual-cognitive problems can be overcome through training. One study of field dependence showed improvement among elderly drivers in field-dependent tasks after a lengthy training program (46). However, it is impossible to tell whether the drivers learned to overcome their field dependence or simply learned to perform the

tasks better. The study did not measure changes in field dependence as related to other tasks or to actual driving. Similar reservations apply to a study that claimed to obtain improvement in the peripheral vision of older drivers through training (47). What improved was the recognition of silhouettes, and an equal improvement occurred without training. Arenberg (41) found improvement in a visual retention task through practice alone.

Whether or not training can truly overcome limitations in perceptual-cognitive functioning, it can certainly help older people identify and compensate for their problems. Compensating measures include (a) minimizing the amount of driving done under conditions that impose a heavy perceptual and cognitive load (extensive driving or unfamiliar surroundings), (b) enlisting the cooperation of others to help share the load (allowing a passenger to navigate or read road signs), and (c) exercising alternatives to reduce the perceptual-cognitive load (for drivers, using less-traveled roads; for pedestrians, crossing only at controlled intersections).

Motor Functions The following aspects of motor capability have been found to be related to age and accidents:

1. *Reaction time:* Probably the simplest motor capability is reaction time. Although this function has been widely tested among drivers, it has not shown significant relationships with accidents for age. Olson and Sivak (48) found no difference between younger and older drivers in time to respond to road hazards. Quimby and Watts (49) obtained a similar result for responses to filmed hazards. So-called "choice" reaction time, where certain cognitive functions intervene between stimulus and response, has been more vulnerable to the effects of age, but is really more appropriately considered a perceptual cognitive function.

2. *Motor skills:* Brainin et al. (4) found older drivers deficient in motor control skills including backing, lane-keeping, maintaining speed, coming to a stop, handling curves, and negotiating left turns. There is, however, no research linking these deficiencies specifically to accidents.

3. *Motor disabilities:* A number of pathological conditions can limit a driver's strength, range of motion, and coordination (11). Some of these are age related, including arthritis, hemiplegia (stroke), and Parkinson's disease. A number of other motor disabilities that are more numerous within the older population simply because there has been more time for such disabilities to occur include loss of limbs or other disabilities resulting from disease or accident. Brainin et al. (50) reviewed a number of investigations into the relationship between various disabilities and traffic accidents with no conclusive result. However, McKnight (51) found that physically disabled drivers paid a penalty in inconvenience, discomfort, and fatigue.

Although no formal research into remediation of motor skill deficiencies could be found, a substantial improvement in vehicle control skill as a result

of in-vehicle training conducted by the American Automobile Association (AAA) has been reported. Most of the improvement was attributed to simply learning the correct skills, which suggests that some of the deficiencies observed by Brainin et al. were due to lack of proper instruction at the outset. Even where age-related physical disabilities are irreversible, AAA reports that their effects can be greatly offset through selection of appropriate vehicles and use of vehicle accessories and special aids designed to assist physically limited drivers.

Affective Variables The foregoing discussion of age-related problems has focused solely on variables related to the ability to drive. A number of variables relating to the emotions (affective variables) have also shown relationships with both age and driving. Research has found older drivers to be lacking in confidence and aggressiveness (4), to display stubborn and selfish behavior (52), to be inclined to underestimate risk in driving (53), and to be more competitive and less willing to admit mistakes (54). Among pedestrians, Mathey (55) reports a tendency to shade traffic rules in their own favor and a tendency to expect drivers to make allowances for them. The caveats offered earlier concerning differences among individuals and cohort effects should be borne in mind when interpreting the results of these studies.

The literature discloses no studies involving the attempt to modify affective variables among older drivers specifically. Only one systematic attempt to improve driving through affective change has been reported (56), and the small sample employed rendered the results less than conclusive. However, it would seem desirable to inform older drivers of the nature of affective changes that tend to occur late in life and their possible effect on driving. Although there is no assurance that older drivers will recognize or do anything about such changes, an effort to overcome the effects of such changes is more likely to be made if drivers are aware of the changes that are occurring.

Performance Problems

Turning from the mental and physical problems that produce unsafe performance to the unsafe behavior itself, information concerning age-related performance problems comes primarily from studies of driver performance, records of traffic violations, and accident reports. Information concerning performance problems of older pedestrians comes primarily from accident reports.

Performance Studies A number of researchers have observed the driving behavior of older people (4, 40, 57–60). Because the various studies overlap considerably, it is pointless to attribute specific findings to individual studies. The specific problems include the following:

1. *Speed*: misjudging speed, driving too slowly, excessive braking;

2. *Search*: inattention, inadequate scanning, failure to observe to the rear, and pulling out without looking;

3. *Vehicle control*: less precise visual control, including deficiencies in maintaining path, maintaining speed, changing lanes, coming to a smooth stop, backing, left turns, and right turns.

Nolan (61), Ysander and Herner (12), and McKnight et al. (62) provide information about performance problems reported by drivers themselves. Many older drivers reported that when they had been drinking or had taken medication, it was becoming increasingly difficult for them to handle traffic conditions, as well as backing up, entering and leaving expressways, changing lanes, passing, entering and leaving parking spaces, handling intersections, turning left, and driving when tired.

Use of alcohol appears to be less of a problem among older drivers and pedestrians than it is for younger age groups (63, 64). When drinking problems are encountered, they tend to have arisen late in life as a result of frustration, depression, or a stressful event (65).

In contrast to alcohol, drugs of the legal variety seem to be a somewhat greater problem among older drivers and pedestrians than their younger counterparts. Although the elderly make up 11 percent of the population, they purchase 25 percent of both prescription and over-the-counter drugs. One study found that those over 65 averaged 13 prescriptions a year (66). In addition to the danger posed by the direct effects of these drugs is the increased danger resulting from different pharmacological reactions and interactions among drugs (67).

Traffic Violations The types of traffic violations sustained by older drivers have been summarized by Waller (68), Planek and Fowler (69), Harrington and McBride (70), and the National Safety Council (NSC) (15).

The most frequent citations for older drivers involve failure to heed stop signs, traffic lights, no-left-turn signs, and other signs and signals. These citations have not been attributed to willful disregard so much as to the failure of older drivers to take notice. These behavior deficiencies have been attributed to more fundamental deficiencies in vision, general attention, selective attention, attention sharing, field independence, and information processing. Older drivers are also frequently cited for right-of-way violations, but these are primarily in connection with accidents.

Accidents A third source of information concerning age-related performance deficiencies is the accidents in which older drivers and pedestrians become involved. Information on the relative involvement of older drivers in accidents has been provided by Brainin et al. (4), McKnight et al. (62), Moore and Sedgely (71), Partyka (72), and Maleck and Hummer (73). The overinvolvement of older drivers in accidents includes the following categories:

1. *Right-of-way*: Most right-of-way citations are issued for intersection accidents in which the cited driver was judged to be at fault. The typical reason for a right-of-way violation is the failure of one driver to see or adequately judge the speed and distance of an approaching vehicle. Such accidents are judged to be the consequence of driver problems with general attention, selective attention, judgment of speed and distance, and field dependency, as well as lack of adequate visual search.

2. *Left turns*: Many right-of-way violations involve left turns. To the problems underlying other right-of-way violations may be added limitations of visual field, which hamper detection of an oncoming vehicle as the older driver looks to the left along the intended path.

3. *Backing and parking*: Backing and parking accidents are generally attributed to physical difficulties that make it difficult for many older drivers to rotate their upper torso to see parked and approaching vehicles behind.

4. *Slowing and stopping*: In rear-end collisions, older drivers are more likely to operate the vehicle that was rear-ended. Many of these accidents result from sudden slowing or stopping in the traffic stream. Contributing factors are believed to be confusion, resulting from deficiencies in vision and information processing, and inordinate slowing for turns, necessitated by physical inability to turn the steering wheel quickly.

Studies of pedestrian accidents do not reveal marked differences between elderly pedestrians and other adults (20, 55, 75–77). Problems leading to accidents among elderly pedestrians include the following:

1. *Gap judgment*: misjudging the distance of approaching vehicles and the interval between vehicles;

2. *Attention*: stepping off of the sidewalk while distracted, following other pedestrians into the street after the light has changed;

3. *Visual search*: walking into pedestrians who are approaching, watching the traffic light instead of traffic;

4. *Expectation*: misinterpreting the motion of motor vehicles, assuming that other drivers will yield;

5. *Haste*: impatiently crossing after waiting, crossing mid-block between parked cars.

There is a possible cohort effect in pedestrian behavior. As pointed out by the Organization for Economic Cooperation and Development (OECD) (78), the elderly of the future may not perform like those of the present. Also, it should be noted that the fault for pedestrian accidents does not lie entirely with pedestrians. Howarth and Lightburn (79) found that drivers tend to look to pedestrians to resolve conflicts. Also, Zuercher (80) found drivers to be more aggressive toward pedestrians who look old.

Performance Training Needs All of the performance problems that have been described define training needs. Some of the problems simply result from lack of awareness of appropriate performance, for example, not knowing how to properly enter or leave a freeway. The training need here is rather simple—to provide instruction in proper procedure. Other problems arise out of diminished capabilities that cannot be easily altered. Training in such instances must help drivers compensate for deficiencies. For example, although drivers may not be able to correct the perceptual and cognitive deficiencies that often cause them to become confused and stop suddenly, they can be taught to respond to their confusion in ways that are less injurious, such as continuing with the traffic flow until the first opportunity to leave it safely.

A truly effective training program is one that not only teaches the proper way to do things but also anticipates the most likely errors and helps students to guard against them. One of the shortcomings of training programs for older drivers in past years has been that not many have instruction tailored specifically for older drivers. Although they may do a good job of describing the right way to do things, they do not help students to anticipate and overcome the specific mistakes that they are liable to make.

Driver Training and Information Programs

A great number and variety of training programs have been developed to help make driving safer and more comfortable for older people. The earliest training programs for older drivers were typically local ones conducted by universities, automobile clubs, and safety councils. Until the 1980s, the only national program available was the Defensive Driving Course offered by NSC.

Three national programs that have been specifically tailored to older drivers are 55 Alive/Mature Driving of the American Association of Retired Persons (AARP), Safe Driving for Mature Operators of the AAA, and the recently developed Coaching Mature Drivers of the NSC. The AARP program, having the organization's entire membership to draw from, has the largest annual enrollment—over 200,000 in 1986. By the close of the decade, an annual enrollment of approximately 300,000 to 400,000 is projected. No other program for older drivers approaches these numbers at the present time. The annual enrollment in the AAA program is somewhat under 10,000 per year. The NSC program was only recently completed.

Content of Training Programs

The most important aspect of any training program, including a program for drivers or pedestrians, is its content—what it teaches. Many of the early

programs for older drivers were driver improvement programs, with little or no attempt to tailor their content to the specific problems of age. For the purpose of discussion, content can be divided into two categories:

1. *Age-general*—instruction that addresses the problems of all drivers, and
2. *Age-specific*—instruction that deals specifically with the problems of older drivers.

Most of the training programs for older drivers are quite comprehensive with respect to general information. However, they vary considerably in the extent to which they deal with the problems that have been identified in the previous section. Although the various programs give extensive coverage to the specific problems of age, they do not go into all of the training needs that have been described. Perhaps the greatest shortcoming is not helping drivers to anticipate some of the specific problems they are likely to encounter, such as not being able to turn far enough to look over the shoulder on lane changes or to look out the rear window when backing, or tending to slow or stop suddenly when confused. This is not a criticism of the programs; it may not be possible to teach, within the 8-hr length of the three programs cited, all the content needed to fully address all the problems with which older drivers are confronted.

Training Methods

Almost all the programs intended for the improvement of older drivers, including the three just mentioned, are taught entirely in the classroom. A few of the organizations that conduct these and other programs also offer in-car instruction. However, students rarely take it. In-car instruction provides an effective way of identifying the specific deficiencies of individual drivers, both to the instructor and to the student. Brainin et al. (4) concluded on the basis of their road test of older drivers that in-car instruction could be of considerable benefit to older drivers.

The primary reason for the absence of in-car instruction in most programs for older drivers is economic. Even when drivers furnish their own vehicles, the cost of in-car instruction can range from \$25 to \$50 an hour as compared with as little as \$10 for an entire 8-hr classroom program. The AAA program offers in-car instruction as an option but reports that only about 5 percent of the students elect to take it. About three-fourths of these are women.

Program Support

The three major older-driver training programs are supported both by the organizations developing the program (AARP, AAA, and NSC) and by the

older drivers participating in the program. Support from the developing organizations includes the cost of developing the curriculum and its materials as well as the cost of publicizing the program. The personnel and facilities costs associated with actually giving the program are supported by student fees. The participation of local businesses and private agencies has often been enlisted to provide publicity and facilities. For example, over 200 banking institutions now cooperate in administration of the 55 Alive/Mature Driving program through the cooperation of the AARP and the American Bankers Association.

Enrollment Incentives

By far the most vexing problem in efforts to improve the performance of older drivers through training is simply getting drivers to take it. A study by McKnight et al. (81) indicated that less than 2 percent of the licensed driving population would voluntarily enroll in a driver improvement program. In the past the overwhelming majority of drivers enrolled in programs like the Defensive Driving Course were either employees whose organizations covered the costs and permitted attendance on company time or those convicted of traffic violations, who were attending in order to reduce accumulated points or to keep from having their licenses suspended. Current incentives for participation beyond the prospect of self-improvement include insurance discounts and license retention.

Insurance Discounts The device that has been increasingly used to induce the older driving population at large to enroll in training programs is the insurance discount. Reductions in insurance premiums of 5 to 10 percent have been offered to drivers who complete approved programs.

In recent years groups seeking increased enrollment in driver improvement programs have succeeded in obtaining legislation that specifically provides for insurance discounts. In a few states, the legislation merely permits underwriters to offer discounts and in others discounts are required. In addition, some states fix the amount of the discount and others leave it up to the insurance companies. In 19 states, the discount is extended only to older drivers; in 3 states, it is offered to participants of any age.

The rationale for offering insurance discounts is that participation in a program will lower the participants' accident liability and therefore reduce their claims. The state of New York found that drivers taking the driver improvement programs had a better loss-premium ratio than those who did not, even after a 10 percent premium discount (82).

The soundness of a discount from an actuarial viewpoint does not depend on the effectiveness of the program in reducing accidents. Research has shown rather consistently that drivers who volunteer to participate in any type of

safety-oriented program have better traffic records than those who do not, both before and after the program. Simply volunteering to participate in a program is an indication that a driver is a better risk than the population at large. A problem arises when an insurance company is already giving a discount to drivers with good records. If a training program does not actually reduce accidents, the discount that drivers are offered may not reasonably exceed that received already.

Currently, the enrollment in older driver training programs is relatively low. Even the 200,000 enrolling in the AARP program corresponds to less than 1 percent of the eligible membership, and only a portion of the enrollment actually comes from the membership. In New York only 1 to 2 percent of all eligible drivers were enrolled in driver improvement programs in 1983-1985, despite the offer of a 10 percent insurance discount (82). Unfortunately, no breakdown of participation rates by age is available. Although insurance discounts are apparently effective in inducing many older drivers to participate in training programs, only 1 to 2 percent of the eligible population is represented.

License Retention As mentioned earlier, one source of enrollment for driver improvement training programs is those convicted of traffic violations. The earliest violator training programs operated through referral from individual courts. Judges would offer convicted offenders the opportunity to attend a driver improvement program in lieu of license suspension. The availability of training programs provided judges an alternative to purely punitive sentences. As states began to keep records of traffic violations and set up a formal process for dealing with repeat offenders, a driver improvement course often became a step in that process. Some courses were operated by the state; others operated under referral from the state.

The literature discloses no driver improvement system in which special courses have been set up specifically for older offenders. Such special courses would be very difficult to administer. Drivers over 55 account for an extremely small proportion of the violator population and to form classes of sufficient size to be practical would, in most areas, introduce an extensive delay between conviction and treatment. This problem would not, of course, arise if there were regularly scheduled courses for older drivers to which offenders could be referred. However, organizations that run such courses are typically loathe to put violators in the same class with those who are there voluntarily.

In some states drivers who have volunteered to take courses have been allowed to earn credit that could be applied to future traffic violations. It takes but a moment's reflection to realize the absurdity of allowing traffic violators to escape penalty because of prior participation in a program that obviously did not work. In most instances, the provisions that allow drivers to "bank"

credit for training against future violations resulted from quirks in the law that have since been eliminated.

The need and desire to retain a driver's license can be a powerful motivator in the case of older drivers. A way in which this motivation might be exploited to induce far greater participation in training programs will be dealt with later in the discussion under New Developments in Training.

Driver Information Programs

Most of the time spent in current driver improvement programs is devoted to the simple delivery of information. Obviously, there are other ways to receive information than sitting in a classroom, and a number of efforts have been made to provide information through other means.

A recent report by Worthington et al. (83) identifies a number of systems for delivery of traffic safety information to older drivers and pedestrians. Although the various systems are not evaluated in either absolute or comparative terms, the findings point to organizations with which older people have frequent contact as offering the best access route. These organizations include churches, senior centers, retirement groups, professional and trade associations, physicians, and various types of stores (particularly supermarkets).

Broadcast and print media are reported as having ready access and high credibility with older people. However, the prospects or means of getting messages disseminated to such a circumscribed target group as the older population have not been described. The authors note that public service announcements are singularly inappropriate because of the hours at which they are generally presented. Some 21 organizations are identified as being prepared to develop and distribute informational materials to older drivers and pedestrians (83).

Although informational programs can reach a far greater segment of the older driving public than the 1 to 2 percent reached by formal training programs, they have no way to ensure that the information provided is being read and absorbed. When information is delivered in a classroom, instructors can take steps to make sure that students are paying attention, including giving tests, calling on students in class, and conducting discussions. However, when information is delivered through handouts or mailouts without any requirement to read the material, the effect on driving performance is often nonexistent (84). About the only step that can be taken to see that it is read and absorbed is to make it intrinsically interesting. This can be a formidable task when the information being disseminated concerns the audience's own deficiencies or the risk to which these deficiencies expose them.

One avenue of communication with older drivers that has been utilized in the past is the license renewal process. Here written material can be coupled

with a license examination to provide an incentive to study and absorb the information. Research has shown such coupling of materials and tests to be effective in reducing accidents (45, 85). Special manuals for older drivers have been prepared by the U.S. Department of Transportation and AAA. Use of the licensing process as a means of communicating information to drivers is discussed more fully in the paper by Waller in this volume.

Unfortunately, the trend in recent years has been away from renewal testing. To reduce the length of lines in licensing stations, many states have permitted renewal by mail for drivers with clean records. This issue will be dealt with further, along with other possible ways of reaching older drivers, in the next section.

Basic Driver Training

The discussion up to this point has been confined to training and information programs intended for the improvement of older, experienced drivers. There are, however, significant numbers of drivers each year who are seeking instruction to learn how to drive. Some have never driven before, whereas others learned to drive when they were much younger but have done little driving in recent years.

No statistics are available on the age distribution of older drivers in basic driving school instruction. However, an informal survey of driving schools shows that the single biggest group in the older-driver population consists of married women who, because of the death or illness of a husband or merely the desire for independent mobility, are learning to drive or starting to drive again. The size of this group has been diminishing, and should continue to do so as the older age groups are characterized by women who learned to drive early and who have continued to drive on a regular basis.

Remedial Instruction

Many experienced drivers are afflicted with disabilities that alter the nature of driving tasks for them and necessitate substantial relearning. Some of these disabilities are age related, such as arthritis and hemiplegia. Other disabilities such as loss of limbs, although not age related, tend to be more common among older people simply because with passage of time the likelihood increases that an older person will be exposed to conditions producing a disability.

A number of remedial instruction programs have been established for recently disabled drivers, primarily by rehabilitation hospitals and clinics and by universities (86, 87). These programs offer special training aids such as simulators and modified vehicles. Most severely disabled drivers become

aware of these resources through the medical facilities at which they are treated.

Paradoxically, the biggest problem in providing remedial instruction is with drivers having less severe disabilities. They are often treated in hospitals that do not specialize in rehabilitation and where personnel are not knowledgeable in the resources that are available. This leaves it to the afflicted drivers not only to retrain themselves but to discover which diminished capabilities need retraining.

Effectiveness of Programs

There has been as yet no truly conclusive evaluation of the effectiveness of training or information in improving the performance of older drivers. As far as programs dealing specifically with older drivers are concerned, not many evaluations of effectiveness have actually been attempted.

Training Programs The most ambitious attempt to evaluate an older-driver training program was that reported by McKnight et al. (62) in which volunteers from the AARP program were randomly divided into two groups. The "trained" group was offered the program immediately, whereas those in the control group were deferred to a date after the evaluation had been completed. The two groups were then compared with respect to self-reported accidents (which were verified to have included officially reported accidents).

No differences materialized between drivers participating and those not participating in the program. Unfortunately, only 21 percent of the 10,000 drivers who volunteered to participate in the training program actually finished and furnished follow-up accident data. Curiously, the proportion of drivers in the control group who furnished follow-up accident data was identical—21 percent. However, the drivers remaining in the two groups were no longer random samples. Although the trained and control groups had the same accident rate before the program, they differed significantly with respect to a wide range of variables. Those who volunteered for and completed training had significantly fewer prior traffic violations and drove fewer miles. Despite this bias, the reported accident rate following administration of the program was almost identical for the trained and control groups. The results do not prove the ineffectiveness of the AARP program in particular or older-driver training in general. The lack of adequate numbers and statistical control prevented a conclusive evaluation.

The inability to maintain the randomness of groups being compared in evaluation of the AARP program is a problem that has been encountered in evaluating most adult driver-training programs. Although drivers can be assigned to programs at random, no one can force them to participate in the program to which they have been assigned. Given the volunteer nature of

older-driver training, the prospects of ever conducting a truly conclusive evaluation are not good.

The only alternative to a pure, random experimental evaluation of older-driver training is a quasi-experimental comparison, in which groups that volunteer for training are compared with those who are not, with differences between the groups being controlled statistically. Some recent evaluations of adult training programs for motorcycle operators have shown that differences between volunteer and nonvolunteer groups are largely eliminated when control is maintained for age, sex, prior experience, and driving record (82, 88).

Information Programs The only highly controlled experimental evaluation of older-driver information programs found in the literature is that reported by McKnight and Edwards (45) in which 8,000 license renewal applicants over age 55 were randomly divided into two groups, one group taking a test based on its content, the other group renewing licenses without having taken a test. A subsequent analysis of driving records showed no significant differences in accidents or violations over a 2-year period. These results conflict with those that were obtained from drivers in other age groups. The authors speculate that a more favorable outcome might have been obtained had the sample size and the range of information provided been as great as that for the other age groups.

Pedestrian Training Programs

There are two aspects to providing pedestrian training programs: developing an effective program and building an effective delivery system. The latter may well be the more difficult; pedestrians are harder to reach than drivers, who must apply for a license.

European Programs

Europe has been far ahead of the United States in developing pedestrian interest groups. The International Federation of Pedestrians is made up almost entirely of pedestrian groups from European countries. These groups serve as pedestrian advocates, working with federal and local governments and the media, and also provide educational programs. Although most of these are for children, where the major interest lies, some have been tailored to the elderly, containing materials distributed by pamphlet or the media or sometimes verbally by traffic officers and others in the traffic safety establishment.

In England local road safety offices have the responsibility for providing instruction to elderly pedestrians within their jurisdictions. This responsibility is met primarily by visiting organizations for the elderly to show films, give

talks, and distribute printed materials. They also work through personnel of social service agencies, visiting health services, and volunteer groups (89). The content of instruction includes the importance of (a) wearing glasses and hearing aids when they are required (i.e., not taking them off when going outside); (b) not going out under conditions of poor visibility, slippery surfaces, or high-density traffic; (c) being as conspicuous as possible; (d) using what safety facilities are available (e.g., footbridges and subways); (e) crossing at proper locations; and (f) using the "green cross" code for crossing streets (90).

Mathey (55) emphasizes that training must be in real traffic and must teach the elderly to "deal flexibly" with actual and difficult traffic situations. The AAA (74) also emphasizes that the most effective way to train is on the street. Swedish (91) and Dutch (92) work with children has also shown this to be essential. However, not only is such a program expensive, there is no reasonably extensive delivery system and persuading people to invest the amount of time required for such programs would be difficult.

A review of pedestrian training throughout Europe by OECD (78) concluded that group approaches, such as presentations in retirement clubs or homes, were not very effective because many people are required to train very few. They recommended individualized approaches in which older pedestrians are provided information through families, home health services, and home helpers.

U.S. Program

In the United States, there are three organizations with ready access to large numbers of the elderly and concerned for the safety of elderly pedestrians: AAA, AARP, and NSC. Each has a program under way.

The AAA's aim was to produce guidelines for local communities (74). They point out that programs depicting the elderly as decrepit are offensive and that this picture is not true of the elderly outside institutions (about 95 percent of elderly). The AAA training program involves three 1/2-day sessions, the last one involving practice in real traffic in the street. It is the only one that provides advice on techniques to practice. The real question is whether people will invest the time required and whether it can reach a large number of the people who really need it.

The AARP's program (93) has different aims. The emphasis is on the individual's responsibility for his own safety (which includes the advice to cease trusting drivers to do the right thing), awareness of safety measures of all types in the community, and political activism for better safety measures, along with advice on how to organize and run a concerned citizens' group.

This approach is expected to get people more involved than a purely informational program and also has the potential for reaching more people than just the groups trained. In addition, the sponsoring organization is large and composed entirely of the target group. The program is brief: a one-hour presentation of slides with a taped commentary, followed by group discussion.

The NSC has a contract to implement the Federal Highway Administration's Operation Pedsaver. The aims are (a) to produce a program implementation guide with handout literature and a complete set of material for the promotion and coordination of a pedestrian safety program, (b) to develop grassroots support for pedestrian safety, and (c) to solicit program sponsors (94).

New Developments in Training

The 1980s have not been years of significant programmatic inquiry into the improvement of older drivers or pedestrians. However, some developments that have occurred outside the realm of programmatic study involve reexamination, self-appraisal, and subscription television.

Reexamination

Licensing agencies reexamine drivers both at periodic intervals and whenever there is cause to question their ability to drive safely. Use of reexamination purely for purposes of renewing or not renewing licenses lies outside the scope of this paper and is well covered by Waller elsewhere in this volume. However, the reexamination process can also be used to induce drivers to enroll in and complete training programs. Given the difficulty in finding suitable training incentives, the possible use of reexaminations is worth considering.

The state of Illinois now offers a 3-hour classroom program on rules of the road to help drivers prepare for the written examination. It is offered at some 520 locations around the state in order to be readily accessible to everyone. Although not exclusively for older drivers, its attendance comes primarily from that group.

Although programs such as that in Illinois are encouraging, they obviously do not reach all eligible drivers. Some 16 states do not even require in-person license renewal if a driver has a clean traffic violation record. Only three states selectively test older drivers.

An alternative to the use of reexamination to induce participation in training is the authority that license administrators have to test any drivers for cause. The "cause" is typically a record of persistent traffic violations. Actually, few violators are tested because few violations are the result of inability to drive.

In this case, "reexamination" more often means an interview, hearing, or instruction program.

Currently, reexamination of older drivers occurs primarily in response to complaints from members of the driver's family. However, several states have instituted procedures under which police officers who issue a traffic citation to an older driver can indicate on the citation whether they believe that the violation results from some deficiency on the part of the driver. When a copy of the citation reaches the licensing agency, it triggers a request that the driver come in for a reexamination. Although the reexamination may result in a written or road test, or both, it could also take the form of an instruction program. No state currently appears to employ reexamination for this purpose.

In two recent efforts, tests have been developed that would quickly screen renewal applicants for sensory and perceptual-motor shortcomings capable of affecting driving. These tests use video display terminals that permit the testing to be integrated with automated color vision, choice reaction time, spatial judgment, and anticipatory tracking. By using an adaptive testing sequence, applicants manifesting no problems can complete the sequence in a few minutes. Only those showing difficulty would receive the full test, which could run 10 to 15 min. Applicants showing poor overall performance would then be required to take a road test. As yet, no such system has been tested on actual license applicants.

Self-Evaluation

One characteristic of older drivers that tends to be an obstacle to their participation in training and information programs is their reluctance to admit that their driving has become deficient. To help overcome this, training programs for older drivers often include self-evaluation checklists. The most systematically developed self-evaluation is that of Malfetti and Winter (95, 96). Their self-appraisal presents 15 situations rated by older drivers for their frequency of occurrence: "always or almost always," "sometimes," "never or almost never." After answering the questions, drivers add up their scores, which place them in one of three categories: "stop" (red), "caution" (yellow), and "go" (green). The main body of the appraisal is, however, a detailed discussion of the issues addressed by the questions.

The 15 situations rated include affect (e.g., "traffic situations make me angry"), behavior ("I wear a seatbelt"), and interactions with the traffic system ("How many accidents have you had during the past two years?"). All are situations having special importance to the safety of older drivers.

Development of the self-appraisal form began with a large pool of situations and responses recommended by researchers and practitioners as being particularly critical to the operating safety of older drivers. Those showing

low correlations with the entire pool were eliminated. The reason for this is unclear. Certainly one would expect some correlation across responses, that is, for those who respond unsafely to one situation to respond unsafely to others. If increasing age leads to less safe responses, then some correlation should be induced merely by the differences in the ages of those responding. However, to delete a particular response because it does not correlate highly with other responses is questionable.

The self-reported scale showed positive but low correlations with the results of a road test (those practices that were on both the road test and the rating form only correlated .09 with one another). It is possible that a longer form, incorporating more situations, would provide a better overall appraisal of drivers. However, the purpose of the self-appraisal is not simply to measure potential, but to pave the way for improvement. A greater number of situations would have increased the length of the discussion portion of the self-appraisal, risking disinterest on the part of readers.

The self-appraisal developed by Malfetti and Winter is certainly a step toward the remediation of older drivers. It would be unfortunate if it were the last such step. Further investigation, encompassing a wider range of internal consistency, would seem to be necessary if the idea of self-appraisal is to be fully exploited.

Subscription Television

A new wrinkle in the search for ways of getting information to drivers is subscription—closed-circuit and cable—television. Small local cable television stations are often short of material to cover their programming hours. They therefore are characteristically a good outlet for public service information. Information bearing on the topics that have been described earlier has been aired in such forms as discussions; lectures by experts in the field; films, videos, or other audiovisual presentations; and televised public events bearing on problems of the older driver.

Probably the biggest limitation to the use of cable television is simply the rather small audiences that nonnetwork television tends to generate. However, viewing by the target audience could be enhanced by publicizing those programs dealing with the older driver in materials mailed to older people (pension checks, mailings from local old-age assistance groups) or through newsletters and other publications sent to older drivers.

A service that has increased markedly in recent years has been the creation of small, private, closed-circuit television stations operating under the auspices of certain groups by and for their own membership. Retirement homes have been among the leading sponsors of closed-circuit stations, which is due at least in part to the amount of spare time that people can devote both to running the station and to viewing the programs.

PROPOSED CHANGES

Discussions of the state of the art and new developments in training and information programs suggest changes that could be made to the benefit of older drivers and pedestrians. Those changes that seem to be most feasible to implement and most likely to produce beneficial results are improved instruction, increased enrollment, and better information dissemination.

Improved Instruction

The instructional programs that are available to help older drivers are comprehensive in scope and employ proven methodology. However, they are not without room for improvement. Areas in which content could be expanded include the following:

1. *Safety practices*: defensive driving, emergency procedures, and other aspects of safety practice that are potentially beneficial to all drivers, regardless of age;
2. *Common problems*: problems that most commonly affect drivers and pedestrians of advanced years as an aid in helping to detect the effects of such problems;
3. *Common errors*: the type of errors that drivers and pedestrians are most likely to make as a direct or indirect result of age-related problems; and
4. *Assistance*: ways in which the effects of problems can be eased through assistance by passengers, vehicle accessories, driving aids, and so on.

The organizations that have developed and offered programs for older drivers and pedestrians would do well to review the content of their programs systematically against a comprehensive list of learning needs. It may not prove feasible to accommodate all these needs in one or even a series of programs. However, the decision on content of the training program should be made in consideration of the full range of training needs and an attempt to rank these needs in terms of the extent of importance, their relation to safety, and the prospects for obtaining improvement.

Increased Enrollment

Obviously, the best instruction in the world will not accomplish very much if people do not take it. At this time it appears that less than 2 percent of older drivers, and even fewer pedestrians, are willing to enroll in formal programs of instruction. Significant steps toward increasing enrollment must be taken if training is to have a real impact on the safety of older drivers and pedestrians. Three such steps are use of insurance discounts, exploitation of the license process, and publicity.

Insurance Discounts

As incentives to participation in training programs, insurance discounts for older drivers are of limited value, as shown by the small proportion of eligible drivers seeking such discounts. Although publicizing the availability of both the programs and the discounts may increase the number of takers, the low enrollment among populations in which they are already publicized suggests that something more is required.

One obvious step in making discounts a greater incentive would be to increase the size of the discount to a point where it actually becomes an incentive to training and not merely taken for other reasons. It seems very unlikely that insurance companies will increase the size of the discount offered or that state legislatures will require a larger discount in the absence of convincing evidence that the training is producing a proportional reduction in claims. Such a demonstration may hold the key to an increase in both the size of insurance discounts and the number of states requiring that discounts be offered.

License Process

One shortcoming inherent in any volunteer driver improvement program is that those who voluntarily seek improvement are typically the ones who are least in need of it. For those who, through a poor traffic record or other evidence of unsafe performance, show a need for improvement, training can be made a condition for license retention. At this time, the majority of licensed drivers who are receiving driving instruction in the United States are doing so in order to keep their licenses. Steps that could be taken to make better use of the license process as a means of inducing participation in driving training programs by older drivers are the following:

1. *Screening:* Research should continue that would lead to quick screening methods capable of being integrated into the license renewal process to identify potentially unsafe drivers for more extensive examinations. An effective screening process must be (a) brief enough to avoid adding to the queues at licensing stations, (b) automated to minimize requirements for additional personnel, and (c) reliable enough to identify drivers with severe problems and not involve large numbers of false positives.

2. *Reporting:* Techniques should be devised that will aid and encourage police, family, friends, and others to accurately identify those with conditions leading to unsafe driving and to refer them to licensing agencies for examination.

3. *Referral:* Those drivers, as revealed through screening and reporting processes, who are capable of alleviating or compensating for their problems through instruction should be identified and referred for training.

Experience with the Illinois license renewal training program suggests that introduction of a screening program will produce a substantial increase in the numbers of older drivers volunteering for instruction. Proportions might be further increased by coupling the examination process with training. Pennsylvania, for example, by allowing instructors to administer a license examination more than trebled the number of enrollees in a motorcycle safety program.

The use of license reexamination as a means of inducing participation in training is hampered by (a) resistance to requiring reexamination on the basis of age alone, (b) the lack of a screening process capable of quickly identifying potentially hazardous conditions during the routine renewal testing of all drivers (coupled with a reduction in renewal testing generally), and (c) the lack of a widespread program for early identification of problem drivers through analysis of accidents and traffic violations. These issues obviously affect training, but they are really licensing issues and, as such, lie outside the scope of this paper. However, the potential role of licensing in encouraging training should be considered. Any changes in the licensing process as it applies to older drivers should not be limited to the question of who may or may not be licensed but should include the conditions under which a license may be retained, with participation in training being one of those conditions.

Publicity

Drivers and pedestrians cannot participate in instructional programs if they do not know about them. The literature review disclosed no surveys involving public awareness of the training programs that are available, but it is the belief of those operating the programs that lack of awareness is one of the chief obstacles to widespread participation. A much more ambitious effort to publicize the existence of programs, their content, and benefits of participation (particularly discounts) should certainly be initiated. Efforts to publicize programs can make use of the same access routes to older drivers that would be used to disseminate more general driver and pedestrian safety information.

Better Information Dissemination

Even with all the inducements to participation that have been described, it is optimistic to think that even a substantial minority of older drivers or pedestrians will participate in formal instruction programs. The rest must be reached through less formal channels of communication. Public information approaches that can and should be greatly utilized include the following:

1. *Private sector:* Greater involvement in disseminating public information should be sought by private-sector organizations having frequent contact

with the elderly. The participation of the American Bankers Association in administration of the 55 Alive/Mature Driver program provides a good example of the way in which the private-sector organizations can provide access to older drivers and pedestrians. Any organization having significant numbers of older people among its clientele is a candidate for a similar type of involvement.

2. *Public assistance agencies:* Individuals and organizations providing assistance to the elderly provide a potential avenue of communication that is now underutilized. These resources include physicians, hospitals, clinics, and other organizations providing service to older people and to their relatives and friends. Supplying such contacts with timely and accurate information concerning problems of older drivers could aid them in providing more and better assistance. Physicians can distribute information that will help older drivers anticipate the debilitating effect on their driving of whatever illness they are being treated for.

3. *Affinity groups:* Older people have shown an increasing tendency to band together in retirement communities, mutual-help organizations, and social and recreational groups; this grouping can be exploited to distribute available driver and pedestrian informational materials. Such materials could include pamphlets and brochures, posters, videos, and lists of speakers. The costs of such materials could be underwritten by public and private organizations.

RESEARCH NEEDS

This discussion has highlighted three areas in which further research is clearly needed: (a) behavioral causes of accidents, (b) identification of deficient drivers, and (c) effectiveness of training programs.

Behavioral Causes of Accidents

The ability of training to reduce older-driver and pedestrian accidents could be greatly improved by focusing particular attention on those behaviors most likely to lead to such accidents. The pedestrian behaviors leading to highway accidents have been rather well identified. However, the behavior of drivers is less readily observable and therefore less often reported. Although research cited clearly sheds some light on the behavioral antecedents of drivers, it falls far short of pinpointing behavioral causes.

What would be of greatest benefit to the identification of behavioral causes would be in-depth investigations of accidents involving older drivers. A number of multilevel accident investigations have been conducted in past years, but none has focused specifically on accidents involving older drivers.

The samples include all ages; nevertheless, the numbers of older drivers have been quite limited—particularly the numbers of truly elderly drivers.

The National Accident Sampling System (NASS) is an ongoing accident investigation program capable of furnishing in-depth behavioral information. The system uses police reports across the country to select proportional samples of accidents. Frequently, various categories are oversampled for in-depth information on variables of particular interest (e.g., heavy vehicles). It would take a highly disproportionate sampling of accidents involving elderly drivers to furnish enough behavioral information to make reliable estimates of the extent to which various behavioral problems contribute to older-driver accidents. Such a sample would be capable of providing valuable input to the improvement of older-driver training programs.

Identification of Deficient Drivers

If drivers cannot be called in for reexamination on the basis of age alone, the only way of identifying deficient drivers to refer for training would be through some rapid screening process that could be applied to drivers of all ages. As previously noted, such a process must be expeditious enough to avoid creating queues in license stations, fully automated so as to avoid imposing additional personnel requirements, and accurate enough to assure identification of deficient drivers without large numbers of false positives. Outside of some very recent unpublished work, little effort has been undertaken along these lines. The MARK II vision tester described in Schieber's paper in this volume deals solely with deficiencies in vision and requires far too much time to be employed in routine license screening. Although there is no assurance that any system meeting the specified requirements can be developed, the potential value is sufficiently great to warrant further exploratory research.

Effectiveness of Training

The prospects of public support through training of older drivers could be enhanced by valid evidence of its benefit in improving safety and mobility. The availability and magnitude of insurance discounts are particularly sensitive to training effectiveness.

The most conclusive form of research, random experimentation, is unlikely to prove feasible when the treatment (training) is purely voluntary. However, quasi-experimental comparisons of those who elect and those who do not elect to take training are capable of providing an acceptable assessment of training effectiveness with (a) collection of adequate data on accident-related variables and (b) use of appropriate statistical controls to isolate the effects of training. The comparisons that have been performed to date have not met these conditions.

CONCLUSIONS AND RECOMMENDATIONS

Based on the research and practice that have been studied in the preparation of this paper, the following conclusions and recommendations can be offered.

Conclusions

1. To reduce the vulnerability of older drivers and pedestrians to traffic accidents and at the same time preserve their independent mobility, there is a need for programs of information and education.

2. The effect of diminished capabilities leading to the unsafe performance of some older drivers and pedestrians can be significantly reduced by modifying or compensating for such performance.

3. A number of driver and pedestrian training programs have been developed to address age-related problems. These programs are available to almost everyone at little cost.

4. Current driver and pedestrian information and education programs reach but a small fraction of the people who could benefit from them. Even where insurance discounts are available to the drivers who complete training, participation does not exceed 2 percent of the population.

Recommendations

1. The effectiveness of older-driver training should be assessed by comparing the accident records of trained versus untrained drivers, with statistical control over demographic characteristics, prior driving record, mileage, and other factors that might affect the relative accident exposure of the groups being compared.

2. Should training be found an effective accident countermeasure, efforts should be undertaken to induce greater numbers of older drivers to participate in training programs. Such efforts should include (a) publicizing the availability of insurance discounts and increasing their size, where appropriate, and (b) identifying drivers whose records of accidents and violations indicate a need for remediation and requiring their successful participation in training as a condition for license retention.

3. States should develop processes to facilitate and encourage reporting to the licensing authority those drivers whose observed performance indicates that they are potentially hazardous to themselves and others. The processes should be adapted to the specific needs of law enforcement officers, physicians, family, and friends.

4. The participation of private business, public assistance agencies, and volunteer groups should be enlisted in the efforts to disseminate to older drivers and pedestrians (a) information capable of improving their safety and

mobility and (b) information concerning the availability of training and informational programs.

5. A survey to identify the means currently used by states to identify unsafe drivers and a program of research should be undertaken to devise rapid, automated, and reliable screening methods capable of cost-effectively identifying potentially deficient drivers for more intensive examination.

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Improving Safety for Older Motorists by Means of Information and Market Forces

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Older people have an increased risk of being killed in traffic accidents, both as vehicle occupants and pedestrians. Although they drive less than younger people, they have more accidents per mile traveled than younger adults who are over the age of 25. Much of this increased risk is directly attributable to changes in physical and cognitive abilities that lead to certain characteristic errors of judgment or failures of perception.

The special needs of older people and the special risks they face have not yet received much attention in the design of motor vehicles, highway environments, or licensing systems. However, because older adults are projected to account for an increasing share of the population well into the next century, mitigating these risks becomes all the more important.

This paper reviews research bearing on one strategy for reducing these risks, namely, providing older consumers with better information about their special needs and in particular with information about vehicular features that should improve safety. Such information could be beneficial in several ways. First, it could lead older drivers to make more frequent use of safety features and equipment already on their vehicles or available for retrofitting. Second, by influencing older consumers' purchase decisions, it could upgrade the average safety of the vehicles they drive—especially those features that most

closely address the special risks they face. Third, by enhancing older consumers' preferences for safety features relative to other product attributes, it could influence manufacturers' marketing, planning, and vehicle design decisions. This in turn could lead to improved vehicle safety or safety information for all consumers.

Just how likely is such a scenario, and what sorts of programs aimed at consumers are most likely to bring it about? In this paper the potential of consumer information to alter older people's vehicle purchase behavior is examined. The discussion draws from literature on consumer information processing and decision making, mass communication, persuasion and attitude change, and the characteristics of older adults as learners and consumers. It also draws on the results of a focused survey of existing programs aimed at reaching older people as consumers or motor vehicle drivers.

The main conclusions that emerge from this review are that (a) very little of the information that is now directed at consumers about automobiles focuses specially on safety features; (b) almost none of the safety-related information that does appear is directed at the special needs of older drivers; (c) such information, if disseminated widely and if suitably packaged, would very likely increase older drivers' awareness of these safety issues and of the fact that sound vehicle design affords protection; and (d) if such information were incorporated in driver retraining programs or otherwise effectively disseminated, it might well change some consumers' behavior in purchasing new automobiles or safety equipment for retrofitting to a currently owned automobile. If purchasing behavior were to change on a wide scale, it is plausible that it might encourage manufacturers to make or market their products differently, but no formal evidence is adduced to estimate how much alteration in consumers' behavior would be required.

The review begins by briefly describing the specific types of accidents for which older drivers are at elevated risk and the sensory, cognitive, and behavioral factors that contribute to those accidents. (For a more comprehensive treatment of the safety literature, see Volume 1, Chapter 3, of this report.) Next, the review describes several vehicle features that could play a role in reducing some of these age-specific risks. In a discussion of whether and when providing people with information has an effect on safety-related or preventive behavior, it is argued that change sometimes occurs but is likely only when careful thought has been given to how the information should be designed and presented. The potential effect of consumer demand on product supply is also reviewed.

The next section discusses various sources of information now available to consumers and describes existing programs that are designed to inform, educate, or retrain older drivers. Possible mechanisms for integrating information about vehicle safety features into these programs are discussed. This is

followed by a section on specific questions that might fruitfully be addressed by future research. A final section presents conclusions and discusses their policy implications.

SAFETY RISKS OF OLDER DRIVERS

As a group, older drivers generally have had good driving records. When the amount of driving they do is taken into account, however, older drivers have more accidents per vehicle mile. The types of accidents for which they are disproportionately at risk include those caused by making improper turns, failing to yield the right-of-way, and disregarding traffic signals (1-3). In contrast, they are less likely than younger drivers to cause accidents by speeding, driving recklessly, or driving while intoxicated.

The tasks that seem to pose special difficulties for older drivers—and that undoubtedly account for many of these age-specific driving risks—include changing lanes, passing, turning, noticing signs, and reacting appropriately to traffic conditions (4, 5). These problems in turn reflect the greater prevalence among older adults of functional impairments in certain key physical and mental abilities, including the loss of static and dynamic visual acuity, contraction of visual field, deterioration in dark adaptation, increase in glare sensitivity, increase in auditory threshold, and slower perception and reaction times (6-8). In addition, older drivers often suffer from reduced mobility of the neck and trunk, which can make it more difficult for them to maneuver quickly and to monitor traffic conditions to the sides and rear of their vehicles.

Panek et al. (9) identified three basic abilities that are important predictors of the frequency of involvement in automobile accidents:

- *Perceptual style*, or the ability to extract relevant information from a complex visual scene;
- *Selective attention*, or the ability to attend to a single message in the presence of competing messages;
- *Perceptual motor reaction time*, or the speed with which the person processes incoming information and responds to it.

These variables do, in fact, correlate with drivers' accident records (10) and may help explain older drivers' occasional failure to respond to signs and signals and the greater difficulty they seem to have in reacting to complex or rapidly changing traffic situations.

IMPORTANT VEHICLE SAFETY FEATURES

No attempt is made here to list all the vehicle design features that may result in increased safety for consumers. A few examples, however, provide a

specific context for discussing how relevant information might be packaged and how existing programs might be improved. The following examples were among those that members of an expert panel recently named as especially relevant to the needs and problems of older drivers (11).

Safety Belts and Passive Restraints

Although important for all drivers, safety belts are especially important for older drivers because of their greater susceptibility to injury. Improved design of shoulder belts should be possible. In addition, older drivers might especially benefit from the design of belts that are more easily reached, fastened, and released. Survey results suggest that older drivers are twice as likely as younger drivers to report that they have trouble reaching their safety belts (22 percent versus 10 percent) and are also more likely to report this as a reason for not using belts (11). Automatic safety belts may therefore be especially advantageous for older drivers who have difficulty buckling and unbuckling. Air bags are similar in offering automatic protection, though only to front-seat occupants in a frontal crash. Because older drivers are at greater risk of injury in a crash of given severity, the additional protection afforded by a combination of safety belts and air bags should be especially valuable for them.

Mirrors

Because older people experience greater difficulty turning to check on blind spots, they stand to gain especially from mirrors with improved design and placement (interior and exterior). These are available but not as widely marketed or purchased as they might be.

A-Pillar Design

For similar reasons, older drivers have greater difficulty compensating for blind spots caused by placement and size of supporting A pillars at the corners of the vehicle.

Windshield Wipers

Lateral visibility can be heightened by increasing the width of the sweep. Visibility in the lateral areas of the windshield is important to safety when making turns. Older drivers are especially likely to have accidents while turning.

Power Steering and Power Brakes

Power steering and power brakes provide assistance to drivers with less than average strength, helping them control the vehicle safely. In addition, power brakes permit left-foot braking, which enables the driver to achieve shorter stopping distances.

Antilock Brake System

Antilock brakes prevent the wheels from locking so that the driver loses the ability to steer during an emergency. (Such an emergency may be a more serious problem for older drivers, who often show less ability to react quickly in these situations than younger drivers.) Such a braking system is now available only on imported cars and is quite expensive. If it could be made available on higher-volume domestic models and if consumers were willing to pay for it, the cost would come down considerably.

Instrument Panel Design

Simplicity of design, accessibility of controls, and legibility are probably especially important for older drivers, who may have special difficulty in quickly locating the important part of a complex visual display.

Seat Design

Older drivers have weakened musculature and less flexibility in their spines and are therefore apt to become uncomfortable sitting in most automobile seats for even moderate periods of time. This problem could be reduced by designing seats with less padding and more support for the lumbar region. Improved lateral support would also be helpful. Seats that are designed to prevent too much forward and downward movement of the buttocks on collision would reduce the risk of injury. Bench seats are preferable to bucket seats.

Vehicle Size

Accidents involving small vehicles are much more likely to result in fatalities or serious injuries. This is true even in single-vehicle collisions and when two vehicles of equal weight collide (12). For that reason, all consumers are safer driving medium-sized or large vehicles than small ones. Because older drivers are the most vulnerable, they stand to gain most from the protection afforded by larger and heavier vehicles.

High-Mounted Brake Lights

Features that make a vehicle more conspicuous or that visibly signal its driver's intentions and encourage other drivers to keep a safe distance reduce the likelihood of rear-end collisions. High-mounted brake lights, sometimes referred to as collision-avoidance lights, do all of these things. They may therefore be an especially important safety feature for older drivers, who sometimes drive at slower speeds than the surrounding traffic and are thus at increased risk of being struck from the rear.

The safety features listed above vary widely on a number of dimensions. Some are expensive, others inexpensive. Some are now available on all vehicles (but in designs that vary widely in safety); others are unavailable on most or all vehicles. Some anticipate advances in safety engineering that should soon be made; others merely require the widespread adoption of designs that have already been implemented in passenger vehicles. Some require active consumer cooperation if they are to be used successfully; others are part of the structural characteristics of the vehicle and require nothing of the driver beyond purchase of a vehicle that is equipped with them. Variations along these and other dimensions can be quite important in determining how readily consumers will seek out or accept these features and what sort of information will make that more likely.

EFFECT OF INFORMATION ON CONSUMER DEMAND FOR SAFETY FEATURES

An important issue is whether information affects consumer demand for safety features, because some research studies suggest, on the face of it, that there is no effect. If research has established that efforts to improve consumer safety by informing them about safety features are unlikely to work, then a serious review of whether it makes sense to pour resources into this approach should be made. This issue is addressed in a later section of this paper.

As it happens, there are good reasons to be optimistic despite the existence of seemingly negative findings. Most of the negative findings have emerged from studies evaluating information campaigns designed to educate consumers into better health or safety habits. All too often, rigorous evaluation yields no apparent effect on behavior (13-15). For example, Robertson and colleagues conducted a controlled evaluation of the effects of a television campaign to increase seat belt use; they found no effects (16). Although this study is frequently cited to support the contention that it is difficult or impossible to change safety behavior through the use of mass media, that is probably far too strong a conclusion. In fact, the study provides little evidence on what effects the message had, or why. No process measures were obtained,

nor is there much evidence that would allow the determination of the quality of the messages used, which is important in determining whether they should have had an effect. (Poorly designed messages tell little about the capacity of well-designed messages to influence behavior.)

Similar points could be made about most other studies that have yielded negative findings. Most often, either the campaign itself or the measure of its outcome is too flawed to permit determination of where failure occurred or what the results might mean for well-designed campaigns.

On the positive side, there have been successful information campaigns that have produced long-term changes in consumer health or safety-related consumption patterns. A prominent example is the Stanford Heart Disease Prevention Program's Three Community Study, sponsored by the National Heart, Lung, and Blood Institute (17, 18). This program relied on community education through the mass media to change knowledge and behavior related to cardiovascular risk (smoking, exercise, and diet). In one community, a mass media campaign was the only intervention. In a second community, the intervention was supplemented with intensive face-to-face instruction of high-risk individuals. A third community served as a control group.

Results showed significant improvements in physiological measures of risk (e.g., blood pressure) in each of the communities where the intervention was conducted. Risk in the control community increased during the same time period.

This study, along with other all-too-rare examples (19–21), suggests that it is possible to make worthwhile changes in people's health and safety habits through the use of well-designed information interventions. On the other hand, the existence of numerous failures should make the phrase "well-designed" a necessary qualification. Efforts to simply put information "out there" and hope people will attend to it, grasp its potential relevance, and change their lives as a result are doomed in the main to fail.

EFFECT OF CONSUMER DEMAND ON PRODUCT SUPPLY

A second important issue is whether a change in consumer demand in response to information is likely to be of sufficient magnitude to induce a supply response. Consider the following positive scenario for change mediated by market forces. Safety feature X, not currently supplied by most manufacturers because of insufficient demand and high unit production costs, is prominently featured in a safety information campaign. Consumers become interested and begin inquiring in dealer showrooms about this feature's availability, even on midpriced and lower-priced models. Meanwhile, a small retrofit market begins to grow quite rapidly. Manufacturers respond by

increasing production, and decreases in unit production costs are passed on to consumers in lower prices, stimulating further demand. Eventually, supply and demand reach a new equilibrium, but at a much higher level than before the boost in demand provided by the information campaign.

How likely is such a scenario, and what are the conditions that facilitate or impede its occurrence? Not surprisingly, the answers to these questions depend on many factors, including the structure of the market and "location" of the segment providing increased demand; the price elasticity of demand, both by the older driver and other potential purchasers; the initial cost to the manufacturer of making the safety feature; the marginal cost of making and installing additional units (the supply curve); and the time required to respond. An economic perspective suggests that increased consumer demand will produce a supply response only when the demand can be met at a price that the consumer is actually willing to pay and when supplying the demand is on balance profitable or otherwise beneficial to the manufacturer.

Thus, increased demand will not always produce a supply response. One of the most common reasons is that a substantial initial investment may be required to supply the demand. There are other reasons as well, however. If a manufacturer makes an undifferentiated product line, for example, it is possible that supplying a demand on the part of some consumers can increase prices sufficiently to suppress demand by other consumers. In such a case, manufacturers can actually lose market share by responding to the demand. A similar problem can occur in marketing a product. Unless the feature to be marketed offers a good fit with the overall image of the product line, the manufacturer's marketing department may be reluctant to call the consumer's attention to it. Thus, much could depend on the extent to which consumer preferences vary in a way that creates conflicting demand. This is in turn related to the issue of product differentiation. If manufacturers can respond to demand by creating a special product line aimed at that particular market, they may be more likely to respond than if they must take the substantially greater risk of altering their entire product line.

In analyzing the process by which a supply response may occur, it is also useful to distinguish a marketing response from a design or engineering response. The former may occur much more quickly than the latter, given the length of the product design cycle. Changes in marketing may be substantive (reallocating available products to different markets) or nonsubstantive (putting more emphasis on safety features in advertising campaigns). Even nonsubstantive changes, however, may have important long-term effects. If a manufacturer changes its advertising in response to a perceived shift in consumer concerns, this change can contribute further to the shift to which it is responding, in a positive feedback loop. Moreover, any *sustained* change in basic consumer concerns, such as an increased concern for safety features

vis-à-vis other attributes such as performance or fuel economy, is almost certain to influence design decisions in the long term.

One important factor influencing the likelihood of a supply response is the extent to which the safety feature can be economically offered for retrofit or as an optional feature on a new car purchase, or whether it can only be offered as a standard design feature on a new vehicle. Products that can be offered to the retrofit market have a greater potential supply response because of the greater potential demand. Similarly, features that can be offered selectively only to those who want them will tend to have much stronger supply-demand elasticities than those that must be bundled with a complex set of other features.

The safety features that could benefit older drivers vary considerably in several of the aspects previously described, including the initial costs to the manufacturer of providing them, their likely retail cost, the extent to which they are apt to appeal to a wide range of consumers in addition to the older driver, and whether they can be provided at reasonable cost for retrofitting. Some devices, such as well-designed rearview mirrors and high-mounted brake lights, would appear to be good candidates for supply response to increased demand by consumers but are (possibly for that reason) generally available already. Others, such as improved seat and A-pillar design, are less likely candidates for some of the reasons mentioned previously.

To the extent that other conditions make a supply response possible, older drivers constitute a particularly favorable source of demand. As a group, they are more affluent than younger consumers and more likely to make repeat purchases if they are satisfied with a product. Moreover, the fact that they form an increasingly large share of the population makes them an attractive market for future growth, even beyond the attractiveness dictated by their current numbers. For these reasons, a shift in consumer preferences among older consumers could have a disproportionate influence on producers' design and marketing decisions.

It should be recognized that manufacturers have other incentives besides profit and market share for developing and marketing features that improve vehicle safety. One such incentive is product liability. Any device that reduces the number or seriousness, or both, of injury accidents, especially those that can be attributed to design limitations or manufacturing faults in the vehicle, thereby has some attraction for manufacturers as well as consumers. Publicity campaigns that disseminate information to consumers about the state of the art in vehicle safety capabilities do not, of course, raise that standard; they may, however, hasten the process whereby improvements in design are adopted as the current standard used for judging whether a design is adequate.

SUCCESSFUL INFORMATION CAMPAIGNS

A thorough review of behavioral science principles that are applicable to the design of successful information campaigns is beyond the scope of this paper.

Suffice it to say that a vast body of theoretical and empirical knowledge has accumulated, much of it quite usefully addressing this question (22, 23). A few important examples that seem especially applicable to the issues addressed in this paper follow.

1. *Information will have the greatest influence when it specifically addresses the audience's needs.* This may seem obvious, but all too frequently communicators present the target audience with information that the communicator finds relevant (or simply has available) rather than putting it in a form that is useful for the audience (24, 25). This has been an especially frequent problem in information disclosures mandated by consumer protection legislation.

2. *Audiences seldom change their behavior in response to information they already have.* Again, it is surprising how often communicators' campaigns are designed to change a target audience's behavior by telling the audience what it already knows. That is one reason why antismoking campaigns that try to change smokers' behavior by telling them that smoking is dangerous have seldom worked. Smokers already know that smoking is dangerous; ignorance is not the barrier to change.

3. *Information campaigns work best if they take advantage of the audience's existing motivation (that is, give people information that helps them do what they already want to do).* Nearly always, this requires preliminary work to explore the target audience's existing beliefs, values, and goals. Many older drivers, for example, may be aware that they experience difficulties that affect their driving safety and may also be quite concerned about it. If so, they may be quite responsive to messages that give them some constructive way of handling this situation.

4. *People are likely to respond more favorably to information that empowers them than to information that makes them feel powerless.* A persistent problem for those who design programs aimed at encouraging consumer safety or prevention practice is that information that emphasizes a danger may produce avoidance rather than coping responses. Although the social and psychological studies of this problem suggest that people's responses in these situations are complex, one way to increase the probability that a coping response will occur is to emphasize what can be done to control or eliminate the danger (26, 27).

5. *Communications will have more influence on behavior if they contain information that is relevant to decisions.* Often, the information presented in a communication seems designed to maximize the recipient's understanding of the topic rather than to be most useful to the decisions the recipient must make (24). If a communication is to improve people's decisions, it must emphasize those facts or other aspects of the problem to which people's decisions are most sensitive.

6. *People are more likely to use information if it is provided to them in a way that takes into account how and when they will use it.* For example, consumers seldom use the nutrition information on food labels (28) even though they overwhelmingly endorse the regulation requiring it (29). One reason may be that the information is displayed on each individual product rather than by product class, so that comparison is difficult (30). Timing can be important. Information is most likely to have an effect on people's decisions if it is made available to them while they are in the process of making a decision, rather than before they contemplate one or just after they have made it. Again, this may seem obvious, but a good deal of consumer product information reaches consumers only after they have made a purchase decision. For automobile safety features, information made available at the point of purchase is likely to reach many consumers in time to affect their choice of model or features.

7. *Information can have an especially strong effect on behavior when it induces a change in mind set or leads people to reframe the way they think about alternatives (31).* For example, many consumers consider themselves to be in the market for purchasing an automobile only during certain limited times, when they think they need one or for some other reason the time seems right. The rest of the time, such consumers consider themselves to be out of the market and are apt to pay much less attention to new information that would be relevant if they were planning a purchase. In such a circumstance, information that leads consumers to reconsider whether they should replace their current vehicle may be especially effective. Similarly, many consumers, when purchasing a replacement automobile, exhibit what Howard (32) has called "routinized response behavior"—automatic repurchase of a previously chosen alternative, in this case, a vehicle of the same size, type, equipment, and make as the one they previously owned. The routinized nature of the response is apparent not so much from the repetition of a previous choice as from the absence of any consideration of alternatives. An informational intervention that induces consumers who would normally make a routinized choice to make an active and considered one instead could have important effects on behavior.

8. *Large-scale educational efforts are most likely to reach people when they are presented on a sustained basis through multiple channels and are reinforced at the community level.* Research on the diffusion process (33) offers important insights into the processes of social change. Perhaps most important, it suggests that the longer-term effects of an informational intervention can be far greater than the measurable short-term effects. Although initially a media campaign promoting safety may change the behavior of only a few people, social modeling can greatly multiply this effect. Moreover, a sustained campaign of educational messages can eventually change many of those who were resistant during the early stages (34).

If there is a common theme to the foregoing principles, it is that designing an effective strategy for informing consumers—one that stands a good chance of facilitating appropriate changes in their behavior—requires careful thought and planning and often formal or informal research. It requires careful analysis of why consumers now behave the way they do, what they know, and what they want. It requires analysis of the context surrounding the behavior one is trying to affect. Finally, it requires considering these issues separately for different behaviors (e.g., purchase versus use of a safety item) and for different types of consumers, because the answers will often be quite different from one type of product to another and one type of consumer to another.

SOURCES OF CONSUMER INFORMATION FOR OLDER ADULTS

With this general perspective, an examination of the channels and specific sources through which older consumers now get information is made, focusing especially on agencies, organizations, and programs that devote at least some attention to automotive safety, or that could be led to do so.

Mass Media

Like most Americans, older adults spend a considerable amount of their time watching television—more, indeed, than younger adults, at least until age 70 (35–37). Some researchers believe that television has substantial effects on older people's values (38), although there is by no means universal agreement on this.

Only in the last 15 to 20 years have marketers begun to target elderly consumers as an attractive market segment (39). Still, the automobile industry does not yet seem to have targeted older consumers for special mass advertising, although they are to some extent taken into account indirectly in the demographic profiling of markets for different lines of automotive products.

The mass media and especially television are widely believed to serve an “agenda-setting” function (40), determining not so much what viewers think as what they think about. If so, television advertising and public service announcements could enhance consumer awareness of vehicle safety issues generally, quite apart from the role they might play in conveying more specific information.

In considering the potential for a television or radio-based campaign to reach older consumers, however, it is well to keep two things in mind.

First, there is as yet little evidence that public service announcements are an effective way to produce behavioral change for anyone (22); and second, the frequent practice of broadcasting public service announcements very late at

night means that many older viewers, who tend to watch earlier in the day, never see them.

Consumer-Oriented Magazines

Both of the two most popular consumer-oriented magazines, *Consumer Reports* and *Consumers' Research*, cover issues of safe vehicle design. *Consumer Reports* usually addresses safety features in the context of an overall assessment of a vehicle (or, more often, group of vehicles). That is, information on safety features is mentioned along with information on performance, fuel economy, comfort, and styling. In recent years, the magazine has published few articles specifically focused on vehicle safety, neither has it separately addressed the needs of older drivers.

Consumers' Research, in contrast, has published several articles and shorter items on vehicle safety issues. In particular, it has provided continuing coverage of developments in air bags. This is in keeping with the magazine's general emphasis on health and safety issues. It has not, however, focused on older drivers.

The Car Book, by Jack Gillis (41), an annual guide to automobile purchase that covers over 600 cars, places a strong emphasis on safety information. It devotes an entire chapter to safety, including a summary of the U.S. Department of Transportation crash test performance results that includes not only overall index numbers but also separate ratings for driver and passenger protection, windshield retention, windshield passenger protection, and fuel leakage. The book also contains a discussion of various aspects of automotive safety, including doors, windshields, safety belts, and child safety seats. Buying tips are offered, though not on every feature. There is an extended discussion of how to buy a child safety seat. The special problems of older drivers do not receive separate attention.

Government Programs

Federal

The National Highway Traffic Safety Administration (NHTSA) has brochures and other materials on automobile safety features, although none are specifically directed at older drivers. These materials include leaflets on air bags and other automatic protection devices, a booklet on collision and the role of safety belts in reducing the risk of injury, a booklet summarizing crash test results for recent models under NHTSA's New Car Assessment Program, a handbook of instructions for complying with regulations that pertain to imported motor vehicles, and a leaflet on child safety.

It may be worth noting that NHTSA apparently has no capability of filling topically oriented requests from consumers; specific titles must be requested.

This obviously limits the usefulness of NHTSA's information services in situations in which the person handling the request is not completely familiar with the materials that are available.

State

Nineteen states and the District of Columbia have proposed or passed legislation requiring insurance companies to provide discounts to drivers 55 and over who complete a driver retraining program. Most states approve retraining courses developed by national organizations like American Automobile Association (AAA), American Association of Retired Persons (AARP), and the National Safety Council, but some (e.g., Washington) have also developed their own curriculum and training programs. These state-level programs might be willing to adopt (or adapt) model materials developed for multistate use.

Institute and Foundation-Supported Efforts

The Insurance Institute for Highway Safety (IIHS) and the Highway Loss Data Institute (HLDI) maintain bibliographic information on a wide range of topics concerned with automobile safety. In 1984 IIHS published *The Injury Fact Book* (42), a comprehensive analysis of statistical patterns of injuries that draws on data from a wide variety of sources.

In September 1986 IIHS published a one-page fact sheet on crash deaths and injuries among elderly drivers. The fact sheet summarizes statistics on excess risks for older people. An earlier status report, published in April 1984, also covered age-related patterns in injuries and fatalities extracted from *The Injury Fact Book*.

IIHS provides vehicle crash safety information free of charge and frequently announces the availability of this information. Dissemination is limited to those who request it, however.

Organizations for Older People

Neither the National Council on Senior Citizens nor the National Council on the Aging conducts any programs concerned with the older driver.

AARP developed and runs the 55 Alive/Mature Driving course, which is offered nationwide and is open to anyone 50 or older. AARP provides the program, materials, and instruction through a network of trained volunteers, who work in community centers, churches, and senior citizens centers. The course consists of 8 hr of classroom instruction divided into two half-day sessions that together cover six segments: overview, physical changes, interacting with traffic (two segments), accident prevention and adverse driving

conditions, and perception and course wrap up. Automobile maintenance receives extensive treatment in the segment on accident prevention, but safety features and factors to consider in purchasing an automobile do not. A list of vision safety tips includes three suggestions that implicate purchase behavior: "Replace windshields that are badly scratched or deteriorated. Avoid heavily tinted windshields as they reduce the amount of light you need to see. . . . You may wish to use a curved or 'convex' mirror." Otherwise, the emphasis is primarily on reducing risk through one's actions as a driver.

The instructional approach emphasizes active participation in the learning process and discussion with peers. In keeping with those concepts, the course is conducted by volunteers 50 and older who are recruited and trained by AARP from among its members. Volunteers receive preinstruction training in how to conduct discussion groups, followed by supervised practice teaching. Once trained, they receive ongoing supervision supplemented by participation in annual in-service training workshops. Instructors are responsible for recruiting their own students and finding rent-free facilities in which to hold the course.

The entire program is administered by 10 field coordinators and 50 state coordinators plus a District of Columbia coordinator, who are assisted by 320 assistant state coordinators, each of whom is responsible for a particular geographical area. Coordinators at all levels volunteer their time but are reimbursed for out-of-pocket expenses.

In 1986 AARP's 55 Alive program graduated 126,000 students. Discussions with assistant state-level coordinators suggest that the potential market for the course may be much larger than that. Relatively little advertising is done, yet there can be long waiting lists at the state level. A more intensive marketing and coordination system along with an increase in the size of the volunteer force of instructors might produce a much larger crop of graduates.

AARP also publishes *Modern Maturity*, a bimonthly magazine containing articles of interest to older citizens. With a circulation of 23 million (AARP's current membership), this magazine offers an extremely attractive channel for reaching older drivers with vehicle safety information.

American Automobile Association

AAA offers one of three driver retraining courses in the national market—Safe Driving for Mature Operators—available in 20 states and the District of Columbia. Like AARP's course, AAA's comprises 8 hr of instruction, in keeping with the requirements of most states that mandate insurance discounts.

AAA has 167 clubs in the United States and Canada; 45 to 50 of them are active in the mature driver program. Nothing firm is available on the number

of drivers whom the program has reached or the number to whom it is available. AAA has 26 million members, however, so the number of older drivers to whom the program is available is obviously quite large.

States differ in their approaches to licensing. Some maintain state control of retraining programs; others license commercial operators who are trained or certified, or both, by the state. In the latter case, AAA decides at the state level whether to market its course directly to the public, hire trained instructors to teach it, or market it through commercial agencies.

Each club operates autonomously but may seek assistance from national headquarters. Fees are set by the clubs for the courses they offer. Advertising approaches also vary depending on state regulations and local club policy. In general, the programs are advertised by word of mouth. *Clubways* magazine usually contains a brief notice concerning the availability of the course and the laws pertaining to insurance discounts.

The club offers its own course directly to the public in 13 states. All of these states report that the course is fully subscribed, with waiting lists. Given the relatively low level of advertising, this suggests that there may be a substantial untapped demand for this sort of training.

The course is organized around eight topics: Introduction (how age affects driving), Seeing, Communicating, Adjusting Speed, Margin of Safety, Driving Emergencies, Your Car, and You the Driver. The Your Car section is written from a preventive maintenance standpoint rather than from that of a prospective purchaser. The back of the course manual, however, contains advertisements for driver aids, some of which are safety oriented (e.g., mirrors and collision avoidance lights) and all of which are available for purchase from AAA. These aids are described in language that suggests a marketing rather than an educational perspective.

In addition to the mature driver course, AAA distributes two other sets of materials oriented toward the older driver. The first is a Public Affairs Committee pamphlet entitled "The Older Person's Guide to Safe Driving," prepared by a freelance writer partly on the basis of the report *Needs and Problems of Older Drivers* (11). The 25-page pamphlet is unusual in that it contains more than a page of information on safety considerations in buying a new car. Topics covered include size of vehicle, power brakes and power steering, cruise control, clear (untinted) windows, seats, and mirrors. In a separate section the pamphlet covers safety belts and air bags, suggesting that "as air bags become perfected and available, drivers may want to purchase them as optional safety equipment."

Through its Foundation for Traffic Safety, AAA has also recently sponsored the development of a "Test Your Own Performance" booklet aimed at older drivers. This attractively designed booklet contains a 15-item self-rating form that older drivers can use to score their own performance on safe driving

practices. This is followed by a discussion of answers and what they mean. Discussion includes presentation of the pertinent facts (for example, that older drivers often fail to look to the rear) followed by a set of suggestions (for example, drivers with arthritis pain or stiffness that make it difficult for them to look to the rear are encouraged to install a wide-angle rearview mirror inside the vehicle and a right-side mirror on the outside).

The discussion section of this form contains many specific suggestions on ways to improve safety through the purchase of equipment. These suggestions are woven throughout the discussion rather than drawn together in a single place. The document is organized by problem area (driving habits, physical condition, etc.), so that it is appropriate for each suggestion to accompany the problem it is intended to address.

This booklet has many strong design characteristics, including its clear organization and presentation, attractive format, and large type. One of its greatest strengths, however, is the self-rating form, which serves to get older drivers personally involved in the material at the outset.

This booklet has only recently become available, so it is too soon to tell how widely it is being distributed and how favorably it is being received. Nevertheless, it seems to have the potential for widespread and effective use.

National Safety Council

The National Safety Council markets a driver retraining course nationwide. Called Coaching the Mature Driver, the course consists of an 8-hr curriculum that includes two 16-mm films, six narrated slide shows, an additional slide program designed for group participation, and a booklet used to test driver recall. Topics covered include how to compensate for changes in vision, hearing, flexibility, and reaction time; road sign recognition; and safety belts. The curriculum does not cover the purchase of vehicle safety features to help mitigate risks for mature drivers.

The course materials are sold outright by the National Safety Council to agencies that it trains; agencies in turn train instructors to use the materials. The curriculum may also be offered by public training agencies throughout the world that have been certified by the National Safety Council.

Because of the agency arrangement through which the course is offered, statistics on the number of older drivers who take the course annually are unavailable on a national basis.

IMPROVING DISSEMINATION OF INFORMATION ABOUT SAFETY FEATURES

The review of various sources of information currently available to older drivers and consumers makes it clear that few of these sources provide any

coverage of vehicle safety features from the standpoint of possible purchase as opposed to use or maintenance. To a large extent, this reflects the somewhat arbitrary distinction between the older driver-vehicle owner and the older consumer-vehicle purchaser. Driving requires one set of skills, purchasing another. The interrelationship between the two in affecting vehicle and driver safety is easily overlooked.

Fortunately, because the driver-consumer distinction arises from semantic disassociation of these categories, it can be overcome. The recently developed AAA self-rating form is an example of how the problems of the older driver can be discussed in a way that considers both improved driving skills and improved vehicle safety features as solutions to these problems.

Driver Retraining Courses

It should be possible to include more information on vehicle safety features and the older driver in driver retraining courses without making major changes in the course structure or content. One reason for this is that the courses have been designed in modular fashion to accommodate differing state content requirements. Another is that the relevance of this material has already been established by the common emphasis on the special problems of older drivers; thus, no special motivating explanation is needed.

Driver retraining courses offer an attractive means for disseminating this type of information for a number of reasons. First, these courses appear to reach large numbers of older drivers and promise to reach more in the future. There appears to be untapped demand even in the states where they are offered, and the demand will grow as other states adopt similar legislation mandating insurance discounts for older driver retraining and as marketing efforts improve. Second, many or most of the drivers reached may be motivated by genuine concern for improving their own safety and that of others as much as or more than by the insurance discount they receive. (There appear to be no survey data on this as yet, but local coordinators for AARP and AAA programs report high levels of motivation.) Third, the course offers an intensive setting in which to introduce the materials under conditions of high involvement and high attention.

Assuming that it is a good idea to encourage adoption of additional vehicle safety information in driver retraining courses, how might that best be accomplished? One approach might be to develop prototypical materials (e.g., a booklet) on the purchase of vehicle safety equipment from the standpoint of the older driver, prepared in a way that would ensure their compatibility with one or more existing older driver retraining courses. Such a strategy would make it easy for a course to adopt these materials for supplemental use. Integration of the materials into the body of the course would require further steps.

A booklet on the purchase of vehicle safety equipment aimed at older drivers would have the further advantage of being usable as a "stand-alone" document to be disseminated in other ways—through senior citizens' groups, for example.

A second approach might be to encourage states that are contemplating new or revised legislation mandating insurance discounts for retrained older drivers to consider requiring coverage of vehicle safety equipment for state approval. Many states are reluctant, however, to specify too rigidly what must be covered, and some may see the purchase (as opposed to the use or maintenance) of safety equipment as somewhat peripheral to the content of a *driver* retraining course.

Mass Media

The broadcast media offer an attractive channel for increasing public awareness of issues; they offer less promise as ways of conveying specific content. Depending on what older drivers already know or believe, broadcast media campaigns might be considered for the purpose of increasing the salience of vehicle safety design as a factor to consider in purchasing a vehicle. The broadcast media may also be useful in directing older people to specific sources of information (e.g., crash safety test results) or alerting them to the existence of the retraining courses.

The print media on the whole appear to be better suited than the broadcast media for conveying detailed information (23). This suggests a natural division of function in an information campaign: use of the broadcast media to heighten awareness of an issue and to let people know that specific programs or sources of information exist; use of the print media (magazines, books, booklets) to convey detailed information in a form that facilitates greater depth of understanding and also makes it easier to retrieve information.

SPECIFIC QUESTIONS FOR RESEARCH

The design of effective information dissemination campaigns stands to gain a good deal from focused research on older drivers' knowledge, attitudes, and behavior. It would be extremely interesting to know, for example, how many older drivers already consider themselves to be at increased risk for traffic accidents and, if so, how accurately they perceive their strengths and weaknesses as older drivers. Some information on this question can be gleaned from the results of a recent survey of older drivers (11), but much more needs to be learned. It is possible that many of the older persons who give up driving do so out of safety concerns. Some of these drivers may experience significant impairment; others may mistakenly believe that their physical competency no

longer permits them to drive safely. Learning about how older drivers make these judgments and how accurate they are could help the design of useful information interventions. It may also help in efforts to motivate older drivers who could use additional instruction or training to seek it out.

Although much has been learned in recent years about cognitive, perceptual, and physical changes that accompany aging, and although we are beginning to have a good idea of how these changes affect older people's driving skills, there is still much to be learned about how specific training programs can best help to overcome these deficits. The techniques used in most of these programs have for the most part been chosen because they make sense; studies that seek to determine how effective they actually are have been rare.

More research is also needed on older people as consumers of automotive products. What considerations govern their purchase decisions? How do they evaluate automobile safety and how is that evaluation factored into their overall evaluation of a vehicle? How many older people automatically repurchase a previously owned make without giving much consideration to alternatives? How many scale down their minimum requirements for a vehicle (including safety requirements) as a result of their reduced mileage? Answers to these questions and others like them would help to better pinpoint older persons' information needs.

CONCLUSIONS AND RECOMMENDATIONS

The social science literature shows that it is rather easy to design informational campaigns that have no discernible influence on people's health- or safety-related behavior. The existence of successful (and usually carefully planned) campaigns, however, suggests that a properly designed campaign, aimed in an appropriate way at the right target audience, and providing them with new and useful information that is relevant to their concerns (and not just those of the people who designed the campaign), can succeed in changing behavior. There is also ample evidence that media campaigns can succeed quite readily at enhancing people's awareness of an issue. This last point may be quite important when it comes to the special needs of older drivers, because unlike many problems involving public safety, the facts have not been widely aired and debated in public forums. Thus, there is ample room for awareness to grow.

If information can be used successfully to induce a change in consumer demand, is this likely to lead to a supply response? Empirical evidence is mostly lacking, but analysis suggests that several factors will determine the answer—which may therefore depend on the particular technology involved. In the most unfavorable cases, making a safety feature available may require a major capital or other initial investment by the manufacturer, the feature may

have to be integrated into the design of the overall product line, the marginal cost to the consumer may exceed the utility for most consumers, or product differentiation may not be an option. In the most favorable cases, of course, the reverse of these conditions would hold. It is worth noting, however, that producers may have other incentives to upgrade the safety of their products, including a desire to avoid product liability and to avoid future regulatory requirements. If these incentives are present, a marginal increase in consumer demand that would not in terms of short-run profitability justify a decision to supply the market may instead be viewed as an attractive opportunity to pursue longer-term goals. It was noted earlier that demographic trends make the pursuit of the future older-driver market more attractive than it might be if considered only on the basis of its current size. These considerations all lead to the conclusion that changes in patterns of consumer demand among older drivers could affect manufacturers' decisions.

With this in mind, we return to the question of how likely it is that any reasonably scaled information campaign would induce more than a minor shift in consumer demand. Or, to put it another way, what would be required to induce a more than minor shift that is capable of being sustained? Such a change would most likely require a sustained campaign aimed at increasing awareness of particular safety issues for older drivers, and this would have to occur *in the presence of* receptivity to that sort of increased awareness. What this means is that no campaign, no matter how cleverly constructed, could succeed for very long in getting older drivers to think more about their safety needs unless that is what they think they ought or want to be doing. Nonetheless, a well-designed campaign can speed up a process of change that is culturally consistent with other trends in that population. Do these conditions exist? Perhaps—one would need to gather data (or review the data currently available) to make an educated guess. If such data showed that older drivers are receptive to this kind of information, this would offer a basis for judging that a well-designed campaign might in time produce a major increase in awareness that could in turn affect purchase behavior. In the absence of such receptivity, a communication campaign undertaken to induce changes in demand sufficient to alter market forces would probably be a waste of time.

Most of the existing informational programs aimed at older drivers do not reach enough of them to have a noticeable effect on aggregate demand. These programs can be justified on other grounds, however. The purchase of safer automotive equipment is only one of several ways that older drivers can improve their safety and mobility and is not necessarily the most important. Improvement in relevant skills and better knowledge for prevention (e.g., knowing what driving situations to avoid) are obvious alternatives.

Several specific recommendations follow from these conclusions and the earlier discussion:

- Older drivers would benefit from good consumer-oriented printed materials on how to make automobile purchase decisions that take their special needs into account. The search period preceding purchase is when consumers are likely to be especially receptive to printed information, and few existing materials fill this need.

- NHTSA and automobile manufacturers should be encouraged to develop and disseminate safety information aimed specifically at older drivers.

- Manufacturers may find the dissemination of safety information to be a useful and effective marketing strategy in reaching the older-driver market. They should be encouraged to explore this approach. Effective dissemination is likely to require the cooperation of the National Automobile Dealers Association; this should also be strongly encouraged.

- States that have developed curricula for driver retraining programs and states that might wish to use them should consider pooling their resources to develop and evaluate materials for multistate use.

- Driver retraining programs probably have a larger potential market than they have so far reached. By marketing such programs more extensively and training more instructors to teach them, it may be possible to expand their influence.

- There is a need to assess the potential of a sustained media campaign for promoting awareness among older drivers (and their families) of their particular safety needs. The goal would be not to characterize the present state of awareness (that has been done) but to assess how older drivers' awareness and behavior might be changed. Such a study might not have to be on a large scale; the use of focus groups could be considered.

- Instructional and training programs should be evaluated more carefully to learn which aspects work and which do not. Experimental studies that compare two or more variations on a given approach may prove more informative in this respect than comparison between a single-treatment group and an uninstructed control group. Better measures are needed of how instruction affects actual driving performance.

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Crash Protection for Older Persons

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Crash protection as a fundamental design parameter for motor vehicles has achieved recognition only within the last 20 years. The body of scientific knowledge on which effective crash-protective design is based is still relatively small, and is as yet inadequate to allow optimum protection to be specified for the various populations at risk. The input characteristics of crash type, direction, severity, and frequency are reasonably well defined, but the characteristics of the populations so exposed are less well understood. Age, sex, height, and weight are well documented, but tolerance to blunt impacts (which is involved in almost all traffic injuries) and how this tolerance varies throughout the population at risk have been inadequately researched. The outcome parameters of injury severity and frequency, disability, financial cost, and loss in quality of life are similarly poorly defined and delineated.

Conflicts are immediately apparent. If designs are optimized primarily to prevent death among young men, for example, such designs can be far from optimal in minimizing the incidence of the vastly greater number of injuries of lesser severity for the more vulnerable sections of the population at risk. Optimizing vehicle structures for good performance in quasi-legal 35-mph New-Car Assessment Program (NCAP) tests results in particularly hostile vehicles in side-impact collisions with another car at an intersection. Exterior design to minimize trauma to pedestrians leads to lower bumper heights and softer front end structures. These are in conflict with current non-safety-oriented economic standards that govern bumper design.

Nowhere are these conflicts clearer than when a particular segment of the population, such as older persons, is considered. This review will not be able

to produce definitive and detailed recommendations justifiable when measured against the yardsticks of classical epidemiology. That is because there are substantial gaps in the knowledge of frequency, circumstances, nature, and consequences of traffic injuries. However, there is much recent empirical work that offers great promise, and this review will focus specifically on these evolving technologies, which offer specific benefits for older persons. Much of current crash-protective design will help the whole population in a general way, but selection of priorities for older persons is more difficult. Cost-benefit criteria are normally employed in establishing such priorities, but for older persons particularly, there are many difficulties and uncertainties in using strict financial criteria. Some of these issues will be addressed in the following sections.

The purpose of this review, therefore, is to summarize some of the exposure and epidemiological characteristics of older persons in terms of their involvement in crashes as car occupants or pedestrians. Very few older persons are casualties in other categories of road user, such as cyclists and motorcyclists, in the United States. In passing, however, it is worth noting that older persons are frequently injured as cyclists and moped riders in several other countries, some of which are fully industrialized, such as Holland, France, and Japan. This might also become true in some sections of the United States where the climate is appropriate.

After a discussion of the biomechanical characteristics of older persons, the general principles of crash-protective design and some of the new technologies particularly appropriate for older persons are reviewed.

Pedestrian crash protection is covered, and then some suggestions are made for improved crash performance of vehicles to recognize the specific requirements of older persons.

Finally, there is a short discussion on general policy issues relating to crash protection and future research needs, with some specific conclusions and recommendations for the near-term and long-term perspectives.

EXPOSURE ISSUES

In the context of biomechanics and crash performance there is no simple definition of older persons. It is well established that the aging process reduces tolerance to crash forces. This applies not only to bone strength and fracture tolerance but also to the consequences of a given insult for other types of injury. For example, residual brain dysfunction following a given initial injury is greater in older persons than in younger age groups. Likewise the risk of death is significantly dependent on age following a given exposure. Yet such averaging ignores very substantial variations in physiological characteristics, partly because these characteristics are themselves not well defined. Thus,

chronological age is the only available parameter to use in reviewing exposure issues for older persons, but functional age as opposed to chronological age varies substantially in the context of biomechanics.

As is common in most industrial countries, older persons are the fastest-growing segment of the U.S. population. Just over 12 percent of the U.S. population are over 65 years of age. For the seven largest countries in the Organization for Economic Cooperation and Development, 12.5 percent are over 65 and by 2025 that number will rise to 20 percent. In West Germany and Japan by 2025, 1 person in 10 will be 75 or over. Currently in the U.S. 11 percent of current license holders are 65 and over.

The general exposure of older persons has been well documented elsewhere (1), but some conclusions relevant to crash performance are worth summarizing here. For further discussion of exposure and documentation, see Chapter 3, Safety of Older Persons in Traffic, in Volume 1 of this study.

Once involved in a road crash, those over 65 have a higher risk of being seriously injured (AIS > 3) or killed than younger age groups (Table 1). [AIS refers to the Abbreviated Injury Scale, an internationally agreed-on scale that

TABLE 1 AGE DISTRIBUTION OF THOSE INVOLVED AND INJURED IN ACCIDENTS, 1979-1980 (2)

	No. of Involved	Age Distribution (%)			
		Involved	Injured	Seriously Injured	Fatally Injured
Under 5	543,000	3.1	2.7	1.5	2.2
5-9	353,000	2.0	2.7	3.0	2.5
10-14	511,000	2.9	3.7	6.7	2.8
15-24	6,467,000	36.4	40.3	35.1	36.3
25-34	3,520,000	10.3	10.0	7.9	9.9
35-44	1,838,000	10.3	10.0	7.9	9.9
45-54	1,476,000	8.3	7.6	8.2	7.9
55-64	991,000	5.6	5.6	6.3	7.1
65+	893,000	5.0	5.6	8.3	10.5
Unknown	1,185,000	6.7	0.4	0.2	0.6
Total	17,777,000				

classifies the severity of injuries to a person overall and by body region on a scale from 1 (minor) to 6 (death). It relates predominantly to the threat to life from a given type of injury.] This is shown more specifically in Figure 1, where the mortality for specific Injury Severity Scores (ISS), which is the sum of the square of the AIS values for the three most seriously injured body regions, is shown to be strongly age dependent.

Involvement rates (crashes per 10^8 vehicle-mi) for car drivers rise substantially over 65 years, but absolute numbers remain low because of reduced

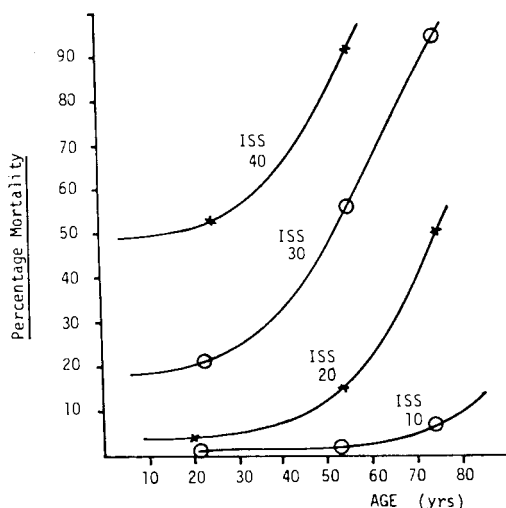


FIGURE 1 Mortality at different ages for ISS 10, 20, 30, and 40 (3).

mileage driven (Figure 2). Fatality rates (fatalities per million population in a specific age group) rise significantly, but only for those 75 and over (Figure 3).

As pedestrians, older persons are overrepresented in both casualties and deaths. Overall, pedestrians make up 16 percent of all traffic deaths in the United States. For traffic deaths involving those over 65, pedestrians make up 27 percent. That proportion is likely to rise substantially as improved technologies and legislation focus on reducing car occupant casualties. For example, in Great Britain, with 95 percent use of front-seat car occupant restraints in 1986, pedestrian and car occupant deaths are almost equal for all ages—35 and 40 percent, respectively. The equivalent numbers for the United States are 16 and 65 percent.

With retirement, substantial changes in life-style can occur, which result in different exposure to risk of involvement in various types of traffic collisions. These general exposure issues are beyond the scope of this review, but they suggest that the exposure and needs of older persons in terms of crash involvement may be significantly different from those of the younger population.

Without an extensive amount of epidemiological investigation, it is not possible to delineate these differences, and there are doubtless substantial geographical and economic factors that confuse the picture. However, there may well be a significant enough older population with different vehicle use requirements and different exposure to crash involvement to justify a vehicle

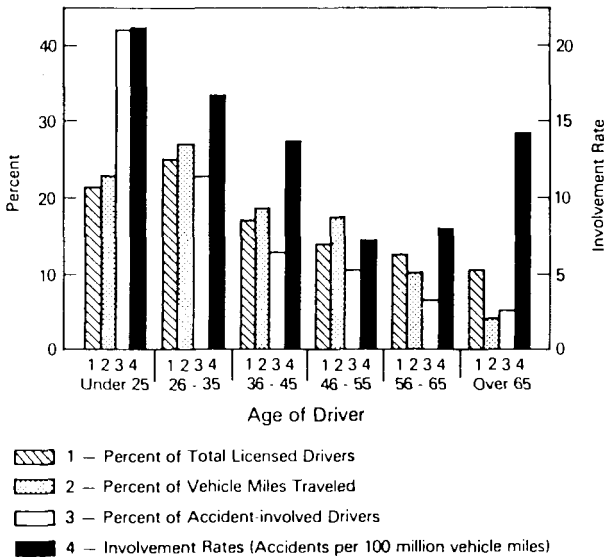


FIGURE 2 Age distribution of accident-involved drivers, 1979-1980 annual average (2).

with specific design characteristics suited to their needs. These design characteristics would include crash performance optimized for the exposure needs of older persons.

For example, one can envisage a relatively small, maneuverable, two-seated vehicle with an interior designed specifically in ergonomic terms and with a very high level of crash performance. Such a vehicle would be specifically propedestrian in design and would meet the highest standards of emission and noise control. In concept this approach might be attractive to relatively affluent older people who live in cities or suburbs with relatively low mileage requirements.

General market trends in vehicle design suggest an increasing fragmentation of the vehicle fleet, with growing numbers of vehicles having special characteristics. The high growth rates of speciality cars—pick-ups, urban vans, car-van hybrids, high-performance cars and other automobiles, offering attractions to particular segments of the marketplace—suggest that there might be a slot for a vehicle with particular attraction for older persons. Clearly, better market intelligence is needed on this point.

Another major exposure difference for older persons in comparison with the younger population is as pedestrians. With retirement comes more walking during the daytime; with a reduction in driving there is an increase in the use of public transport for many older persons and associated with that change in

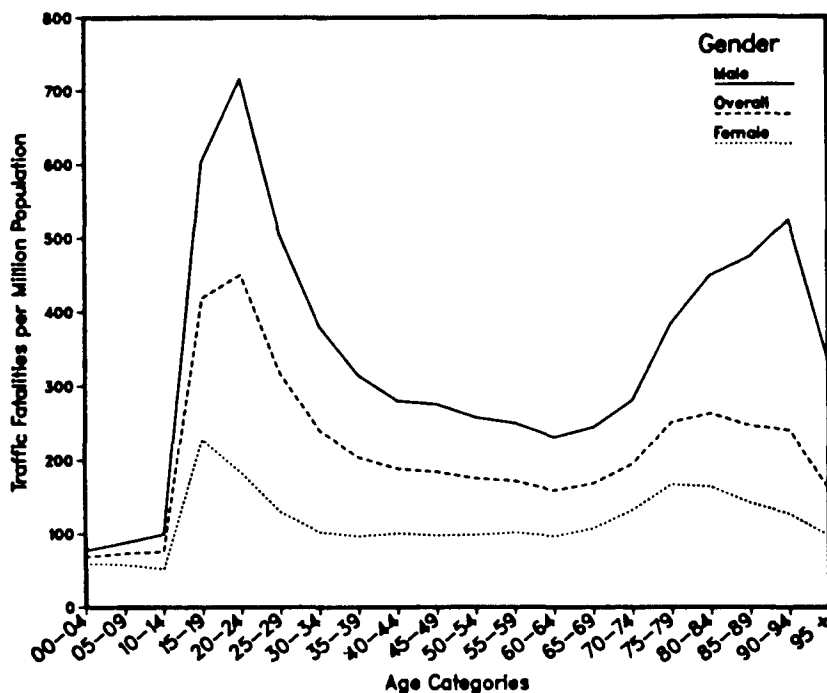


FIGURE 3 Traffic fatalities per million population in 1980 (4).

travel mode comes increased exposure as a pedestrian. Doubtless such changes are partly behind the great increase in pedestrian deaths after age 65 (Figure 4).

EPIDEMIOLOGICAL ASPECTS

Car Occupants

A number of studies outline general patterns of injuries and their severities, but no work appears to have been specifically related to age differences and changing injury patterns. The National Crash Severity Study (NCSS) tabulations show that for all ages the relative frequency of body regions involved varies greatly according to injury severity (Table 2).

A characteristic of serious traffic casualties is the multiplicity of trauma. For the average unrestrained occupant with an overall injury severity of AIS 3, there are 1.3 injuries at the AIS-3 level. For the average fatality there are 2.3 injuries at AIS 3 or more.

It should be recalled that the AIS is a scale of threat to life and does not assess long-term consequences. This is particularly relevant to older persons,

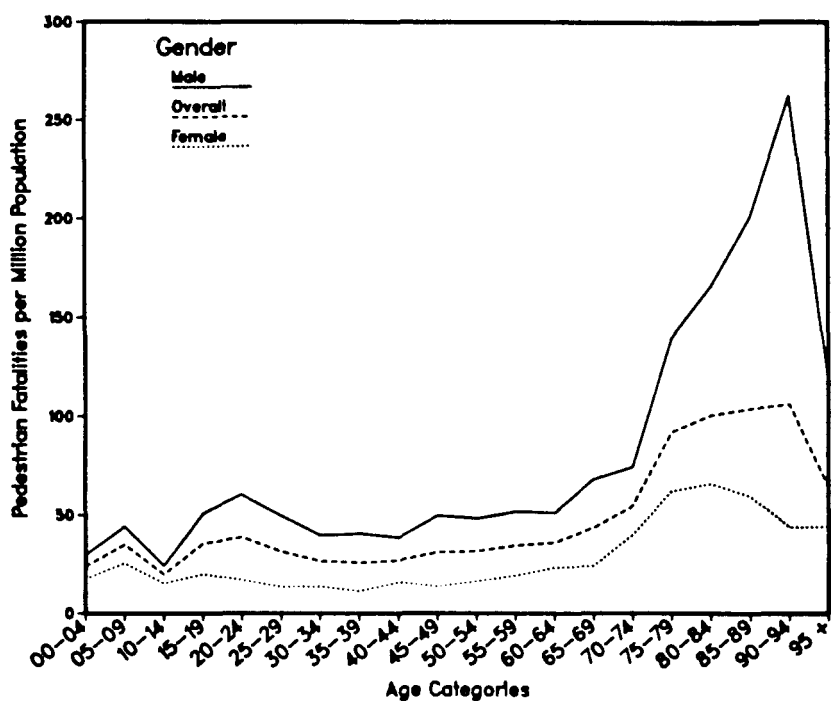


FIGURE 4 Nonoccupant (pedestrian and cycle) fatalities per million population in 1980 (4).

TABLE 2 RELATIVE FREQUENCY OF BODY REGIONS INVOLVED IN INJURIES, 1980 (5)

Body Region	Percentage of Injuries by Severity Level		
	AIS 1 (N = 19,138)	AIS 3 (N = 2,531)	AIS 6 (N = 212)
Head	43.0	10.2	29.7
Leg	19.1	26.1	—
Arm	15.2	12.8	—
Thorax	6.8	36.6	23.1
Neck	8.9	4.2	43.4
Back	4.6	1.9	0.9
Abdomen	1.9	8.3	1.4
Whole body	0.5	—	1.4

who do not recover normal function easily. Because of the relative frailness of older persons, distributions of less severe injuries are particularly interesting. AIS-2 injuries probably lead to more significant impairment of function in older persons, especially those to the head, limbs, and back. NCSS data on the relative frequency of such injuries are given in Table 3.

TABLE 3 AIS-2 INJURIES BY BODY REGION, 1980 (5)

Body Region	No.	Percent
Head	2,053	50.1
Leg	879	21.4
Arm	707	17.2
Thorax	259	6.3
Neck	37	0.9
Back	148	3.6
Abdomen	16	0.4
Whole body	1	0.0
Total	4,100	

The more serious consequences of a given initial injury severity for older persons are shown in Table 4 (6). For example, AIS-3 injuries for those under 50 require 9.7 days of hospitalization. For those over 69 the same injury requires 13.7 days. Apart from subsequent loss of function, on strictly cost terms alone, these data show that lesser levels of injury to older persons are more expensive than the same injuries sustained by younger people.

TABLE 4 DAYS IN HOSPITAL AS A FUNCTION OF AIS AND AGE (6)

Age	AIS	No.	Days	Avg Days
Under 50	1	15,065	2,861	0.1899
	2	3,268	7,825	2.3944
	3	1,422	13,795	9.7011
	4	369	6,659	18.0461
	5	111	3,999	36.0270
50-69	1	2,033	974	0.4791
	2	489	1,451	2.9673
	3	327	3,708	11.3394
	4	57	1,597	28.0175
	5	13	609	46.8462
Over 69	1	515	357	0.6932
	2	157	1,484	9.4522
	3	110	1,506	13.6909
	4	15	340	22.6667
	5	3	175	58.3333

Crash Severity

Cumulative frequency curves of crash severity exposure assessed by the computed velocity change during the crash phase are available in a number of studies, notably the NCSS (5). Figure 5 shows the general relationships between velocity change and injury severity: 80 percent of AIS-3+ injuries and 50 percent of fatalities occur at changes in velocity of 33 mph or less. The curves in Figure 5 show that the conditions that generate many severe injuries are not ones of enormous speed and energy. Thus, changes in the specifics of

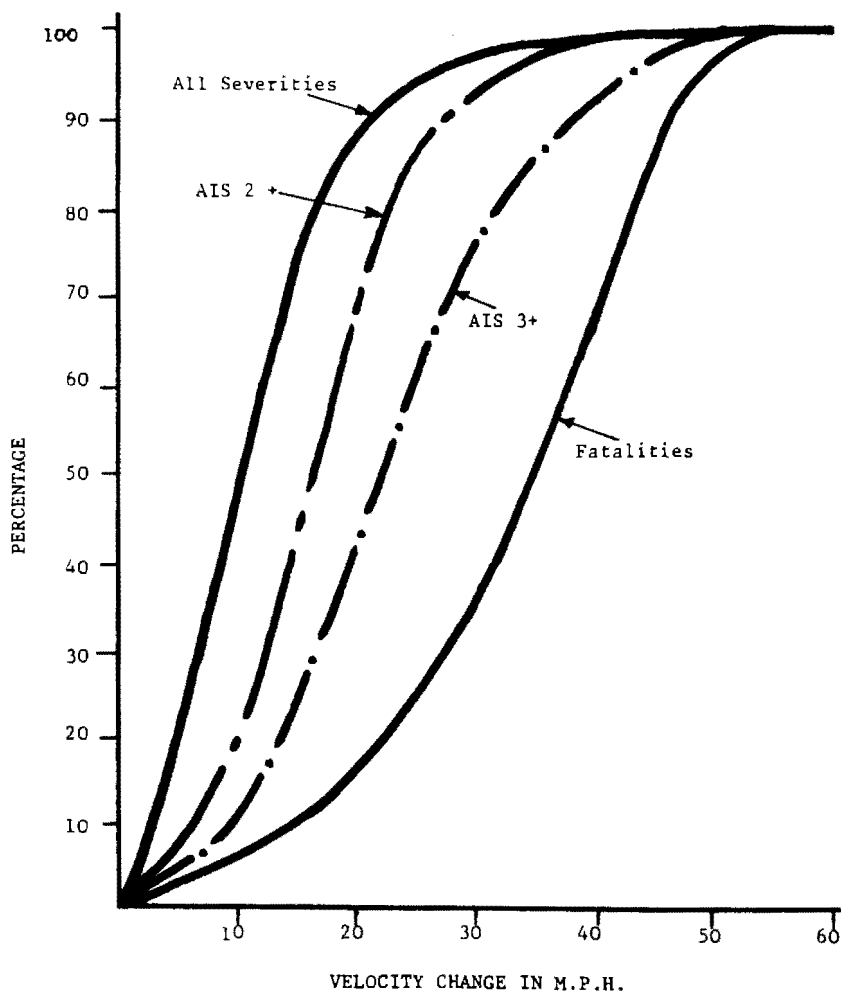


FIGURE 5 Crash severity and injury severity (5).

occupant contact achieved by improved crash-protective design can significantly benefit such population distributions.

For example, if the threshold of contact forces that produce fatal injuries at around 30 mph were increased by, say, 5 mph, because of the steepness of the middle part of the curves in Figure 5, such a small improvement in the threshold for the generation of fatal injury would lead to a significant overall reduction in the number of fatalities.

Age and probability of serious injury (AIS 3+) have been related to crash severity in Figure 6 (2). These data, which are for frontal collisions, show the age effect to be pronounced. The probability of death or serious injury is increased by about 70 percent for those over 60 years of age in comparison with the 20-year-old group (3). Alternatively, the data show that the same probability of serious injury occurs in a crash at a velocity change 7 mph less for the 60-year-old group in comparison with the 20-year-olds.

As a comparison, data from a European study (Figure 7) show the influence of seat-belt use on fatalities in frontal collisions (7). The effect of restraint use is to shift the distribution approximately 6 mph. Such an analysis relates

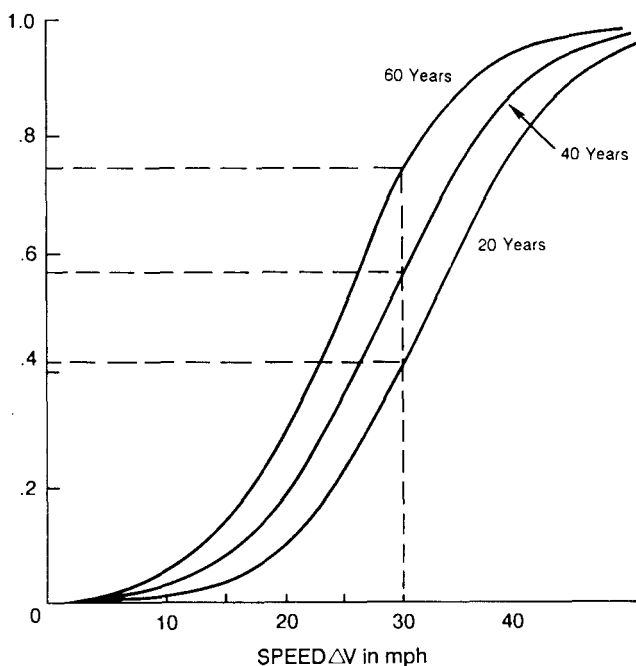


FIGURE 6 Probability of serious injury by age and crash severity (2).

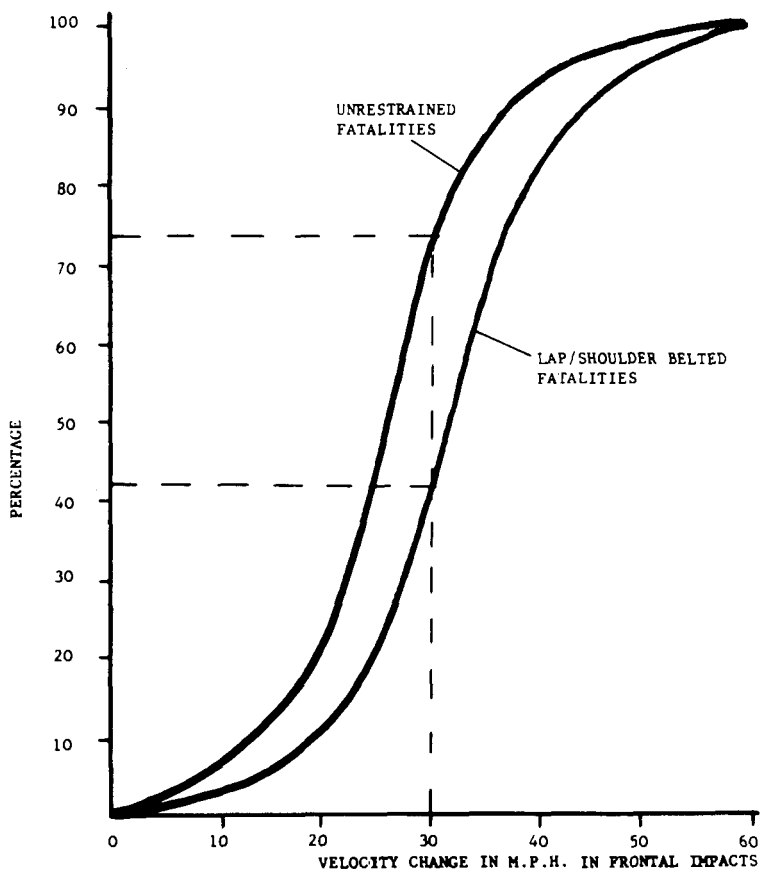


FIGURE 7 Effect of seat-belt use on fatalities (7).

purely to cars in which there is a fatality and does not indicate the benefits of restraints in crashes with lesser levels of injury.

Age and Crash Configuration

Studies in both North America and Europe show a distinct relationship between age and the frequency of various types of collisions. The most detailed study available relates to side impacts; it demonstrates several aspects of crash protection for older persons (8). Data (Table 5) show that young drivers mainly have fatal loss-of-control side impacts with rigid objects off the highway. In contrast, those over 55 have 88 percent of fatalities in vehicle-to-vehicle collisions, and only 12 percent involve off-road objects.

TABLE 5 FATALITIES IN SIDE IMPACTS (8)

Object Struck	Age (years)					
	<35		36-55		>55	
	No.	Percent	No.	Percent	No.	Percent
Other vehicle	61	35	36	74	64	88
Rigid object	115	65	13	26	9	12

The same study describes the relationship between the velocity change of the struck car and the age of occupants on the struck side who died. These data (Figure 8) show a substantial scatter, but a discernible inverse relationship is clear in which, for car-to-car collisions, the over-60 age group is the most affected, particularly at lower speeds (Table 6). The authors propose an age-dependent threshold for survival in terms of a tolerable velocity change in current-technology cars. It is the curve marked A in Figure 8.

In general, one may conclude that, as car occupants, older persons in comparison with younger age groups are

- More seriously injured for a given crash exposure,
- Hospitalized longer for a given initial injury severity,
- Exposed to fewer high-speed frontal collisions,
- Exposed to more car-to-car side collisions, and
- Among survivors, are exposed to more disabling injuries, which are predominantly to the head and lower limbs.

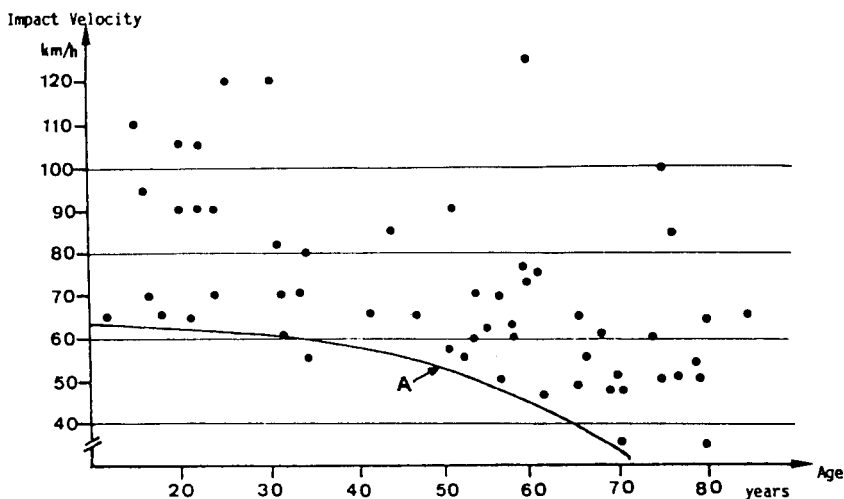


FIGURE 8 Age of fatalities in car-to-car side collisions versus impact velocity ($N = 50$) (A = age-dependent threshold for survival) (8).

TABLE 6 AGE OF STRUCK-SIDE FATALITIES IN CAR-TO-CAR SIDE IMPACT COLLISIONS (8)

Relative Velocity (mph)	Percentage of Fatalities by Age (years)		
	<40	40-60	>60
<33	0	14	86
<39	13	33	54
<45	24	32	44
<51	27	31	42

Pedestrians

Of pedestrian fatalities in the United States, those over 64 years old constitute 21 percent; there were 1,422 such fatalities in 1986. That compares with 4,408 car occupant fatalities who were over 64. The susceptibility of older persons to serious injury and death is clear from a number of sample studies. For example, Figure 9 (9), which is based on U.K. data, shows increasing proportions of more severe injuries with increasing age. This is shown in greater detail in Figure 10; for adults the incidence of head injury declines somewhat with age, whereas the incidence of lower-limb and pelvic injuries increases. Detailed at-the-scene studies of pedestrian injuries have demonstrated the importance of vehicle exterior shape. Figure 11 shows that a bumper that protrudes ahead of the hood line generates significantly more lower-limb

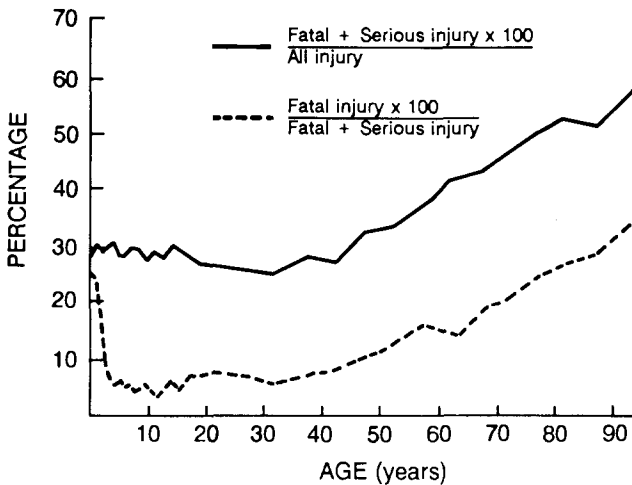


FIGURE 9 Susceptibility of pedestrians to different injury severities by age (9).

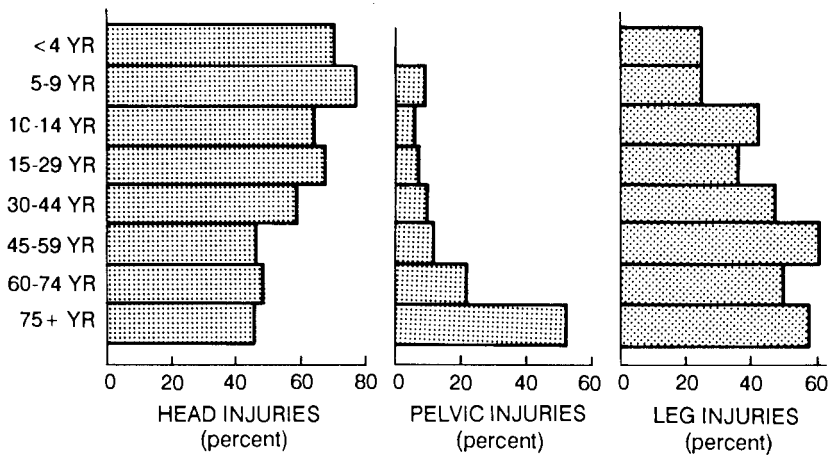


FIGURE 10 Incidence of AIS-2 and -3 head, pelvic, and lower-limb injuries for pedestrians by age ($N = 736$) (9).

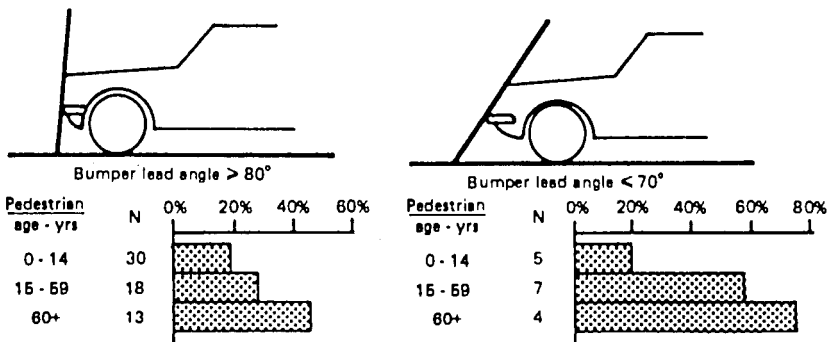


FIGURE 11 Variation in fracture incidence by pedestrian age and bumper lead angle for pedestrian struck at speeds of 21 to 40 km/hr (9).

fractures than does a more upright contour (9). That effect is particularly marked for those over 60.

These findings show that several lower-energy contacts distributed among different points on the lower limb are preferable to a single contact concentrated specifically at adult knee height. A bumper with this type of pro-pedestrian external design will be especially beneficial for older persons.

About 90 percent of pedestrian casualties occur in urban areas, where vehicle speeds are relatively low. The distribution of impact speeds in the United States for all injury severities is shown in Figure 12. About 65 percent

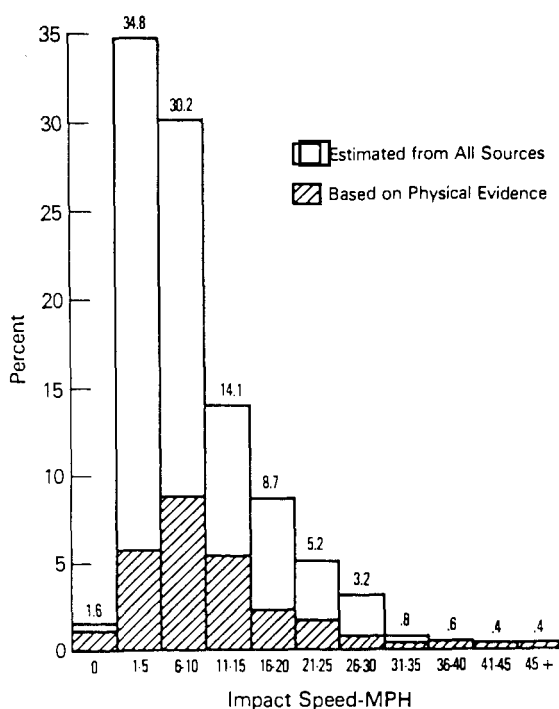


FIGURE 12 Distribution of impact speeds in urban pedestrian collisions (2).

are estimated as occurring at speeds below 10 mph (2). More detailed distributions are shown in Figure 13, where the mean speed for serious injuries [AIS 2+ in this study (9)] is 21 mph.

A substantial amount of detailed crash investigation and experimental studies have elaborated the findings on the nature of the shape and compliance of the vehicle exterior. These can be summarized as follows:

- The vehicle, not the ground, causes most of the serious injuries to the pedestrian;
- A long bumper lead is hostile for the legs and may increase the head impact velocity;
- The base of the windshield for small cars is a hostile zone, frequently struck by the heads of adults;
- The front edge of the hood of many cars leads to serious pelvic and femur injuries, particularly in older persons—a smooth curving contour rising from mid-calf is the preferred profile to minimize trauma to the lower limbs; and

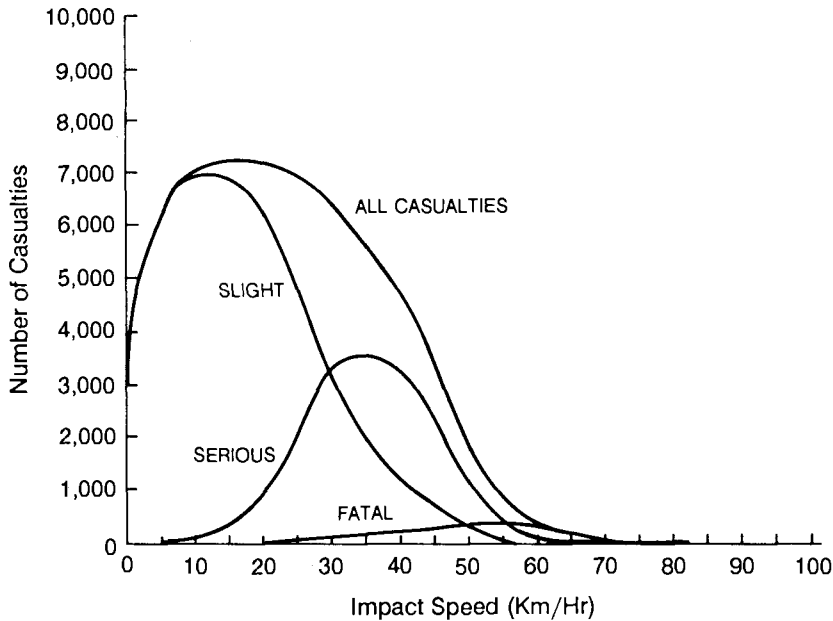


FIGURE 13 Impact-speed distributions for pedestrians struck by the front of an automobile (10).

- The hood can be designed to provide a yielding contact for the head and protection against direct contact with the stiff lower edge of the windshield frame.

It is difficult to predict the benefits of these design changes because current epidemiological data for pedestrians are inadequate. However, in one study it was suggested that if all AIS-2+ leg injuries from the bumper could be eliminated at speeds below 15 mph, there would be a reduction of about 25 percent in overall AIS-2+ pedestrian casualties (10).

BIOMECHANICAL CHARACTERISTICS OF THE ELDERLY

A number of age-related phenomena apply to the ability of the human frame to tolerate blunt trauma. The most well-researched is bone strength. Mineral content of bone, particularly calcium, diminishes with age and with it the breaking strength. Osteoporotic conditions occur in some 20 percent of women over 55, and this pathological condition can also be a consequence of inactivity as a result of some incapacity (11).

The importance of this lowering of the threshold forces to produce fracture has been examined both experimentally and in crash injury field studies. Figure 14 shows the increasing number of rib fractures occurring from the shoulder section of a seat belt for a given sled test deceleration: an average increase of about 3.75, or an increase in injury severity of 0.6 on the AIS scale, per decade over 20 years of age is shown (12).

This implies that an impact load that just begins to produce rib fractures with no displacement when applied to the chest of a 25-year-old man by a standard seat belt may well generate in a 65-year-old multiple, life-threatening fractures with a flail segment, often associated with damage to internal thoracic organs.

This same finding has been shown in crash studies with front-seat occupants using lap and shoulder belts. When standardized by crash severity, the incidence of AIS-2+ chest injuries increases from about 9 percent for 20 to 30 years of age to 35 percent for those over 65 (13) (Figure 15).

Besides such quantifiable changes as fracture resistance of bones, the aging process results in other changes to both bone and connective tissues. Collagen fibers make up much of the matrix of bone as well as being the principal mechanical component in ligaments, cartilage, and muscles. Age produces a loss of extensibility in collagen fibers, which at birth can have elongation values of over 50 percent, decreasing to 40 percent in young adults, and

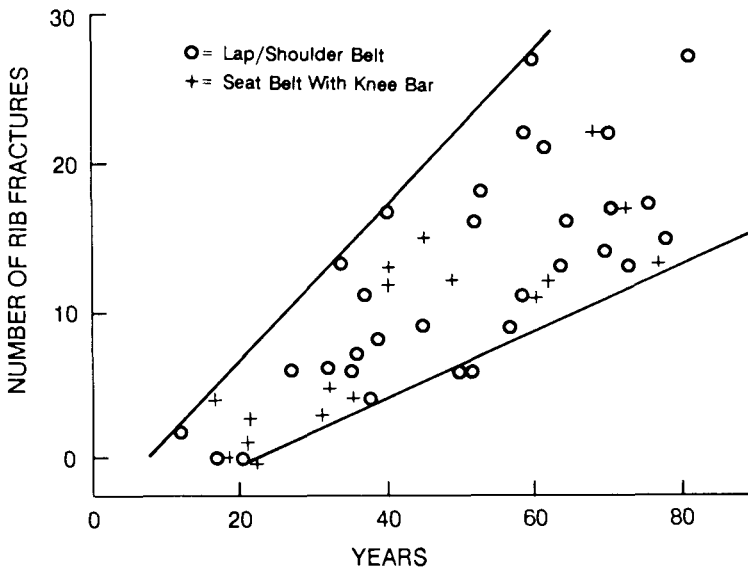


FIGURE 14 Incidence of rib fractures in unembalmed cadavers of different ages restrained by seat belts in sled tests (12).

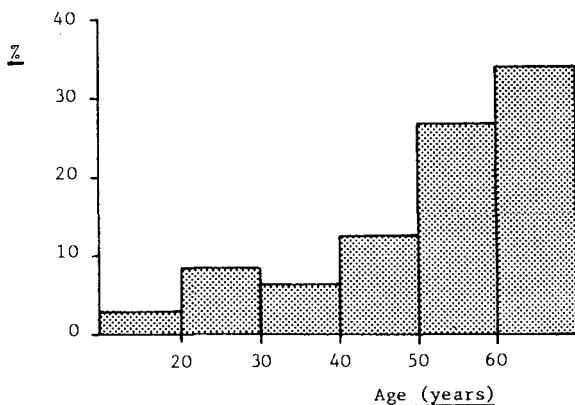


FIGURE 15 Percentage of belt-restrained front-seat occupants in frontal collisions receiving AIS-2+ chest injuries by age (13).

reducing to 25 percent in the elderly. The ultimate strength of the fibers is also reduced with age. As a consequence, joint function and resilience are diminished. Curiously, one biomechanical characteristic that improves with age is the strength of the skin, which shows a marked increase, making it somewhat more resistant to lacerations.

Other changes in the musculoskeletal system occur with age and can have a profound influence on susceptibility to other injuries. One consequence of the aging process is consolidation of the spine; the discs become less flexible and less able to change in water content. Anthropometric data show that from 30 to 65 there is a slow reduction in stature of about 3 cm, due to both compression of spinal disc spaces and changes in curvature of the spine itself. Beyond 65 there is a more rapid reduction in stature of about 10 cm for the next decade. These changes in the geometry of the spine coupled with a reduction in elasticity of the spinal ligaments probably lead to a great reduction in injury tolerance when neck flexion occurs under crash conditions. In severe cases this leads to a greater susceptibility to cord damage.

In addition to these normal aging characteristics, degenerative arthritis is a common pathological condition. The cartilaginous articular surface within joints becomes irregular and is eventually destroyed so that bone-to-bone contact occurs. In itself this is a painful condition, but under impact conditions it may well produce a greater susceptibility to injury when crash loads are transmitted through a joint.

With age the vascular system is also more vulnerable to injury and less adaptable to injury. Atheroma of the arteries is a common feature in older

persons, leading to more serious consequences of blood loss and anoxia. This is especially important in traffic head injuries. Similarly, reduced respiratory performance with age means that the body is less able to respond to traumatic shock, and thus the consequences for both respiratory function and brain function are likely to be more serious in older persons for a given injury. Many of these reductions in biomechanical performance are not directly age dependent, but follow more from a life-style of poor diet, lack of exercise, excessive use of alcohol and tobacco, and other aspects of modern (particularly urban) living.

In conceptual terms one may consider there to be a number of populations, two of which are shown in Figure 16. Current knowledge does not allow these populations to be defined quantitatively as yet, and it is likely that there is a substantial overlap for most biomechanical criteria, particularly bone fracture thresholds. In concept, however, it is clear that crash-protective design should recognize that impact tolerance cannot be represented by single point values for given body regions, which is the current practice for regulations governing vehicle crash performance. Current procedures do not yet recognize this concept of populations at risk, the corollary being that for any given crash condition and tolerance value stated, there will always be some proportion of the population who will not be protected.

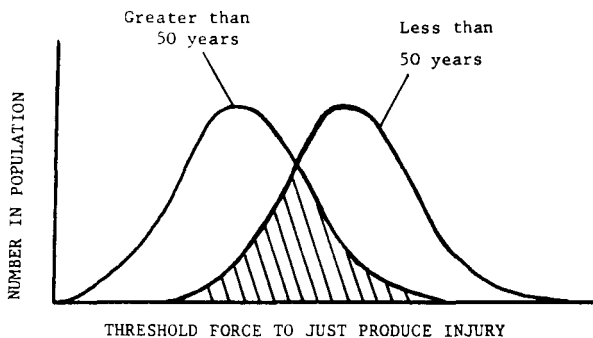


FIGURE 16 Injury tolerance variation for two populations.

Once it is recognized that these population differences exist, optimizing design for certain segments of the general population will become a more realistic procedure. One consequence is that it may be practical to offer optimal crash performance for one end of the population continuum who have both specific biomechanical characteristics and particular exposure parameters in terms of crash frequency, direction, and severity.

OCCUPANT CRASH PROTECTION

Current Practice

Vehicle Occupant Standards

In terms of biomechanical criteria used for assessing crash protection, there are only three parameters in current regulations. These apply to the head, the chest, and the femur, and they only operate in the front-to-back direction; that is, the forces are applied to the front of the head, the chest, and the knees of an occupant sitting in a car as those parts of the body make contact with structures ahead of the initial sitting position.

The Head Injury Criterion (HIC) is supposed to represent a weighted index of the force-time history applied to the head under crash conditions. An acceptable, or tolerable, limit for the index is taken as 1,000, which roughly approximates an acceleration limit of 80 g for 3 msec. An HIC of 1,000 was originally meant to indicate a 50 percent chance of survival, but subsequent work has suggested that it represents a head injury of AIS 3 for some 15 percent of the population. There is, however, much debate by experts over how the HIC, as measured in current anthropometric dummies, actually relates to the population at risk. One might suggest conceptually that an HIC of 1,500 might be a satisfactory standard for the population under 40 years of age, but a value of 1,000 is appropriate for those over 60.

The chest requirement is currently a limit of 60 g for 3 msec in the front-to-back direction. It is likely that a side-impact standard will be promulgated

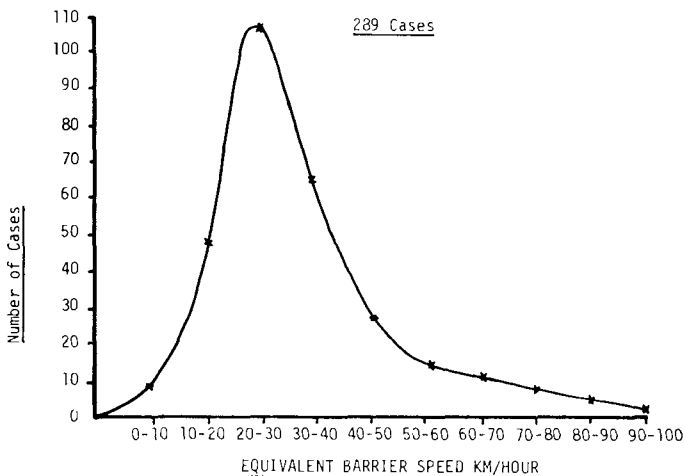


FIGURE 17 Equivalent barrier speed distribution for injury-producing frontal collisions (3).

shortly in which deflection of the chest as measured on a special side-impact dummy (SID) will be used, with a limit of 2 in. for acceptable deflection. The relationship between these thresholds and the incidence of life-threatening injuries in the population at risk is not clear, but even a somewhat arbitrary performance standard represents a start for the side-impact condition.

The femur load is currently set at 2,250 lbf measured in compression of the femur as a result of a knee impact. This is the simplest biomechanical criterion, and it is of interest to explore how a single point requirement such as this femur load limit actually relates to protection levels in the population at risk.

Figure 17 (3) represents a typical distribution of frontal collisions that produce AIS-2+ injuries to unrestrained occupants, and Figure 18 represents the likely distribution in threshold force to produce a fracture of the femur for the exposed population. Figure 17 gives the following proportions of frontal collision speeds:

<i>Speed (mph)</i>	<i>Collisions (%)</i>
0-9	20
10-18	35
19-30	32
31-48	11
49+	2

Consider two different designs of instrument panel that the knees will strike. The first design provides negligible risk of injury up to 9 mph. For collisions between 10 and 30 mph, it produces an essentially constant load of 1,700 lbf, but for collisions above 30 mph, the structure causes very high loads that injure all of the population. Thus, with such a design the following proportion of riders will be injured:

<i>Speed (mph)</i>	<i>Collisions (%)</i>	<i>Persons Susceptible (%)</i>	<i>Persons Injured (%)</i>
0-9	20	0	0
10-30	67	20	13.4
30+	13	100	13.0
Total			24.4

The second instrument-panel design is also constructed to provide negligible risk up to 9 mph. For collisions from 10 to 18 mph it exerts a load of 1,700 lbf, and for collisions between 19 and 48 mph the load exerted is 2,500 lbf, the limit allowed by the current standards. For collisions over 49 mph it causes injuries to all of those at risk. With such a design the following proportions will be injured:

<i>Speed (mph)</i>	<i>Collisions (%)</i>	<i>Persons Susceptible (%)</i>	<i>Persons Injured (%)</i>
0-9	20	0	0
10-18	35	20	7
19-48	43	90	38
49+	2	100	2
Total			40

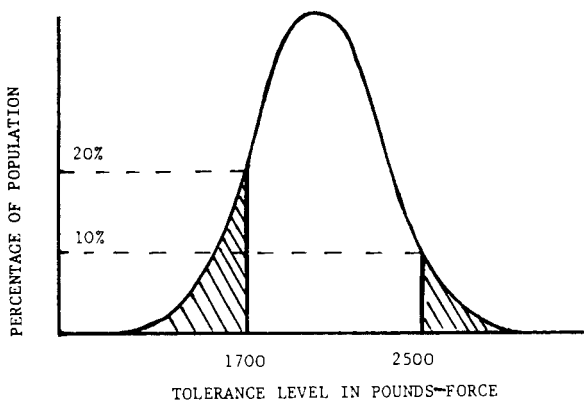


FIGURE 18 Hypothetical lower-limb tolerance level distribution.

This comparison shows that the second design, although it limits loads in higher-speed collisions than the first and would give a better NCAP rating at 35 mph, generates more injuries on an overall population basis. By focusing on providing protection in a relatively small number of high-speed collisions, it generates more injury in the more numerous low-speed crashes among the vulnerable 20 percent of the population.

This realistic, though hypothetical, example shows that recognizing trade-offs in design when populations are exposed to risk is more effective in providing protection than optimizing protection around a single tolerance level for a given crash severity, which is the current practice in the industry because of the way in which the crash performance standards are conceived. Because older persons are at the vulnerable end of the biomechanical spectrum, they have most to gain from a recognition of these factors in terms of future vehicle design.

Besides the three biomechanical performance requirements for head, chest, and femur, there are other regulations that although not actually specifying human tolerance values, do recognize certain biomechanical requirements. For example, permissible seat-belt angles and anchorage positions, head

restraint dimensions, and the energy-absorbing characteristics of steering wheels and instrument panels all imply certain biomechanical characteristics.

Virtually all crash types have the skewed distribution shown in Figure 17, in which there are a large number of low-speed events and much fewer at very high energies. Similarly, population responses vary, probably with a classical bell-shaped distribution (Figure 18), although there may well be a considerable tail on the more susceptible side as the proportion of older persons in the population increases.

Given these two interacting distributions it is highly unlikely that any single design can satisfactorily optimize the crash characteristics of the vehicle to effectively prevent both the small number of fatalities to young men and the much larger number of lesser levels of injury to the vulnerable end of the population. To resolve these issues requires a significant research effort, which may result in setting future standards for several different crash severities and several levels of injury severity. Current head and chest requirements are basically aimed at preventing death. Lower tolerance levels could well be specified for protection against less severe injuries.

Seat Belts

The most effective protection system currently available in all cars is the lap-shoulder seat belt. With its universal use approximately 45 percent of all fatal and serious injuries are prevented in comparison with no belt use. Current seat-belt use is around 30 to 50 percent in states with mandatory use laws and 10 to 20 percent in states without such laws. Survey data indicate substantial differences in use rates by age and type of car, newer cars and imported vehicles having higher use rates than older domestic cars. Also there is some suggestion that older occupants have lower use rates than the average. This may be for attitudinal reasons, but there are experimental data to show that some older people with arthritic limitations have great difficulty coping with current seat belts (14). The main difficulties are reaching and buckling the belts, but comfort is also a problem for those of small stature or who are overweight. Solutions to these problems are discussed in the next section.

In terms of crash performance, Figure 15 shows the increasing incidence of rib fractures in the elderly from seat belts. These data are limited to frontal collisions with negligible intrusion, and they suggest that for older people, current belts are not optimal. Methods of improving that performance are available in terms of preloading the seat belt, a technology of particular benefit for older persons, also discussed in the next section.

Head Restraints

Many head restraint designs allow large amounts of angular rotation of the head before its relative motion is arrested. For older people, who have a

reduced tolerance to such motion under dynamic conditions, there is an increased injury risk. A redesigned, fixed head restraint, one that does not need complicated and sometimes strenuous adjustment, would be of particular benefit to older persons.

Other Energy-Absorbing Subsystems

Current cars have many internal structures that are parts of the crash-protective package. All of these have energy-absorbing characteristics: the steering assembly, the upper and lower instrument panel sections, the door, the A and B pillars, the header rail, and the side roof rail.

Energy absorption should reflect the nature of the forces that will be applied in a range of crash types and severities and to a range of people exposed to risk. The exposure-tolerance distribution issues outlined earlier for instrument panel design therefore apply to a greater or lesser degree to all of these subsystems. For older persons, an especially vulnerable segment of the population, there are many such structures in current cars that are not optimal.

New Technologies

Restraint Systems

Having been relatively static for a decade, occupant protection is now making major advances. "Passive" restraint requirements for certain specified collision types are being introduced following a recent ruling by the Secretary of Transportation, and for the driver those requirements are being met in many cases with air-bag systems. Such systems, however, are supplementary to lap-shoulder belts. Although air bags may allow a car to pass the legal requirements for occupant restraints, they cannot offer adequate protection in the range of actual crash types. Lap-shoulder belts are still required in rollovers, multiple impacts, side impacts, rear-end collisions, and crashes below the firing threshold of the air-bag sensor. Many people erroneously believe that air bags eliminate the need for seat belts. However, none of the current passive restraint systems, whether air bags or static "friendly interiors," provide acceptable crash protection in the real world of collisions without the concurrent use of a seat belt.

For older persons this is particularly important because of their relative vulnerability. Nevertheless, such supplementary air-bag systems and friendly interiors offer additional protection combined with the conventional lap-shoulder belts, and when properly designed would allow older persons to have the same level of protection as is achieved by the younger population with conventional seat belts alone.

Supplementary Air Bags

The current timetable for the introduction of "passive restraint" automobiles is so phased that by the mid-1990s all new cars will meet the requirements for the two front outboard sitting positions in frontal and angled barrier crash tests at 30 mph.

For the driver the technological response is to provide either a passive shoulder belt and an active lap belt or a supplementary air bag mounted in the hub of the steering wheel together with an active lap belt. The injury criteria must be met in the specified crash tests without the use of the active lap belt. The one major exception is in the General Motors Bonneville line of automobiles, in which a door-mounted lap-shoulder belt is offered. In view of the ease with which such a system can be disconnected, it will be interesting to see the level of use of such a system in practice.

The supplementary air bag has the advantage over a shoulder belt in the more severe frontal collisions because in a velocity change of more than approximately 25 mph, a driver restrained only by a shoulder belt can still have face contact with the steering wheel. The injury-producing consequences of such contacts can be minimized by good design of the hub-and-spoke system of the wheel, but because of the relative fragility of the face in serious collisions, some trauma is inevitable. The supplementary hub-mounted air bag reduces this injury risk by cushioning the head and preventing localized facial load.

There is a further benefit of the hub-mounted air bag for older persons. Investigations of actual collisions show that neck strains and sprains are associated with use of lap-shoulder belts in frontal crashes, particularly for women and older persons. The supplementary air bag reduces the amount of neck flexion that occurs by causing the head and torso to decelerate together. This design will therefore be particularly appropriate for older drivers.

It is likely to be about a decade before air-bag technology is available for front-seat passengers generally. One important issue is the problem of the out-of-position passenger, a more likely occurrence than an out-of-position driver and particularly likely with children. That problem coupled with the greater range of passenger weights and sitting heights and the necessarily larger volume required for a passenger-side air bag (approximately three times the volume in comparison with a steering-wheel-mounted air bag) make the technology more difficult and the benefits more problematic. Only one manufacturer, Porsche, offers a passenger-side air bag as a solution to the passive requirements of Federal Motor Vehicle Safety Standard (FMVSS) 208; all others are currently providing passive belts of various types.

Current research with driver-side air bags shows that many of the myths surrounding air bags are untrue. Air bags do not inflate spontaneously because of malfunctions or minor impacts with curbs and garage doors. They do not

present any serious risk to hearing because of noise or overpressure. They do not obscure vision or trap drivers after a crash. The soft nature of the actual facial contacts prevents serious risk to anyone wearing glasses, which is particularly relevant because about 20 percent of older persons wear glasses for driving. No data are available on the consequences of air-bag deployment for cigarette or pipe smoking, but intrinsically such incidences are unlikely to be serious.

It is most important to recognize that cars meeting the passive-restraint requirements of FMVSS 208 with air bags for an otherwise unrestrained occupant do not provide adequate protection in the real world of collisions. As stated earlier lap-shoulder belts or shoulder belts coupled with knee restraints will still be necessary. A study in 1972 (15) showed that if lap-shoulder belts were worn by 75 percent of front-seat occupants or more, the overall benefits would be equal to or greater than those generated by 100 percent availability of front-seat air bags for otherwise unrestrained occupants. That prediction is probably still true with current technologies. Hence there is a continuing need to enhance the performance of seat belts and to recognize the specific needs of the older person in this technology.

Air bags necessarily have a threshold crash velocity change below which they cannot be activated. Current sensors are triggered at a velocity change of about 12 mph in the direction of the reticulating axis of the automobile. This means that the fore-and-aft vector of the crash force must exceed that value. As the impact angle diverges from straight ahead a higher crash speed is required for firing. In side collisions, the air bag will not be activated.

The data shown in Figures 5 and 7 give some indication of the incidence of crashes producing varying injury severities that are below the firing threshold for air bags. Current NCSS data show that for a velocity change of 12 mph or less the following percentages of injured occupants are not protected by air bags (5):

- All injured occupants in frontal collisions with $\Delta V < 12$ mph: 56 percent;
- AIS-2+ injured occupants in frontal collisions with $\Delta V < 12$ mph: 21 percent;
- AIS-3+ injured occupants in frontal collisions with $\Delta V < 12$ mph: 13 percent;
- AIS-6 occupants (fatalities) in frontal collisions with $\Delta V < 12$ mph: 5 percent.

For older people, an AIS-2 injury is likely to result in significant reduction in the quality of life; therefore, an injury of this level can be used as a reasonable criterion for significant trauma. On that basis about 20 percent of occupants with AIS-2+ injuries will not be protected by current air-bag technology in frontal crashes.

Frontal crashes represent about 54 percent of all crash types at the AIS-2+ level. Hence, if it is assumed that air bags do not offer significant protection from or are not released in other crash types—side, rear, and rollover—then air bags will only help in some 43 percent of all AIS-2+ crashes. This illustrates the need for the continued use of seat belts.

Enhanced Seat-Belt Performance

Pretensioning of seat belts, offered on some cars already, is a method that can achieve improved protection above that of current belts. The problem shown in Figure 15 can be diminished for older persons by preloading the seat belt and having the belt elongation characteristics specifically tuned to the geometry of the passenger compartment and the crush characteristics of the car. Advanced design should optimize those factors and also recognize the population differences in body weight and acceptable tolerance values for those using such systems.

It is likely that no single design solution can be achieved for all those requirements. Therefore it might well be reasonable to offer a car designed specifically for the vulnerable population, in essence tuned for the population that is small in stature, older, and involved in low-speed crashes. The feasibility of this concept and its likely benefits need to be explored in further research projects.

Ergonomic Aspects of Seat Belts

Although they go beyond crash performance, technologies that encourage belt use and solve the specific problems of older persons are relevant. The widespread adoption of electronics within the vehicle offers greater seat-belt comfort and convenience. Power-assisted positioning of the seat, with memory recall, allows the seat to return to the best position for each occupant. Lower belt mounting points on the seat give optimum lap-belt position regardless of seat adjustment. Similarly, power-assisted adjustment of the upper mounting point with a memory setting diminishes much of the discomfort of belts that reduces their use by older persons. Certainly an adjustable upper mounting point, now common on current models in Europe, is a necessary requirement for acceptable seat belts for those of small stature.

The seat-belt presenter, demonstrated in the Daimler Benz coupe, is a solution for those with such limited joint motion that the rotation necessary to reach the conventional belt is hard to achieve. With more widespread adoption of electronic systems and power assistance, such devices could greatly enhance the acceptance of belts by older persons.

Current research indicates that well-fitting lap-shoulder belts for the outboard rear seats are appropriate for satisfactory crash protection for adults.

Similar standards of crash performance and ergonomics should apply to the rear seats as well as the front; many current rear-seat belts have inferior details. Center rear-seat occupancy is only 1.5 percent, whereas outboard rear-seat occupancy is 10 times greater—around 15 percent. Hence, a case can be made for having only two designated seats in the rear, with many consequent advantages for seat-belt design. Survey data suggest that rear-seat occupants are either the young or the old, and thus improved restraint systems in the rear are a particular priority for older persons.

In general it is clear that seat-belt design is now being integrated into the basic conceptual package of the vehicle. Belt anchorage requirements influence pillar positions, seat design, and interior geometry and only on that basis will satisfactory systems be provided. With the advent of power-assisted electronics for seats and restraints, many of the problems of seat-belt acceptability will be solved. For older persons in particular there is a need for these advances to reach the marketplace.

Other Crash-Protective Systems

Knee Bars

Some passive restraint systems, notably supplementary air bags for drivers and single diagonal door-mounted passive belts, rely on a distinct structure at knee level to decelerate the lower part of the body, which contains about 50 percent of the total body weight.

Design issues of particular importance for older persons are involved in this system. The reduced tolerance to fracture of the elderly has been discussed, but beyond that, there is posttraumatic arthritis, to which older persons are particularly susceptible. Blows to the knee that do not generate fracture at the time can still cause arthritic problems (16). It may be preferable for the older person to have the lower body restrained at the pelvis by a lap belt, thus diminishing the frequency and severity of blows to the knee. The corollary of this approach is that the position of the lap belt becomes crucial, with abdominal injuries occurring if the belt is misused. This is another example of the conflict between crash performance and everyday acceptability. Single diagonal passive belts offer greater convenience and ease of access. It is clear that a number of solutions should be offered and that an educational effort should be made to explain the various advantages and drawbacks of the several systems.

Windshields

Several antilacerative inner coatings are now being developed for laminated windshields that will essentially eliminate facial lacerations under normal

impact conditions. Injuries from conventional glass windshields are normally relatively minor, so the added protection from the antilacerative development is not great, and it is not a substitute for such restraints as seat belts or air bags. This technology provides a benefit to all who are unrestrained, but it is particularly important in low-speed collisions in which air bags are fired. In such collisions where the necessary velocity change to fire an air-bag sensor is not mobilized, the unrestrained occupant will hit the windshield with his head. The threshold velocity change for current supplementary air bags is in the range of 12 to 20 mph. Figure 17 suggests that there are many collisions below such threshold levels that will generate injury to unrestrained occupants. For the unrestrained older person, therefore, who proportionally is involved in more low-speed collisions, the antilacerative windshield is particularly appropriate.

THE ELDERLY PEDESTRIAN

The general principles of exterior vehicle design for pedestrian protection have already been outlined. The state of knowledge is such that requirements for the bumper, hood edge, and hood can now be written to provide protection for pedestrians in general. Already many manufacturers have in-house standards for the hood that eliminate hard spots in the head-contact zone and protect the pedestrian from direct contact with the stiff structures at the base of the windshield.

Nonmetallic, plastic, and skinned-foam structures for the integrated nose sections of many cars, although introduced for aerodynamic and styling reasons, provide relatively noninjurious impacts for the lower limbs of pedestrians. The Fiero GT shows what can be achieved without generating conflicts with the no-damage requirements for bumpers.

A case needs to be developed for the likely benefits for older persons from such advances. For the elderly, lower-limb injuries are undoubtedly more serious and more disabling than they are for younger age groups. Serious limb injuries can result in emboli and permanent disability for older people more frequently, and the outlook for total recovery is poor. Even a slight lower-limb injury can markedly reduce in the quality of life in older persons if joint function is impaired or if already arthritic articular surfaces are damaged.

In terms of a threat to life, the elderly are clearly more at risk for the same level of injury, as was shown in Figures 1 and 11. However, because of the absence of any agreed-on disability scale, it is not possible to examine quantitatively the benefits from propedestrian vehicle design. As indicated in an earlier section, these benefits are likely to be substantial, particularly for older persons.

COST-BENEFIT CONSIDERATIONS

Priorities for development of crash-protective design and legislation controlling such design tend to be set by consideration of costs and benefits. There are two separate techniques, one absolute and one relative. Cost-effective comparisons are a reasonable method for deciding on one development rather than another. The savings from additional padding to protect rear-seat occupants in side impacts can at least conceptually be compared with the savings that might come from the provision of head restraints for rear-seat occupants. Such comparisons are internal in the sense that many of the uncertainties about the values to be attached to various types of injuries cancel each other out.

That is in contrast to cost-benefit calculations in which a dollar value for a certain development is fixed against a number of injuries projected to be saved. The cost of introducing that development into the vehicle fleet is then calculated. An equation is written in which the costs are compared with the benefits. The implication is that advances can only be justified if the dollar value of the benefits outweighs the cost of the development. Such a technique can easily be used, and indeed is used regularly by many governments, to justify not introducing certain legislation and design improvements.

However, such a technique is suspect because of the great uncertainties in putting actual dollar values on the consequences of traffic injury. Some of the direct costs are easily quantified, particularly treatment-related costs and loss of earnings. For both fatal and nonfatal trauma, the older person (over 65 years of age) shows somewhat higher treatment costs than younger age groups (17), but substantially lower costs in terms of loss of earnings.

Beyond such tangible costs, however, there are a host of quality-of-life issues that are especially important for older people because of their greater vulnerability and their greater exposure to social deprivation if disabled. Loss of mobility, increased dependence on others, and loss of social contact all have an obvious intrinsic worth that cannot be quantified with current techniques in an agreed-on manner.

In the context of crash performance, all that can be said at this time is that the first generation of crash-protective standards was focused primarily on preventing death. Those standards have had a large measure of success, and now there is a need to address nonfatal injuries and their prevention. Because older people suffer particularly from the disabling consequences of relatively moderate trauma, there is a special interest in developing protection against such injury in relatively low-speed crashes.

Cost-benefit and cost-effective analyses should be able to play a role in developing such protection, but the main difficulty centers on an agreed-on method of quantifying disability and quality-of-life issues for all age groups. This is an area in which specific research is required. As a general observation, it is clear that the potential for enhancing the quality of life by minimizing trauma through effective crash-protective design has not been approached

scientifically. The fundamental epidemiological data bases and biomechanical knowledge of human response do not exist at an adequate level for rational and effective preventive health strategies to be introduced. Now that the FMVSS 200 series of standards has been empirically conceived and focused primarily on preventing death, a more Cartesian approach is needed so that more detailed insights into costs and benefits can be made.

CONCLUSIONS

Although superficially it might be thought that, in terms of crash protection, the interests of older persons generally coincide with those of the rest of the population, this review has suggested that, in reality, there are enough differences to warrant a more detailed examination of the specific needs of the older person. These differences arise in four areas: (a) exposure, (b) biomechanics and differing response to injury, (c) occupant crash-protection requirements, and (d) pedestrian protection requirements.

Exposure

Some of the general population characteristics of older persons relate to crash exposure, such as an increasing proportion of women. There are no adequate crash or control data, however, to examine in depth the specifics of crash risk in older persons, mainly because of the absence of discriminating control data on type of driving by environment and time for various age groups.

One may generally conclude that older persons as car occupants are

- More seriously injured for a given crash exposure,
- Hospitalized longer for a given initial injury,
- Exposed to fewer high-speed frontal collisions,
- Exposed to more car-to-car side collisions, and
- Exposed to more disabling injuries, which are predominantly to the head and lower limbs.

For pedestrians, the absence of control data makes it difficult to compare the exposure of older persons with that of other age groups. Once involved in a pedestrian collision, an older person receives injuries more frequently and has more serious and more disabling injuries than younger age groups.

Biomechanics and Differing Response to Injury

This paper shows that older persons have distinctly different responses to injury than younger age groups. A given injury generated by a blunt impact, which is what constitutes virtually all crash loads in both car occupant and

pedestrian collisions, will produce more fractures and more serious injury generally, leading to a greater incidence of disability and a greater risk of death in older persons than in younger ones.

In some instances these differences can be quantified. For example, a seat-belt load in a severe collision that produces a single rib fracture in a healthy young man may well produce a flail chest injury in an older person (over 65 years) with attendant risk of major interthoracic trauma, a life-threatening injury. It is clear that for virtually all types of injury a specific tolerance or threshold level of force can be established. That tolerance level varies throughout the population at risk, and the older person probably represents the most vulnerable quartile. The difference between the most vulnerable and the least vulnerable quartiles is not adequately delineated but is likely to be one or two orders of magnitude.

Current crash-protective standards and current industry practice for crash-protective design do not recognize this fundamental variability in tolerance to impact. Standards are conceived as single-point, pass-or-fail criteria. In reality, for any given performance requirement there will always be some proportion of the population who will not be protected. The recognition of this variability is vital in assessing optimum crash-protective design for older persons. There are some specific types of injuries to which older persons are particularly vulnerable, notably neck and spinal lesions in which reduced disc space and osteoarthritic conditions have a direct adverse effect on the mechanisms of injury.

Occupant Crash Protection

To improve the protection of older persons as car occupants, it is necessary to recognize the differences between younger and older persons, both in exposure (i.e., crash type, frequency, and severity) and response (i.e., injury incidence and severity and disability afterwards). In practical terms this would lead to relatively softer internal structures and less injurious car-to-car collisions, with enhanced performance for older persons in relatively low-speed side collisions. Thus a car manufacturer would meet the basic single-point standards as currently required but would then focus his detailed design to enhance protection for the relatively low-speed crash and the vulnerable end of the population at risk. More fundamental standards should be promulgated in recognition of the problem of vulnerable occupants in low-speed crashes.

This leads to the suggestion that the market be explored to see whether this basic fact of human variability can be addressed by perhaps selling several versions of a basic model or, indeed, developing a particular model specifically for the needs and characteristics of older persons.

Because of the vulnerability of older persons, passive restraints are particularly appropriate, both for ergonomic reasons and for crash protection.

Supplementary air bags are especially applicable for older drivers, but really convenient, comfortable seat belts of the passive variety are also necessary, because air bags alone can intrinsically offer protection only in a limited range of crash types.

Pedestrian Crash Protection

This paper shows that older persons may well be overrepresented in pedestrian casualties. Because pedestrians receive head and lower-limb injuries predominantly and because such injuries frequently lead to significant disability in older persons, there is a particular need to introduce propedestrian concepts into vehicle exterior design. In spite of a number of biomechanical uncertainties, enough is known about the desirable characteristics of vehicle front structures to enact a standard for pedestrian protection.

The current non-safety-oriented economic standards that govern bumper design are not necessarily in conflict with the requirements for pedestrian protection. Predictions of the benefits of propedestrian design for all at risk are substantial, and older persons particularly will benefit from such improvements. As current technology for protecting car occupants is introduced into the vehicle fleet, the problem of pedestrian trauma will rise in importance.

RECOMMENDATIONS

From the foregoing discussion, a number of recommendations can be made both for action and for further research. These are outlined in the next two sections as near-term proposals and research and policy development.

Near-Term Recommendations

Near-term recommendations are as follows:

1. Fundamental to the specification of effective crash protection is a recognition of variability among the population at risk. Older persons have a lower tolerance to impact forces. All of the FMVSS 200 series should be reviewed by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation in terms of its effectiveness in protecting the vulnerable end of the spectrum of the population at risk. Assumptions about differences in human tolerance values will have to be made, but at least the principle of addressing population distributions rather than using single-point values should be introduced into rule making and into assessing the effectiveness of such rule making.
2. A side-impact performance standard should be promulgated by NHTSA to address car-to-car crash conditions. That standard should recognize the biomechanical characteristics of older persons in such collisions.

3. Supplementary air bags and passive seat belts are particularly appropriate for older persons. The timetable for the introduction of passive restraints for both drivers and front-seat passengers should be accelerated by NHTSA to encourage the widespread availability of these devices.

4. The comfort and convenience of many current active and passive belts, as well as their crash performance, are not optimal. Manufacturers should pay greater attention to the detailed design of such systems from the point of view of older persons whose joint movements are limited.

5. The application of electronics to seat and seat-belt adjustments should be encouraged. No single, static seat-belt mounting point can adequately provide correct belt positioning for the population using front seats. The lower mounting points should move with the seat and the upper mounting point should be made adjustable on the B-pillar. Passive belts should similarly provide for a range of occupant sizes and seat positions.

6. Air-bag sensors should be developed by the industry to lower the firing levels for both supplementary air bags and preloaded seat belts. Inadvertent firing, although inconvenient, is to be preferred to nonoperation.

7. A propedestrian crashworthiness standard should be promulgated as soon as possible by NHTSA.

8. Disabilities and reduction in quality-of-life factors, although still difficult to quantify, should be used in rule making by NHTSA as has already been done in other cases. The AIS Committee should be supported in its work toward a consensus on a disability severity scale.

Research and Policy Development

Necessary research and policy development are as follows:

1. Biomechanical studies should be supported by appropriate agencies [Centers for Disease Control (CDC), NHTSA] to delineate the population differences in injury threshold values.

2. Manufacturers should examine the feasibility of offering enhanced crash performance for the relatively vulnerable segment of the population at risk in low-speed crashes.

3. Studies should be initiated by NHTSA to delineate the crash exposure differences for the young, the middle-aged, and the older person, and sex differences should also be examined.

4. Coupled with the foregoing studies, control data on driving exposure should be collected for the various populations at risk of sufficient quality to provide controls for the field accident data files of the Fatal Accident Reporting System, NCSS, and other sources.

5. Both exposure studies and field accident studies should be initiated and coordinated by NHTSA and CDC to investigate the risks, causes, and consequences of pedestrian injuries for the various age groups, but particularly for

older persons. Propedestrian rule making should be accurately evaluated so that before-and-after comparisons can be made.

6. Demographic projections by CDC and NHTSA should be initiated to quantify the impact of the increasing population of older persons on the number of traffic casualties generating disabilities and the requirements that those casualties will have for treatment and rehabilitation. The consequences for health resources should be reviewed by the appropriate government agencies.

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The Safety of Older Persons at Intersections

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The aim in this paper is to examine the ways in which the use of intersections by older persons, both as pedestrians and as drivers, could be made safer and easier. The paper is in three main sections. In the first, accident statistics for older persons are examined with a focus on intersections. Next, possible improvements in the design and operation of intersections are investigated. The paper concludes with a summary of the major findings and recommendations.

OLDER PERSONS AND INTERSECTION ACCIDENTS

The age profile of injuries due to motor vehicle accidents turns out to be very malleable. Its shape depends on what is chosen to serve as the denominator of the injury or accident rate of interest. Thus, when the fatality rate is computed "per licensed driver," noticeable overrepresentation begins around ages 65 to 70; the rate for men is more than twice that of women (Figure 1). However, when the rate is computed on a "per unit of travel" basis, the driver fatality rate has already begun to climb around 50 and the difference between male and female drivers is small (Figure 2).

What one sees in every such graph is a mixture of two phenomena: the frequency with which people are involved in a crash and the chance of injury or death as a result (frailty). Older persons have a greater chance of being fatally injured in a crash of fixed severity. When this effect is accounted for, a very different set of age profiles emerges. Not only does the per-licensed-

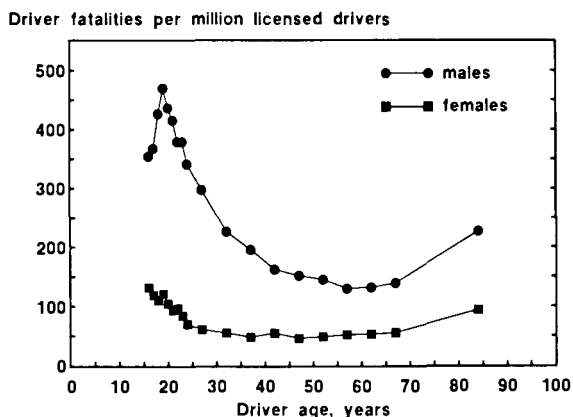


FIGURE 1 Driver fatalities (all motorized vehicles) per million licensed drivers based on FARS and FHWA data for 1983 (1).

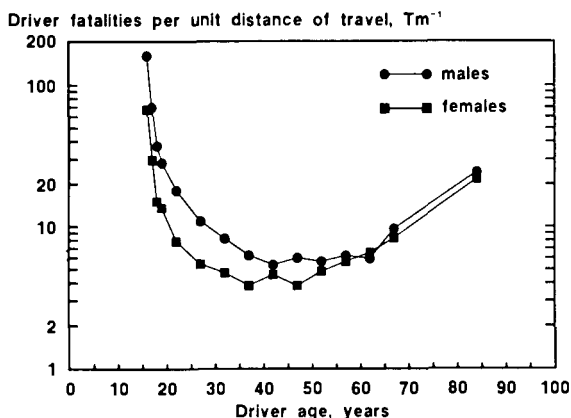


FIGURE 2 Driver fatalities (all motorized vehicles) per terameter (1 Tm = 621 million mi) of travel based on FARS, FHWA, and Nationwide Personal Transportation Study data for 1983 (1).

driver rate show no sign of increasing with advancing age, the rate for older persons is dwarfed by that of young men (Figure 3). Similarly, when the frailty effect is eliminated from the data, the plot of the per-unit-of-travel rate also changes (Figure 4). The rate begins to climb only around age 70, and its ascent is much slower than that in Figure 2.

A look at the corresponding graph for pedestrians (Figure 5), this time on a "per population" basis, shows a sharp upturn in the raw data, again around age 70. As noted before, the solid line mixes involvement with frailty. A

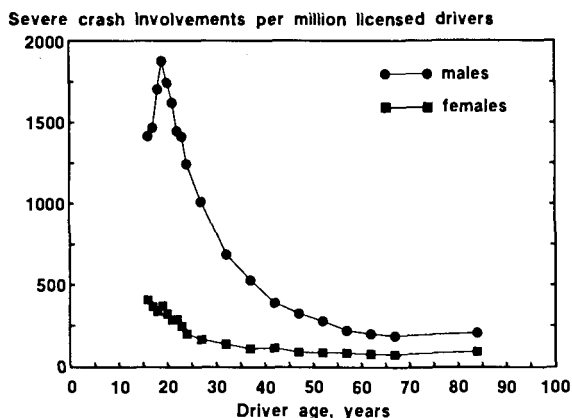


FIGURE 3 Estimated driver involvements (all motorized vehicles) in crashes of sufficient severity to kill 80-year-old male drivers per million licensed drivers (1).

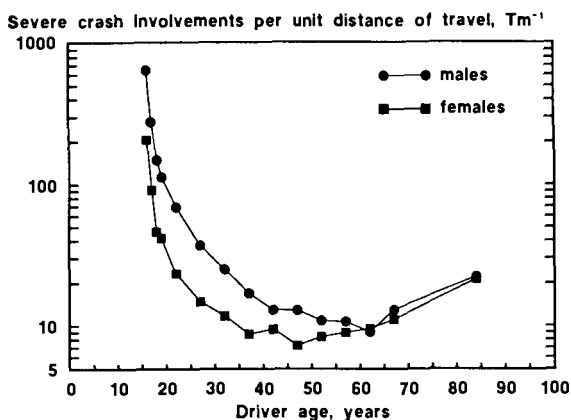


FIGURE 4 Estimated driver involvements (all motorized vehicles) in crashes of sufficient severity to kill 80-year-old male drivers per terameter (1 Tm = 621 million mi) of travel (1).

speculative attempt to separate the two and show involvement alone is represented by the dashed line. The sharp upturn at 70 nearly disappears.

Were one to separate involvement and frailty in foreign data about pedestrian casualty rates per time and distance walked (Figures 6 and 7), one would again find little increase in the accident rate of older pedestrians. One is led to conclude that older pedestrians are not overrepresented in crashes; they are just much more vulnerable. Therefore, we are inclined to believe that the problems of older persons are not so much a matter of degradation in sensory,

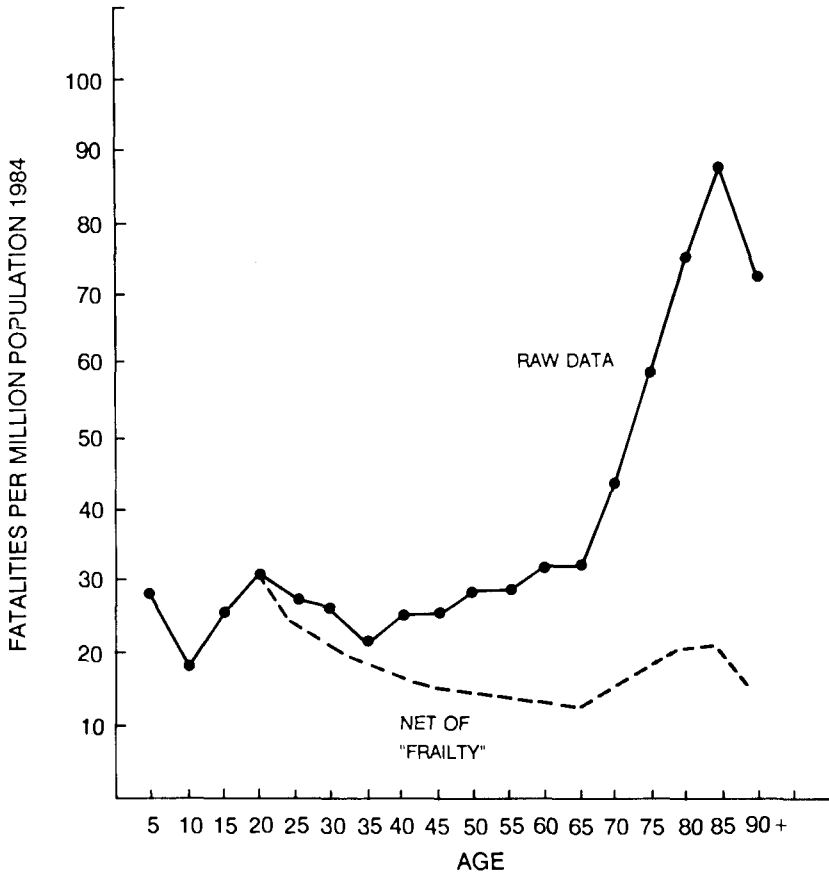


FIGURE 5 Non-occupant (pedestrian and bicycle) fatalities per million population. Note: age shown on horizontal axis refers to first year of 5-year age group.

mental, or psychomotor abilities—for which they may be compensating with success. Their main safety problem is being injured more easily and being able to recover less frequently.

There is a long tradition of motivating need for action on safety by demonstrating the existence of overrepresentation. A review of the connection between overrepresentation and justification of interventions shows little logical linkage between the two. In addition, the debate about overrepresentation tends to be sterile. On one hand, reference to accident statistics does not seem to diminish the diversity in views; on the other, the arguments for action on the basis of overrepresentation seldom seem to be compelling. Perhaps it is

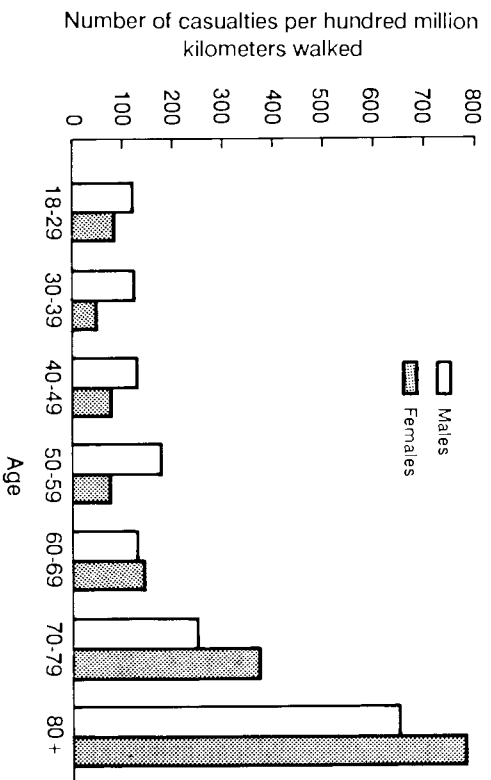


FIGURE 6 Mean number of pedestrian casualties/100 million km walked (2).

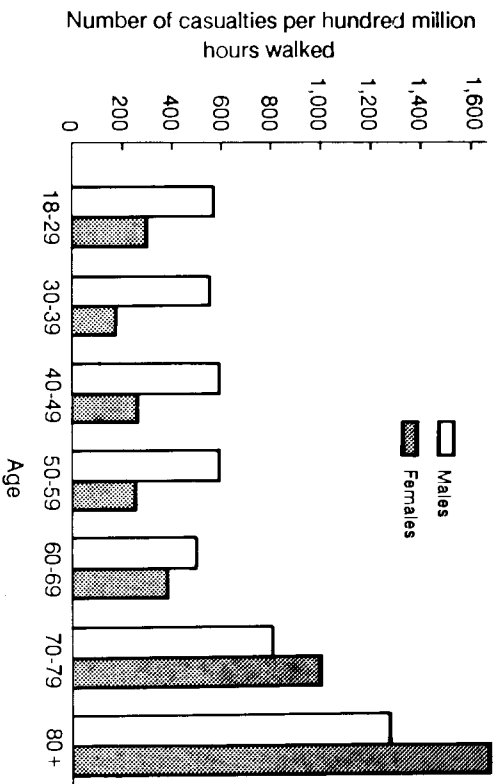


FIGURE 7 Mean number of pedestrian casualties/100 million hr spent walking (2).

better to motivate concern about the safety of older persons with the following argument.

There is little question that as one grows older, it becomes gradually more difficult to cope with the transport system. There is also no disagreement about the importance of mobility for older persons; the more mobile and self-reliant one can be as one gets older, the better for everyone. It follows that if there are opportunities to enhance the mobility and safety of older persons at reasonable cost, such opportunities should be taken. Nothing in this argument depends on the existence of overrepresentation.

In the section that follows, intersection accidents are studied in relation to age. A wealth of information is given, much of it apparently not available from other sources. Accidents involving pedestrians are discussed separately from those involving drivers. Data are given about fatalities, nonfatal injuries (by severity), and accidents involving property damage only.

Pedestrians

More than 500 pedestrians in the 64+ age group are killed each year at intersections. The number of pedestrians killed yearly at intersections in all other age groups is approximately 800 (Table 1). Nearly 6,000 pedestrians of the 64+ age group are injured at intersections; the number of injured pedestrians in all other age groups is approximately 60,000 (Table 2).

TABLE 1 U.S. PEDESTRIAN FATALITIES, 1985

Age	Intersection and Intersection-Related		Other ^a	Total
	No.	Percent of Total		
0-14	172	16.5	869	1,041
15-25	121	9.6	1,133	1,254
26-64	523	17.8	2,408	2,931
64+	<u>524</u>	33.1	<u>1,058</u>	<u>1,582</u>
Total	1,340		5,468	6,808

^aIncludes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

Some 33 percent of fatalities and 50 percent of injuries to pedestrians in the 64+ age group occur at intersections (Tables 1 and 2). Most pedestrian fatalities (at intersections) in the 64+ group occur during daylight. In comparison, more pedestrian fatalities in the 26 to 64 age group occur during darkness (Table 3). Although not shown, a similar pattern holds for injuries.

TABLE 2 U.S. PEDESTRIAN INJURIES FOR ONE YEAR OF THE PERIOD 1983-1985

Age	Intersection and Intersection-Related		Other	Total
	No.	Percent of Total		
0-14	22,658	32.7	46,691	69,349
15-25	20,913	39.2	32,381	53,294
26-64	19,202	26.2	33,763	52,965
64+	5,877	51.2	5,596	11,474
Total				187,082

NOTE: Data do not include noninjury accidents (rated 0 on the Abbreviated Injury Scale).

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 3 U.S. PEDESTRIAN FATALITIES, 1985: DAYLIGHT VERSUS DARKNESS

Age	Intersection and Intersection-Related			Other ^a		
	Daylight	Darkness	Total ^b	Daylight	Darkness	Total ^b
0-14	309	205	172	632	236	869
15-25	33	88	121	171	961	1,133
26-64	151	371	523	461	1,937	2,408
64+	309	215	524	414	643	1,058

^aIncludes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

^bSlight discrepancies are due to the omission of the "unknown" category.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 4 U.S. PEDESTRIAN FATALITIES, 1985: INTERSECTION TRAFFIC CONTROL

Age	No Traffic Control	Signs, Signals, etc.	Unknown	Total
0-14	94	77	1	172
15-25	62	58	1	121
26-64	250	266	7	523
64+	247	273	4	524
Total	653	674	13	1,340

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

Surprisingly, about half of the pedestrian fatalities at intersections (in every age group) occur where traffic is not controlled by either signs or signals (Table 4). For injuries, the situation is different. In the 64+ age group, 2,000 pedestrians are injured at intersections where no signs or signals exist and 4,000 at intersections where some traffic control is provided (Table 5).

TABLE 5 U.S. PEDESTRIAN INJURIES FOR
ONE YEAR OF THE PERIOD 1983–1985:
INTERSECTION TRAFFIC CONTROL

Age	No Traffic Control	Signs, Signals, etc.
0–14	10,949	11,709
15–25	6,284	14,630
26–64	5,273	13,929
64+	<u>1,725</u>	<u>4,152</u>
Total	24,231	44,420

NOTE: Data do not include noninjury accidents (rated 0 on the Abbreviated Injury Scale).

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

Drivers

Nearly 1,000 drivers in the 64+ age group are killed each year at intersections; those killed yearly at intersections in all other age groups number about 4,000 (Table 6). Almost 70,000 drivers of the 64+ age group are injured yearly at intersections; the number of injured drivers in all other age groups is about 900,000 (Table 7). Nearly 40 percent of fatalities and 60 percent of injuries to drivers in the 64+ age group occur at intersections.

Most driver fatalities at intersections in the 64+ age group occur during daylight (Table 8), whereas in the 26 to 64 age group, about half occur during

TABLE 6 U.S. DRIVER FATALITIES, 1985

Age	Intersection and Intersection-Related		Other ^a	Total
	No.	Percent of Total		
15–25	1,542	16.4	7,848	9,390
26–64	2,317	17.7	10,780	13,097
64+	<u>993</u>	<u>36.7</u>	<u>1,710</u>	<u>2,703</u>
Total	4,852		20,338	25,190

^aIncludes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

darkness. Similarly, most driver injuries in the 64+ age group occur during daylight. More than one-fourth of drivers are killed at intersections where traffic is not controlled by either signs or signals. Similarly, more than one-third of driver fatalities and injuries occur at intersections with no traffic control at all (Tables 9 and 10).

TABLE 7 U.S. DRIVER INJURIES FOR ONE YEAR OF THE PERIOD 1983-1985

Age	Intersection and Intersection-Related		Other	Total
	No.	Percent of Total		
15-25	369,998	44.0	471,461	841,459
26-64	519,219	48.2	557,618	1,076,837
64+	69,850	59.8	46,874	116,724
Total	959,067		1,075,953	2,035,020

NOTE: Data do not include noninjury accidents (rated 0 on the Abbreviated Injury Scale) or "unknown if injured".

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 8 U.S. DRIVER FATALITIES, 1985: DAYLIGHT VERSUS DARKNESS

Age	Intersection and Intersection-Related			Other ^a		
	Daylight	Darkness	Total ^b	Daylight	Darkness	Total ^b
15-25	678	861	1,542	2,681	5,144	7,848
26-64	1,247	1,069	2,317	4,830	5,906	10,780
64+	871	120	993	1,308	398	1,710

^aIncludes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

^bSlight discrepancies are due to the omission of the "unknown" category.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

These statistics lead to several conclusions. First, for pedestrians in the 64+ age group, 33 percent of fatalities and 50 percent of injuries occur at intersections. For drivers in the same age group, 40 percent of fatalities and 60 percent of injuries occur at intersections. It follows that roughly half of the safety problem of older persons occurs at intersections. This means that the intersection is a proper target for safety interventions.

Second, a relatively large number of pedestrians over 64 are killed at intersections (about 500 a year compared with approximately 800 in all other

TABLE 9 U.S. DRIVER FATALITIES, 1985:
INTERSECTION TRAFFIC CONTROL

Age	No Traffic Control	Signs, Signals, etc.	Unknown	Total
15-25	544	981	17	1,542
26-64	692	1,599	26	2,317
64+	<u>237</u>	<u>741</u>	<u>15</u>	<u>993</u>
Total	1,473	3,321	58	4,852

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 10 U.S. DRIVER INJURIES FOR ONE
YEAR OF THE PERIOD 1983-1985:
INTERSECTION TRAFFIC CONTROL

Age	No Traffic Control	Signs, Signals, etc.
15-25	151,864	218,133
26-64	182,185	337,036
64+	<u>18,585</u>	<u>51,264</u>
Total	352,634	606,434

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

age groups). The situation is not nearly so bad for injuries (about 6,000 a year in the over-64 age group versus about 60,000 for other ages). Similarly, a fairly large proportion of drivers killed is in the 64+ age group (around 1,000 a year versus 4,000 in younger age groups). Again, the proportion is not nearly so high for drivers injured (about 70,000 a year versus 900,000). The consistent disparity between the proportion killed and proportion injured leads again to the conclusion that a large part of the problem is attributable to the increased likelihood of death as a result of injury.

Third, for overrepresentation to lead to countermeasure identification, it is important to separate involvement rate from frailty. It appears that much of what is seen as overrepresentation in age profiles of accident rates is due to frailty. Older persons appear able to adapt to the traffic environment so as to keep nearly constant the probability of being involved in an accident; they do not appear able to adapt sufficiently to keep the probability of injury or death constant.

Among the more detailed findings, the following deserve highlighting:

- Most pedestrian fatalities and injuries at intersections in the over-64 age group occur during daylight.
- The majority of driver fatalities at intersections in the over-64 age group occur during daylight.

- About half of the pedestrian fatalities at intersections (in every age group) are killed where traffic is not controlled by either signs or signals.
- More than one-fourth of drivers are killed and one-third injured at intersections where traffic is not controlled by either signs or signals.

HOW INTERSECTIONS CAN BE MADE SAFER

Some clues about which ways of making intersections safer look promising and which do not have been provided by the discussion of the problems of older persons at intersections in the previous section. However, to make sensible suggestions about what could be done to alleviate these problems, one needs to understand the features of intersections that affect safety, to have a grasp of the process by which these features come into existence and the reasons these features are selected, and to appreciate the potential costs and benefits of change.

Safety Gains and Social Costs

The prospect of having to deal with death, injury, and misery in terms of dollars and cents is not attractive. However, because this is public money, there is an obligation to spend it effectively. This means not spending that money to save one life when two could be saved for the same amount. Thus, discussing alternative courses of action in terms of costs and benefits is justified.

It would be more meaningful to measure both gains and costs with a common monetary yardstick, but the quality of information available for such an analysis is often insufficient. Nevertheless, it may be revealing to give an example. One necessary element of quantification is a monetary equivalent for an accident saved. The range of estimates is wide, as is evident from Table 11.

TABLE 11 MONETARY EQUIVALENT OF ACCIDENT SAVED (3)

Accident Severity	Thousands of Dollars (1985)		
	NHTSA ^a	NSC ^b	Kragh et al. ^c
Fatal	395.6	256.5	1,348.7
Injury	11.1	13.2	10.1
Property damage only	1.4	1.2	1.9

^aBased on 1983 estimates by National Highway Traffic Safety Administration.

^bBased on 1984 estimate by National Safety Council.

^cBased on Kragh et al. (4).

The monetary equivalent of a representative intersection accident is a mixture of the appropriate proportion of accident severity multiplied by the applicable equivalent from Table 11 (3). The result is usually between \$8,000 and \$45,000 per accident. Break-even charts for an \$8,000 and a \$25,000 accident are shown in Figures 8 and 9.

To show the use of a break-even chart, consider the following example. A stop-controlled intersection has substandard sight distance. It is estimated that of the three accidents that are expected to occur there each year, one is such that it could be affected by improving sight distance (the other two "expected" accidents occur when the road users can see each other clearly). Thus, the number of annual "target accidents" is one. It is also estimated that by extending the sight distance at this intersection by some specific amount, the probability that a target accident will occur is reduced by 20 percent. From Figure 9 it may be deduced that accident reduction alone can justify an annual expenditure of up to \$5,000 when the monetary equivalent of a target accident is \$25,000. (An annual expenditure of \$5,000 is equivalent to a one-time expenditure of about \$42,000 with a 20-year project life and 10 percent interest rate.) If a 2:1 benefit-to-cost ratio is required, the justified annual expenditure is $\$5,000/2 = \$2,500$.

This simple example is sufficient to illustrate what estimated information is needed for an analysis of costs and benefits: the annual number of target accidents, the reduction in the probability of target-accident occurrence

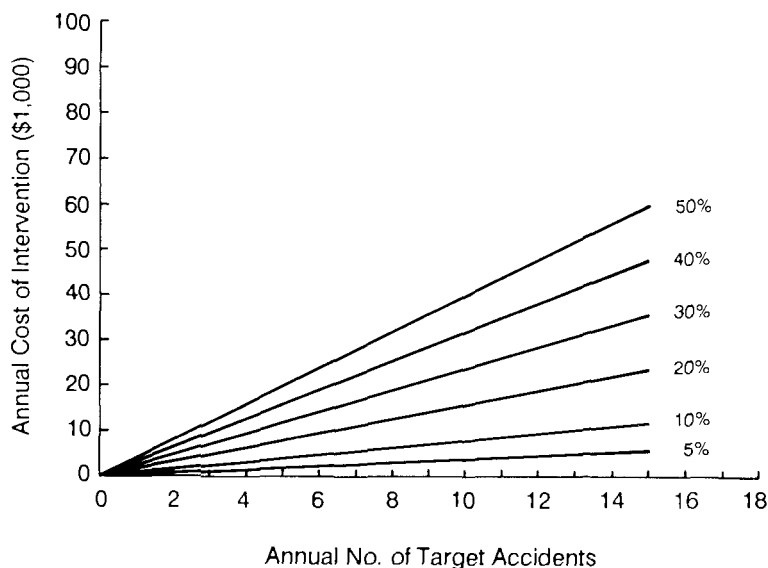


FIGURE 8 Break-even chart: \$8,000 accident.

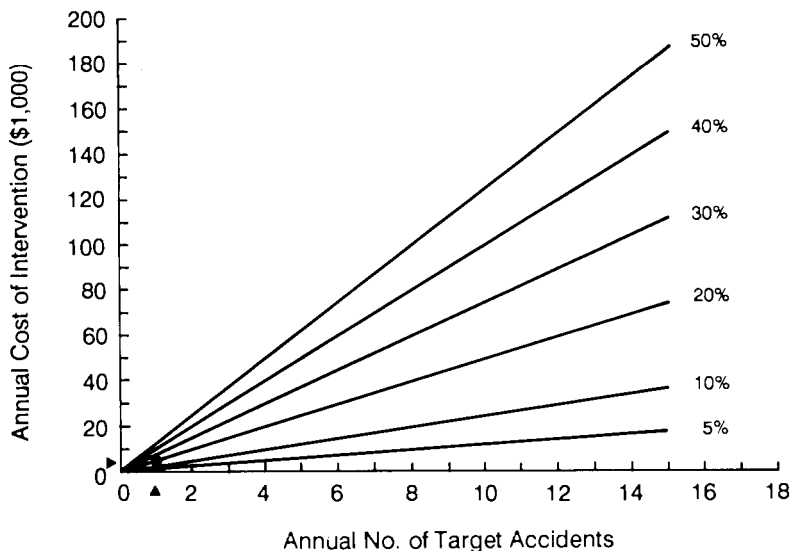


FIGURE 9 Break-even chart: \$25,000 accident.

(which depends on the sight distance available now and what it would be once improved), the cost of the intervention, and the monetary equivalent of the target accidents. Obviously, much of the information required is often not available or is only an approximation. As a result, conclusions based on such analysis must also be tentative and approximate.

The Design Driver

One of the recurring themes in discussions about the compatibility between roads and older persons is the appropriateness in design of using some driver characteristic that fits only a certain fraction of the road user population. Reaction time is one such characteristic. If, say, 85 percent of drivers have a reaction time of 2.0 sec or less, are the remaining 15 percent at peril? The issue, broadly stated, is this: what fraction of the population should be included in the various highway and traffic engineering design standards? Three points may be made. First, because the characteristics of the population are so diverse, a cutoff point must be selected. Second, the larger the proportion of the population to be accommodated, the more expensive the design. Third, the safety implications of a specific cutoff point and of including more of the population are not clear. It may thus be concluded that because the safety issues are unclear, some other basis than safety is being used to set design standards.

Intersection Design

“An intersection is defined as the general area where two or more highways join or cross, including the roadway and roadside facilities for traffic movements within it” (5).

The safety performance of an intersection is strongly influenced by the strategic decisions made before its creation about spacing (density), type (three-legged, four-legged), hierarchy and size (number of lanes, capacity, future traffic control), geometry, and so on. In addition, many intersections that exist today may not have existed a generation ago. This statement cannot be supported by examining the age distribution of those intersections now in existence because such data do not seem to exist. The alternative is to show a specific case (Figure 10). Although no specific case can be taken to represent the whole, and the rate of turnover in the inventory of intersections is not known, there is no reason to think that the process of creating them is going to stop.

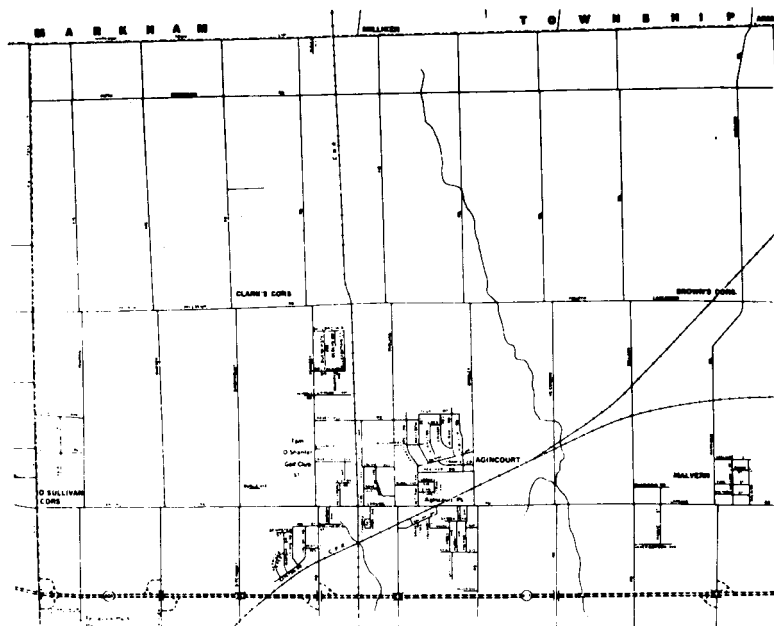
The extent of the intersection safety problem today is in part a result of the strategic decisions made about intersections in the past. By the same token, the extent of the safety problem in the future will in some measure depend on the manner in which these strategic decisions are being made now.

Although it may be natural to focus on safety improvements to existing intersections, such a focus leads to consideration of remedial measures rather than improvements by enhancing safety-related decisions made before the creation of the intersection. The distinction is similar to that between the treatment of existing illness and preventive medicine. Of course, both are important.

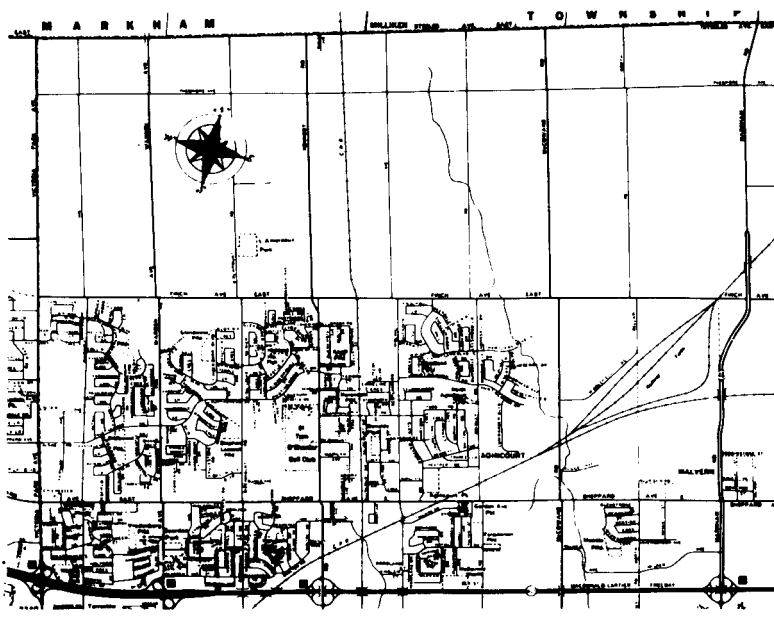
New intersections come into existence in two ways. They may be planned in conjunction with some land development or redevelopment project, or they may be created when a new road is integrated into the preexisting road network.

When land is developed, the street layout is often selected by an architect, engineer, town planner, or land surveyor. It is then approved or modified by the authorities. The eventual street and intersection layout is influenced by the commercial considerations of the developer; by the tax-base interest of the municipality, its zoning bylaws, and other official town-planning documents; and by a variety of established professional practices and design philosophies. These in turn take into consideration such factors as the function of the street, street capacity, access needs, density, and type of land use. In any case, the location, density, hierarchy, and shape of intersections are products of the street and lot layout process.

When land is redeveloped, there is often less freedom of choice. The level of decision making and design in this case is more detailed, intricate, and complex and may involve a variety of professionals and representatives of the

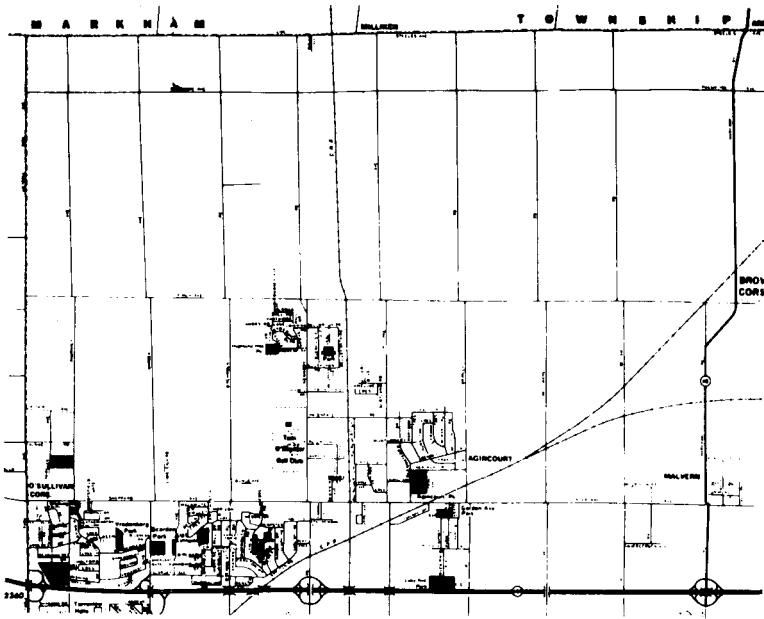


1953

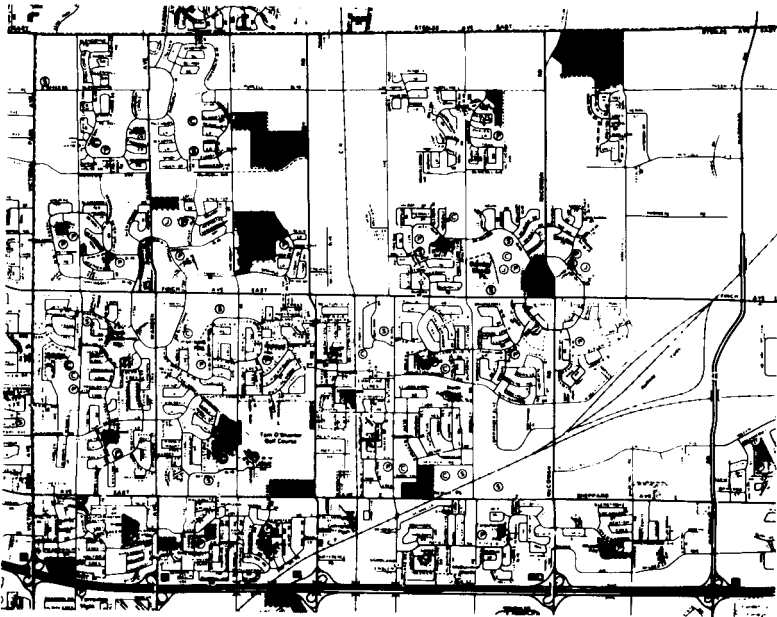


1971

FIGURE 10 The evolution of part of Metropolitan Toronto.



1961



1981

public. Similar constraints often exist when a new road is built into the preexisting network. The decision of where to cross existing roads (route choice, alignment) and how to cross (at grade or grade separated, at right angles or otherwise) often requires detailed engineering and other input.

Once an intersection has been built and equipped with the appropriate markings and traffic control devices, it continues to evolve, as does the pattern of human activity that generates the traffic on it. Increasing volumes of traffic may bring in their wake changes in traffic control devices, demand for restrictions (of turns or parking) to enhance capacity, requests for services not now provided (say, of left-turn bays or pedestrian-actuated signals). Changes in technology and cost may induce replacement of some equipment (say, traffic-responsive microprocessor-based control for electromechanical fixed-time controllers). Advances in engineering know-how and practice as well as shifting societal concerns may also be the agents of change at intersections (e.g., the adoption of new warrants for the installation of pedestrian signals or demands for curb cuts to allow freer use by those in wheelchairs).

A schematic summary of the process that shapes intersections, the professions and professionals involved, and the principal sources that guide their decisions is shown in Table 12. This taxonomy may be a useful framework within which to provide detail about the various decisions that have an effect on the safety of intersections. As is true for all taxonomies, this one is to a large extent artificial. The five classes of decisions or actions (A to E) may be too coarse, overlap somewhat, and perhaps leave important gaps. Still, they serve as a guide for coverage in a systematic fashion.

Accordingly, decision elements A, B, and C will be discussed respectively under the headings Density and Hierarchy; Form, Size, and Angle; Left-Turn Lanes; and Geometrics. Elements D and E will be covered under Level of Traffic Control, Traffic Signal Control, and Crosswalk Markings.

Density and Hierarchy

For pedestrian or driver, old or young, intersections are the most dangerous parts of the road network. This is where the paths of conflicting traffic streams cross, and is therefore where road users will most often collide. The road network weaves individual trips into a specific pattern of traffic streams by adopting a particular intersection density and hierarchy.

The safety problem created by the need to accommodate conflicting traffic streams at an (at grade) intersection can be alleviated but cannot be eliminated. There should be a choice of how many intersections to have (density) and what the proportion of the various capacity classes (hierarchy) should be. Examination of several subdivision plans, some recent and some up to 20 years old, reveals that similar residential densities can be served by a wide

TABLE 12 CREATION OF AN INTERSECTION

Decision Element	Considerations	Practitioner Involved	Information Source
A: Intersection density and hierarchy	Land use, access needs, population density	Town planner, architect, surveyor	a
B: Intersection form, size, and shape	Safety, volume, origin-destination, capacity	Town planner, architect, highway designer, traffic engineer	b, c, f
C: Geometric design (sight distance, channelization, corner radii)	Safety, turning and through volumes, level of service, pedestrian needs, right-of-way, vehicle characteristics	Highway designer	b, c, f
D: Traffic control			
D1: level of control (Stop, Yield, signal, or no control)	Safety, vehicle delay, vehicle and pedestrian volumes, capacity, level of service, speed	Traffic engineer, highway designer	d, f
D2: signal control [coordination, actuation, provision for turns and pedestrians, timing (green time and clearance intervals, Walk/Don't Walk intervals), hardware design]	As for D1, plus Walk speeds, driver perception-reaction time, crossing distances	Traffic engineer	d, e, f
E: Lighting, signing, and crosswalks	Safety, driver and pedestrian characteristics, traffic control, intersection design	Traffic engineer, highway designer	b

NOTE: Information sources are as follows: (a) town planning guidelines, (b) Institute of Transportation Engineers recommended practices, (c) AASHTO geometric design policy (5), (d) *Manual on Uniform Traffic Control Devices* (MUTCD) (6), (e) *Highway Capacity Manual* (7), (f) local policies and procedures.

variety of street networks differing in the number of intersections per mile and per acre. Thus, even within the constraints of reality, the town planner, architect, surveyor, or engineer can devise alternative route networks that may differ significantly in terms of their future safety.

In Finland where roads were undifferentiated, road users were not separated, and land use was mixed, there were 40 to 100 accidents per year per million vehicle kilometers; where roads were differentiated, road users were

separated, and land use was uniform, the corresponding rate was found to be 5 to 20. In Sweden injuries per 10,000 inhabitants were found to vary from 1.4 to 10.4 in different residential areas. In Germany "loop streets" in residential areas were found to have between 7.0 and 16.2 accidents per million vehicle kilometers per year, whereas for cul-de-sacs the corresponding range was 3.1 to 11.5 (8). Thus, one can conclude that alternative designs may differ widely in safety performance.

With this conclusion as a point of departure, both theory and practice were reviewed. A cursory examination of the standard town planning literature did not reveal any guidance on the relationship between the future safety of a development and the street network designed for it. Thus, so it appears, those who design or approve the street and intersection layout do not have explicit guidance in the standard and accessible professional literature. Guidance for traffic engineers is also sparse. Even major source documents such as the Institute of Transportation Engineers (ITE) guidelines offer only the principle that (9, p. 3) "the fewer intersections there are, consistent with other requirements, the fewer accidents there will be." A small sample of consultants and civil servants actively engaged in the practice of street design and approval for land development was contacted. Although several design alternatives are usually examined, consideration of future intersection safety in a proposed development or redevelopment is not quantitatively or explicitly examined in either the design or the approval process.

The need to design street networks with safety in mind appears to be getting considerable attention in Europe (especially for residential neighborhoods in the Netherlands and Sweden), some attention in Australia, and little attention in North America.

Recently Van der Molen (10) summarized the experience with *woonerven* in Holland. Brindle, a leading expert in this field at the Australian Road Research Board, states (11) that street spacing is an example of "potentially effective practices" that "appears not to be covered by the guidelines, nor reflected in common practice." In Sweden, specific guidelines have been compiled (12) giving, for various categories of streets, desirable spacing, with minimums and maximums. (Minimum desirable spacing ranges from 100 m for local streets to 1200 m for regional distributors.)

In North America, the selection of street hierarchy and spacing appears to be largely a matter of local tastes and the design philosophy of the planner or architect. It does not fall naturally under the heading of geometric design or traffic engineering. This is perhaps why important organizations such as the American Association of State Highway and Transportation Officials (AASHTO) and ITE either are vague or give no firm guidance on this matter. Where guidance is given, safety does not seem to be one of the criteria considered explicitly. Thus, for example, recommended spacing for arterial

streets takes into account (13, p. 540) "typical urban traffic demands, considerations of traffic signal timing and freeway distribution requirements." In other cases, some recommendations are made on the basis of considerations central to a specific discipline but marginal in the broader context of transport planning. ITE (14) suggests that intersection spacing on major streets is "strongly related to left turn storage requirements on the major street." In another ITE document (9, p. 1) safety is recognized as the first factor to consider in the design of a road network and "principle" No. 13 is that "there should be a minimum number of intersections." However, only the usual standards of geometric design such as sight distance, pavement width, or curve radii are discussed in useful detail.

Thus, it is distinctly possible that street networks are being built that are inferior in safety. This is particularly important for the safety of older persons. They, as a group, carry out more of their activity as drivers or pedestrians close to their residence than do younger cohorts.

Two questions arise. First, do feasible alternative street designs differ significantly in future safety? Second, will the difference have some impact on the eventual selection of an alternative? The answer to these questions determines the magnitude of the potential benefit. If practically feasible alternatives do not differ much in safety or if considerations other than safety determine the final outcome, the action contemplated can have no benefit.

Neither question can be answered on the basis of current experience or data. On the matter of intersection density it may be interesting to note that on some highways the accidents per 100 million vehicle-mi increase from 200 to nearly 600 as the number of intersections per mile increases from 0 to 12 (5, p. iii). Explicit and quantitative attention to safety in the formulation of feasible street and network alternatives might produce a 10 to 20 percent reduction in future intersection accidents. Were the development or redevelopment project to contain concentrations of older persons, explicit and quantitative attention to their future safety would have a somewhat higher payoff for this cohort.

The cost of implementing such a safety-conscious design is, first, that of developing the ability to comply with it; second, that of engaging in a quantification of safety for important development and redevelopment projects; and third, that of ensuring compliance with the design.

Consider a subdivision development for 2,000 persons. If in new residential areas there are about 6 accidents per 1,000 persons a year (8, p. 90), the number of target accidents is 12. With an assumed effectiveness of 10 to 20 percent and the monetary equivalent of an accident of \$25,000, the break-even cost is \$30,000 to \$60,000 a year. The one-time cost of safety-conscious design and its supervision, amortized for a long period of time at 10 percent, comes to \$300,000 to \$600,000. Even if a 3:1 benefit-cost ratio were required, an investment in safety-conscious design of about \$100,000 seems easy to justify.

Most products (appliances, drugs, toys, etc.) cannot be put into service without explicit attention to their health and safety performance by both manufacturers and regulatory agencies. Because the building of roads and intersections has important health and safety repercussions, it seems extraordinary that, contrary to common practice with other products, a road network may be designed, approved, and built without explicit consideration being given to its future health and safety performance. A strong case exists for consideration of the following recommendation for action:

- When an area is being developed or redeveloped, the “safety future” of several alternative street networks should be explicitly evaluated.

Before the foregoing requirement is implemented (and thereby development is encumbered by additional engineering costs and society by another layer of regulatory and surveillance activity), it is appropriate to demonstrate that the payoff is indeed substantial. Accordingly, the following research is recommended:

- Research should be undertaken to determine the differences in safety performance of alternative feasible street networks (including intersection density and hierarchy) in development and redevelopment projects.

The first recommendation is far reaching and therefore may not be easy to implement. However, some less far-reaching actions could be implemented easily and in the shorter term.

It is a matter of common sense and responsibility that professional work be based on professional knowledge. At this time, there are no documents to consult for guidance in assessing the future safety of a proposed street network. Such a source, with simple tables or graphs, would be welcomed by current and future professionals alike and would promote the development of a more safety-conscious professional practice. Accordingly, the following action is recommended:

- Guidance should be provided for professionals in estimating the future safety performance of the street networks they design and approve. Ways should be sought to ensure that such guidance will be published and used in undergraduate training and professional development.

Much of the needed research has already been done and has been published. It needs to be assembled and critically reviewed so as to determine what the best practice is on the basis of the information available. This gives rise to the following research need:

- A procedure should be devised on the basis of current research by which the safety performance of a planned street network can be quantified. The

procedure developed will be used to provide the guidance specified in the preceding recommendation.

These recommendations for action and research appear to mesh well with a new proposed ITE policy for residential streets (15), which recognizes the inadequacies within and on the collector and arterial road system and the need for professional involvement in resolving the resulting problems.

The first of the preceding recommendations agrees in spirit with those for a safety-conscious design process in the recent TRB Special Report 214 (3, pp. 190–193). The other recommendations are similar in spirit to what has been recommended in the same report for safety research and training (3, pp. 208–212). In fact, many of the recommendations here should be considered an added argument for the Special Safety Task Force that Congress has asked the Secretary of Transportation to set up.

Form, Size, and Angle

Form The two most common forms of at-grade intersections are that with three legs (T-intersection) and that with four legs (cross intersection). In some cases (e.g., when a new road is built across existing roads), no real choice of form exists. In other cases (e.g., when a new subdivision is designed), both intersection forms could be used. It appears that, as in the case of intersection density and hierarchy, the selection of intersection form is more a matter of taste than of explicit consideration of future safety.

The T-intersection has only 9 possible conflict points, whereas the cross intersection has 32. Thus, for older persons the relative simplicity of the former is attractive. Because the safety of older persons at intersections could be significantly affected by the choice of intersection form, more explicit guidance is needed about the safety performance of alternative intersection forms under different traffic and pedestrian flows. Once such guidance is available, choice of form for new intersections should be made on that basis.

Of the existing authoritative guidelines, two are worth mentioning. In the ITE guidelines for subdivision streets it is stated (9, p. 3): "From the standpoint of hazard, use of two T-type intersections with proper offset is preferable to using one cross-type." The AASHTO Green Book (5) recommends that the staggering of intersections be done only if traffic crossing the major street is moderate.

Size Intersection size, or number of approach lanes, and type of traffic control are based on a match of capacity with design (demand) volume. For any particular intersection, there does not seem to be much practical latitude for choice: once the design volumes have been ascertained, the number of approach lanes follows. The design volumes in turn are determined by intersection density, hierarchy, and form.

Even though the latitude for choosing the proper number of lanes is limited, two issues deserve mention. First, wide approaches (more than two lanes in each direction) make the accommodation of pedestrians difficult. Not only is the crossing hazardous, the need to provide for pedestrians reduces the capacity of the intersection (16). Second, the size of an approach is affected by the decision to build a left-turn (storage) lane. This decision affects the safety of pedestrians as well as vehicles. More will be said about both subjects later.

To some extent, the physical size of the intersection depends on the width of the lanes. The ITE guidelines (9) suggest a minimum lane width of 11 ft and specify 12 ft as "desirable." It is also suggested that wider lanes be avoided because they "increase pedestrian crossing distances." Nevertheless, according to the guidelines, a range of opinions exists, with tolerable variations of lane width from 9 to 14 ft. One philosophy of particular interest is that narrowing intersection lanes not only reduces pedestrian crossing distances, but also lessens the speed of motorists, and therefore enhances safety, particularly for pedestrians. For lane-width selection, AASHTO (5) differentiates among local, collector, and arterial streets, and furthermore whether these are urban or rural. Thus, for example, the minimum lane width for a local road in a rural area is 9 ft (5, p. 464), whereas in an urban area a lane should be (5, p. 474) "at least 10 ft wide. Where feasible they [lanes] should be 11 ft wide." Still, where severe limitations exist (5, p. 475), "9 ft lanes can be used in residential areas." Still different considerations apply for the width of a lane used for turns, which is governed by the kind of vehicles assumed to be turning. Thus, for example, a single-unit truck or bus that before turning occupies 8.5 ft of a lane sweeps a path 13.6 ft wide as it turns (5, p. 730). A semitrailer takes 8.5 to 20.6 ft. One can readily see the safety issue that emerges: how to mediate between the need to accommodate larger turning vehicles and the interest of the pedestrian whose crossing distance is thereby prolonged.

Angle The angle at which the centerlines of the intersecting roads meet is the intersection angle. It is commonly agreed that it should be a right angle. Some sources give 75 degrees as the minimum, whereas AASHTO states (5, p. 724): "Angles above approximately 60° produce only a small reduction in visibility, which often does not warrant realignment closer to 90°." In this context, "visibility" usually means "unobstructed sight distance" (5, p. 774), that is, how far one can see with the appropriate turning of the head. However, the need for extensive head movement is in itself a problem for the older segment of the driving population, which may not have been taken into account in AASHTO's geometric design policy. Fortunately, most intersections are built at right angles. Because the need to engage in extensive, often difficult and slow head movement at acute-angle intersections may be a real difficulty for older drivers, affecting their safety, the use of an acute angle in intersection design should be explicitly justified.

Left-Turn Lanes

Safety is an important benefit in the provision of left-turn lanes, which can reduce opportunities for rear-end collisions. In addition to safety benefits, left-turn lanes also reduce vehicle stops and delays and make the intersections simpler to use, thus benefiting older drivers.

In fact, it would appear that the only reasons for not providing a left-turn lane are either that the right-of-way is not available or is too costly or that the road space is needed to carry through traffic. There is perhaps another reason, which has not yet been explored: that a left-turn lane prolongs pedestrian walking distances or narrows the refuge island.

In principle, therefore, the decision to provide a left-turn lane should be made on the basis of a comparison of benefits and costs. To illustrate how such a comparison would be made, consider the addition of a left-turn lane to an intersection approach. The right-of-way, construction, and maintenance costs are, say, \$60,000, which is equivalent to about \$7,200 a year. Calculations (based on traffic flow and approach speed) show that on the approach one should expect to see one rear-end accident a year. If the monetary equivalent of a target accident is \$25,000, it takes a 35 percent reduction in rear-end accidents to break even on accident reduction alone. Were a 35 percent reduction obtainable, the other benefits (reduced delay, increased freedom from conflict) might go toward increasing the ratio of benefits to costs.

Several attempts have been made to come up with a set of guidelines based on the economics of the situation (17–21). Although AASHTO does not provide guidance beyond recommending that left-turn lanes be installed where volumes are high and speeds fast, several jurisdictions have warrants based on volumes and approach speeds (22–24).

A considerable body of information already exists about the safety effects of left-turn lanes. Thus, ITE guidelines (14) quote Box (25) in suggesting that “studies have demonstrated that accident experience is significantly reduced when left-turn storage lanes are provided at intersections of 2-way major streets.”

An FHWA report (26) suggests that the provision of left-turn channelization at nonsignalized intersections, if combined with curbs or raised bars, will reduce accidents by 70 percent in urban areas and by 65 and 60 percent in suburban and rural areas, respectively. If channelization is painted, accidents will be reduced by 15 percent in urban areas and by 30 and 50 percent in suburban and rural areas, respectively. At signalized intersections, it is suggested (26) that left-turn channelization with a left-turn phase will reduce accidents by 36 percent; without the left-turn phase, by 15 percent. It is also suggested that adding left-turn lanes without signals can decrease accidents by 19 percent on urban two-lane roads, and by 6 percent on urban roads with more than two lanes, and increase accidents by 6 percent on rural roads with

more than three lanes. Adding left-turn lanes with signals will reduce accidents in the last two categories by 27 and 54 percent, respectively.

Jorgensen and Associates (27) give costs and safety benefits of adding left-turn lanes. These lanes are estimated to reduce accidents by varying amounts depending on whether the intersection is rural or urban; is four-legged, cross, or T; or has added signals. Adding turn lanes without signals at four-legged intersections increases accidents 6 percent and with signals at rural T-intersections, 42 percent. Jorgensen and Associates also reproduce the California Division of Highways accident reduction factors, which specify that left-turn lanes reduce accidents by 15 or 36 percent if a turn phase is added to the signal. The basis of all these data is not clear.

Elsewhere in the literature, there seems to be agreement that left-turn lanes considerably reduce rear-end accidents but might increase left-turn accidents, but perhaps this only occurs because there tend to be more turns when left-turn lanes are provided. For example, McCoy et al. (28) did a cross-sectional study of uncontrolled approaches to two-lane rural highways and found that those with left-turn lanes had a lower (not statistically significant) rear-end accident rate and a higher (not statistically significant) left-turn accident rate than did those without. At least one study [David and Norman (29)] concurs that left-turn lanes are not always safety-effective.

To sift through this mass of evidence and select what is valid is a major undertaking because much of what is reported suffers from serious deficiencies of method. We speculate that left-turn lanes reduce rear-end accidents mainly, and the amount of reduction may vary from 20 to 60 percent.

In summary, it is clear that in many circumstances left-turn lanes are of benefit to all. Nevertheless, again there is no authoritative guidance on the conditions under which a left-turn lane should be built, which may cause opportunities for improvements to be forgone. If the profession chooses not to issue complex warrants because of the variability in local conditions, the practitioner should be provided with a clear procedure enabling him to determine the quantitative descriptors of the situation and how to make a rational decision on the basis of local conditions. Currently, such a procedure does not seem to exist, thus, the following recommendations:

- The knowledge now available should be critically reviewed, summarized, and cast into the form of a procedure usable by engineers.
- A procedure to analyze the need for left-turn lanes should be included in the ITE handbook or perhaps even in the AASHTO geometric design policy.

Geometrics

This section includes discussions of sight distance, channelization, and curb-corner radii.

Sight Distance The provision of proper sight distance is thought to greatly reduce the possibility of conflict. How much is proper depends on the type of traffic control, but the philosophy remains the same—to enable a vehicle entering the intersection to avoid conflict with vehicles on other approaches. The most conservative provision is for uncontrolled intersections. Preferred practice (5) is to provide a clear “sight triangle” that allows drivers to see the intersection and the traffic on the intersecting road in sufficient time. Uncontrolled intersections are perhaps few, and ITE (9) recommends that the intersection of local streets be designed to operate without any traffic control device whenever possible. For uncontrolled intersections AASHTO (5, p. 777) suggests using “2.0 sec for perception and reaction plus an additional 1.0 sec to actuate braking.”

An entirely different case arises when the vehicle has to stop at the intersection before crossing or turning. Now it becomes important to complete the maneuver safely even if another vehicle comes into view just as the maneuver begins. In calculating the time required to complete a crossing maneuver, AASHTO (5, p. 781) suggests using 2.0 sec as the interval between the driver’s first looking for oncoming traffic and the instant that the car begins to move. Shorter times may be used in urban areas. It is noted (5, p. 782) that the required sight distance is only very slightly affected by the reaction-time value chosen. Thus, using 1.0 sec instead of 2.0 sec reduces sight distance by about 15 percent.

There is a great deal of evidence that although older persons do not necessarily react much more slowly to stimuli, they do take longer to make up their minds, particularly in complex situations. In addition, the decision to enter an intersection (from a minor road) requires extensive and repeated head movement, a task that becomes increasingly difficult with age. Thus, the situation that a driver faces when approaching an intersection or when deciding to enter an intersection after stopping is indeed complex.

The currently used sight distances may place some older persons in difficult situations. We conclude that the safety of older persons at intersections may be adversely affected when too short a design reaction time is used in the calculation of intersection sight distance and that further study of this issue is required.

The FHWA synthesis (30) gives results of several studies. The first finds that in projects aimed at improving intersection sight distances, safety benefits outweigh costs 5.33 to 1. Because of faults in collecting and analyzing those data, the results are not reliable. The second study cited also indicates a large accident reduction by removing obstructions at intersections. However, in this case high-accident locations were selected for improvement, and it is possible that much of the noted reduction was due to regression to the mean. Two more studies, one pertaining to rural intersections in Michigan and the other to

Virginia, indicate that intersections with poor sight distances have higher accident rates.

Additional information is given by David and Norman (29), who found intersections with a shorter "sight radius" to have generally higher accident rates. The study uses its findings to provide estimated accident reductions obtainable by increasing sight distances (29, p. 76). Unfortunately, these results cannot be trusted either. The authors calculate accident rates at sites that differ in "sight radius" and attribute the difference to visibility only. Of course, sites that differ in "sight radius" differ in several other important respects as well. This single-variable cross-sectional method of analysis leads the authors to many paradoxical conclusions (e.g., more illumination or the provision of left-turn lanes increases the accident rate).

On the whole, research results reinforce the premise that longer sight distances at intersections are in the interest of safety. However, there is no useful guidance on the circumstances in which long sight distances are important and the extent of safety improvement that can be expected.

As noted earlier, the design reaction time (e.g., 2.0 sec) only influences sight distance slightly when a truck is the design vehicle. In this case, the time needed to accelerate and clear the intersection dominates the design calculation. The same is not true when a car is taken to be the design vehicle.

Were almost all intersections designed with sufficient sight distance so that trucks could cross them safely, there would be no reason to worry about older drivers of passenger cars because cars need much less time than trucks to accelerate and clear the intersection. Unfortunately, not only do the AASHTO guidelines neglect to state clearly that intersections must have sufficient sight distance to allow trucks to cross safely, they even allow for larger-than-normal acceleration when a passenger car is assumed to be the crossing vehicle (5, p. 782). The only guidance given is that the designer use (5, p. 19) "the largest design vehicle likely to use that facility with considerable frequency." Therefore, there may exist in the United States many intersections deemed not to be used by trucks with "considerable frequency" at which a serious problem may exist for all drivers encountering a truck. We do not know how many intersections in the United States fall into this category. Therefore, stock-taking is recommended first:

- A survey of design practice (what proportion of intersections are designed to be crossed safely by trucks) and of existing intersection sight triangles (what proportion of intersections can be crossed safely by SU and WB-50 units) should be conducted.

Should it turn out that a significant proportion of intersections have been built and are being designed so that they pose a potential safety problem, thought should be given to the modification of design standards and procedures and

also to a program of remedial action. Accordingly, the following is recommended next:

- Research to ascertain the relationship among intersection accidents, conflicts, and the sight triangle should be conducted, and a program of remedial action should be established for the rectification of those intersections at which such action is cost-effective.

The last consideration is modification of existing design standards and procedures. The sight triangle provided depends on what the designer selects to be the largest vehicle to cross with "considerable frequency." This is so vague that one could elect to design for an accelerating passenger car and build intersections with rather short sight triangles. Because of the large site-to-site variability it does not seem sensible either to declare explicitly what "considerable frequency" means or to demand the use of a longer reaction time in all designs. Rather, a design procedure is needed that allows and requires the design engineer to examine the safety and cost consequences of the sight triangles at each intersection being designed. The benefit of such a design process would be that the potential for inexpensive safety improvements is not overlooked nor do rigid standards force the unjustified expenditure of resources. Thus, the following is recommended:

- The standards and design procedures for intersection sight triangles should be modified because there is reason to believe that when a passenger car is taken as the design vehicle, the sight distance is too short for many older drivers, who take longer to make decisions, move their heads more slowly, and wish to wait for longer gaps in traffic. The modification should require an explicit analysis of safety and cost consequences in each case.

Suppose that the engineering required will cost \$500 per intersection, or about \$60 annually. Suppose furthermore that at an average intersection at which the issue of the sight triangle arises there is 0.2 target accident a year. It takes only a reduction of 1 percent in the probability of target accident occurrence to justify the added cost of engineering. This kind of "back-of-the-envelope" calculation shows again that investment in sound safety engineering pays better than remedial action after the hazard has manifested itself in the form of accidents in police records.

Channelization The merits of channelization have been widely recognized and it is commonly used in practice (5, p. 752):

An at-grade intersection in which traffic is directed into definite paths by islands is termed a channelized intersection. An island is a defined area between traffic lanes for control of vehicle movements. Islands also provide an area for pedestrian refuge.

Various minimum dimensions for islands are suggested in sources such as the AASHTO geometric design policy (5), for example, minimum width (4 to 6 ft) for pedestrian refuges, minimum area to command drivers' attention (50 to 100 ft²), and minimum length of side for triangular islands (12 to 15 ft). With regard to when islands might be considered useful, the *Traffic Control Devices Handbook* (31) suggests that they be used to reduce pedestrian clearance intervals or to accommodate those who walk more slowly than the "design" walker, or both, and that they are particularly useful in urban areas, on exceptionally wide roads, or at irregularly shaped (skewed) intersections where the combination of heavy pedestrian and vehicle volumes can make pedestrian crossing difficult or dangerous.

The safety effect of intersection channelization projects is described by Hagenauer et al. (30, Chap. 5). In one study the channelization of intersections was found to reduce accidents by 32 percent and injury accidents by 50 percent. In another study intersection channelization projects had an average benefit-cost ratio of 2.3.

In the context of this paper, two situations deserve special attention. First, inasmuch as channelization in general serves to simplify an otherwise ambiguous and complex situation, it stands to reason that, when an existing intersection can be channelized, doing so might enhance both the safety and the mobility of older persons. In this case the interests of the older person seem to coincide with the interests of others (pedestrians and drivers).

The second situation to be considered is the case in which the intersection is still on the drawing board and one has to decide whether it will be large enough to allow channelization. In this case the interests of pedestrians and drivers may not coincide. The presence of islands is unlikely to offset the disadvantage of large intersection size for the pedestrian.

Another element deserving attention is the provision of refuge islands. Their dimensions and minimum sizes to accommodate wheelchairs are discussed in the AASHTO geometric design policy (5, p. 758). The *Manual on Uniform Traffic Control Devices* (MUTCD) defines refuge islands as (6, p. 5A-1) "a place of safety for pedestrians who cannot cross the entire roadway width at one time in safety because of changing traffic signals or oncoming traffic." The MUTCD also lists conditions in which refuge islands are particularly useful: on multilane roadways, in large or irregularly shaped intersections, and in signalized intersections to provide a place of safety between different traffic streams. The manual also suggests that refuge islands do not have to be a part of a channelization scheme or the continuation of a median.

In summary, the safety of older persons at intersections would be positively affected by more extensive use of channelization when conditions make it practical, and pedestrian safety could be particularly enhanced by the provision of refuge islands even when these are not part of a comprehensive channelization scheme.

Curb-Corner Radii Curb-corner radii are the radii of curves that join the curbs of adjacent approaches. Their purpose is to facilitate the movement of right-turning vehicles, usually trucks, and their increasing size affects safety negatively in a number of ways.

First, the larger the curb-curve radius the larger the distance that the pedestrian has to cover when crossing the road. Thus, for a sidewalk whose centerline is 6 ft from the roadway edge, a 15-ft corner radius increases the crossing distance by only 3 ft. However, a 50-ft radius increases this distance by 26 ft (or 7 sec of additional walking time). It is widely believed that the longer the crossing distance the greater the hazard to pedestrians, even though, when the corner radius is large enough, there may be space for refuge islands. Second, larger curb radii may induce drivers to negotiate the right turn at a higher speed. Third, the larger the radius the wider the turn, which makes it more difficult for the driver and the pedestrian to see each other.

The design of curb-corner radii is covered in considerable detail in the AASHTO geometric design policy. The main determinant is the selection of the design vehicle. Typical minimum recommended radii are 30 ft for turns by passenger cars and 50 ft for single-unit trucks (5, p. 736). For rural conditions the policy leans toward serving the single-unit truck. In urban areas (5, p. 742), "curb radii of 10 to 15 ft are reasonable However, on arterial streets carrying heavy traffic volumes it is desirable to provide corner radii . . . of 30 to 50 ft for most trucks and buses to expedite turns."

It is worth noting that the design philosophy is in this case single-mindedly vehicle oriented. Although there is no substantial problem with 10- to 15-ft radii, the desire to expedite turns by large vehicles at intersections on urban arterials and at most rural intersections makes these crossings inhospitable to pedestrians in all three ways mentioned earlier. One could contrast this design philosophy to the alternative shown in Figure 11 (32). This design is not without obvious merit. It is an attempt to make the pedestrian visible and to reduce the speed at which vehicles might turn, which is desirable at intersections in which complex situations might arise. The safety of older persons at intersections and particularly of pedestrians may be affected when large curb radii are provided. Therefore the shaping of the curbs at intersections so as to recognize the interests of both the pedestrian and the driver deserves attention.

Traffic Control

Level of Traffic Control

Going from lower to higher levels of traffic control, the main choices are (a) none, (b) Yield sign, (c) Stop sign (two-way or multiway), and (d) traffic signal. Decisions on appropriate levels of traffic control are guided by warrants such as those provided in the MUTCD (6).

Yield and Stop Signs In general, Yield signs are warranted where it is seen necessary to assign right-of-way to the major road "but where a stop is not

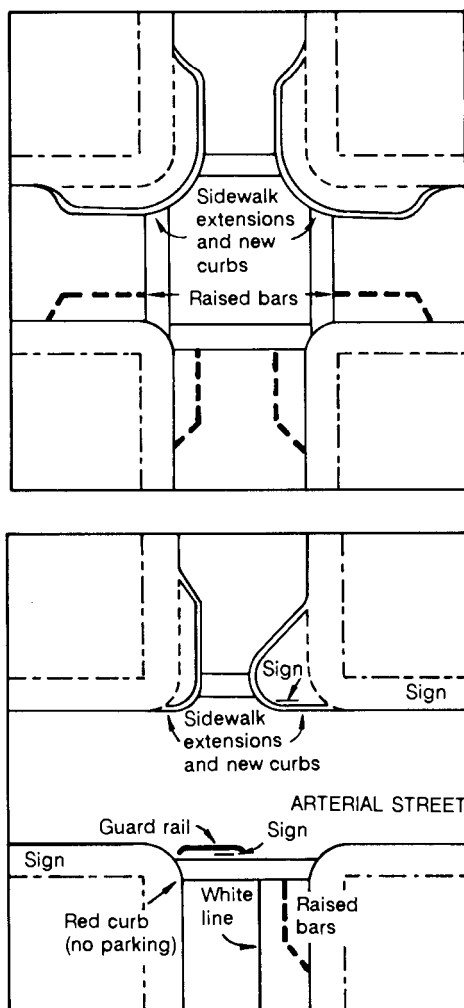


FIGURE 11 Pedestrian-conscious intersection layouts (32).

necessary at all times, and where a safe approach speed on the minor road exceeds 10 mph" (6). Stop signs are warranted, among other circumstances, "where application of the normal right-of-way rule is unduly hazardous" and "where a combination of high speed, restricted view, and serious accident record indicates a need for control by the STOP sign" (6). Multiway Stop signs are considered "an interim measure" where volumes call for a traffic signal but there is no money to install one. They are also warranted where five or more correctable accidents occurred in a year.

In practice, the Yield sign is seldom used (even though it does not appear to be less safe than a Stop sign). Which intersections are left uncontrolled, which get the two-way Stop, and which are equipped with multiway stops depends strongly on local practice and pressures. As a result, many Stop signs and the majority of multiway stops are installed even though they are unwarranted in the spirit of the MUTCD. In many cases, the installation of Stop signs is in response to demands from the public. (Often the reason is safety, but sometimes the real motive may be neighborhood pressure to keep through traffic from using residential areas.)

As one might expect, the safety of an intersection can be significantly affected by the level of traffic control provided. Thus, for example, the replacement of two-way Stop control by four-way Stop control reduces accidents by 50 percent or more (33). Table 4 shows that of the 524 pedestrians 64 years and older who were killed at intersections in 1985, 247 were killed at intersections with no traffic control.

Little is currently known about the safety implications of various forms of control at intersections. As a result, little substantive guidance is provided to professionals on this matter. The opportunity for safety gains by providing such guidance should be pursued.

Studies on the safety effect of changing from no control to Stop or Yield control are cited in two main sources [FHWA synthesis (30) and National Cooperative Highway Research Program (NCHRP) Report 162 (27)]. In the synthesis a comprehensive review of several studies by Hall et al. (34) is cited in which it was found that Yield signs at low-volume crossings reduced accidents by 20 to 60 percent and that little additional reduction (10 percent) was achieved by using Stop signs instead. Hall et al. provide no further information about these studies, however. These reductions appear to accord with those found by Kell (35), who found 44 and 52 percent fewer accidents after conversion to Yield control in two cities. NCHRP Report 41 (36) gives accident reductions of 23 and 63 percent after conversion of three uncontrolled intersections to Yield control. None of these studies give any information on whether or how the size of the safety effect depends on volume. One work that purported to address that issue is a cross-sectional study by Stockton et al. (37), who found that in urban areas uncontrolled intersections with major-road volumes of less than 1,500 vehicles per day had fewer accidents than Yield-controlled intersections with similar volumes. Stop-controlled intersections had the highest rate. For volumes between 1,500 and 4,000 vehicles per day, Stop-controlled intersections still had the highest rate, but Yield control had a lower rate than no control. Because Stockton's study, unlike the others mentioned, is not a before-and-after comparison, one cannot infer that the different accident rates are due to differences in traffic control.

Some of the foregoing evidence is old (dating from the 1950s), much of it relies on very few data, most of what is written consists of quoting what

someone else has quoted on the basis of a third person's findings, and the experimental setting is such that when one encounters contradictory evidence (e.g., the findings by Stockton et al.), it is difficult to come to a consensus.

If Yield and Stop signs were used according to the spirit of the MUTCD, they would have a positive safety effect. However, as these signs are used in practice, it is more difficult to anticipate their effect. It appears that Yield signs are largely nonexistent and that most Stop signs induce a Yield type of behavior by drivers.

Insight about the costs and benefits of Stop and Yield control can be provided by citing two well-known studies. In the first, Stockton et al. (37) estimated annual capital costs along with vehicle operating and user time savings for various types of control conversions and entering-volume combinations (Table 13). The difference in annual accident rates for existing intersections with each type of control was then taken as due to differences in control, which is perhaps incorrect, as mentioned earlier. On this basis, they suggested, for example, that in some cases conversion from Yield to Stop control will increase accidents, and vice versa. With the expected accident costs taken into account, Table 14 specifies the conditions under which one or the other of the minor forms of control would be preferred.

The other study is by Upchurch (38), who performed a sophisticated analysis of vehicle, user, and accident costs for Yield- and two-way and four-way Stop-controlled moderate-volume intersections (those that do not warrant signalization but had more than 500 vehicles per day on the minor road). (In contrast, Stockton et al. studied intersections with less than 500 vehicles per day on the minor road.) Upchurch concluded: "For accident rates used in this

TABLE 13 AVERAGE ANNUAL HIGHWAY COSTS OF STOP, YIELD, AND NO CONTROL (37)

Existing Control	Proposed Control	Highway Agency Cost (\$)		Expected Avg Annual Savings (\$) by Minor-Roadway Volume (vpd)				
		Three Legs	Four Legs	100	200	300	400	500
Major-Road Volume ≤2,000 vpd								
Stop	Yield	7	11	240	480	720	960	1,200
Stop	No control	5	5	44	88	132	176	220
No control	Yield	14	23	196	392	588	784	980
Major-Road Volume >2,000 vpd								
Stop	Yield	7	11	244	488	732	976	1,220
Stop	No control	5	5	155	310	465	620	775
No control	Yield	14	23	88	176	264	352	440

NOTE: vpd = vehicles per day.

TABLE 14 RECOMMENDED CRITERIA FOR
SELECTING LEVELS OF INTERSECTION CONTROL
(37)

Sight Distance	Accident History	Major Roadway Volume	
		<2,000 vpd	>2,000 vpd
Adequate	0	No control	—
Adequate	≤2	Yield	Yield
Adequate	3	Stop ^a	Stop ^a
Adequate	4+	Stop	Stop
Not adequate	—	Stop	Stop

^aIf minor roadway is greater than 300 vpd, Yield control is appropriate for intersections with less than four accidents in 3 years.

study, Yield control is the most economical type of control, regardless of volume.” However, he found it necessary to caution: “This finding must be treated with care because of the uncertainty associated with the accident rates which were used.” [He used, “skeptically,” those rates in NCHRP Report 41 (36).] Upchurch also showed that two-way Stop control might have been preferred sometimes if different accident rates had been assumed. These studies highlight how sensitive the choice of type of intersection control is to assumptions about the safety benefits of making changes. Upchurch laments that “additional research on the safety relationship must be conducted before Yield and Two-way Stop control before Yield control can be recommended to replace Stop control on a widespread basis.”

Because much of the safety problem occurs at intersections that are not signalized, the following research on Stop and Yield sign use is recommended:

- A study should be made to obtain factual data on how Stop and Yield signs affect safety and traffic performance at a specific site and how the policy of such sign installation affects driver behavior at such signs in general.

Multiway Stop A critical review of the substantial body of literature on the safety of conversion from two-way to multiway Stop control was published in 1985 (33). Table 15 (39) confirms that total accidents are reduced by at least 40 percent, with similar percentage reductions for pedestrian accidents. There are some lingering doubts, however; recent work (40) has shown that accidents saved might have “migrated” to surrounding unconverted intersections; also, many traffic engineers believe that excessive control leads to a general disrespect by the public for traffic signs.

Multiway Stop control is known to increase vehicle and user costs; rational decisions to install multiway Stop control can be made by weighing these

TABLE 15 MOST LIKELY PERCENTAGE OF ACCIDENT REDUCTIONS (39)

Accident Type	San Francisco	Philadelphia	Michigan	Toronto	Combined
Right-angle	84	78	64	48	72
Rear-end	-305	20	19	22	13
Left-turn	33	-	-7	25	20
Pedestrian	66	40	-	42	39
Fixed-object	-	-30	-	-	-
Injury	74	74	62	63	71
Total	62	47	59	37	47

extra costs against what appear to be substantial safety benefits. Upchurch (38) found that in most cases two-way Stop control is economically preferable to four-way Stop control. The latter is preferable at low-volume intersections or where the minor-street volume is approximately equal to the major-street volume. As for the Yield sign control, Upchurch found that the decision is very sensitive to assumptions on accident rates. To shed light on this issue, an example is provided.

Consider an intersection with a total entering volume of 1,000 vehicles per hour, equally distributed among its four approaches. On the basis of data from Byrd (41), converting this intersection to four-way Stop control is estimated to increase user costs by about \$10,000 a year. With two-way Stop control such intersections are expected to have about one or two accidents per year. To justify conversion on the basis of accidents saved, and with \$25,000 as the cost of a representative accident, one would have to count on an 80 percent reduction in the expected number of accidents, which is not realistic.

As before, the results of such an example should not be taken to indicate whether a measure can be justified in economic terms. The purpose of the example is to focus on two points. First, the numbers used in the calculation are of a very dubious nature. The user-cost figure is obtained by converting seconds of delay into fragments of cents and summing these for thousands of motorists. It is even assumed that those who do not stop legally incur a cost. The merit of expressing accidents in terms of dollars and the magnitude to be used behind the dollar sign are equally questionable.

The decision to replace control by signs with control by traffic signals is governed by detailed warrants, and the MUTCD now requires (6, Part IV-C) that the decision be based on a comprehensive study. Most signals that are warranted are installed when vehicular traffic volumes are sufficiently high. In other cases, signals can be warranted by some combination of vehicle volumes, pedestrian volumes, and accident records (where five or more correctable accidents occurred in a year).

Traffic Signals

As Table 16 shows, much has been published about the safety effects of installing signal control, but there is little consistency in the results (42–49). There is, however, some empirical support for the intuitive conclusion—that signal installation is likely to increase rear-end accidents and decrease right-angle accidents. If the latter type of accident predominates at a site, it seems likely that, on balance, signals would improve safety at that site.

TABLE 16 CHANGE IN PROPORTION OF ACCIDENTS AFTER SIGNAL INSTALLATION (42–49)

Author	Location	No. of Signals	Percentage of Change by Accident Type				
			Total	Rear-End	Right-Angle	Injury	Left-Turn
Solomon (42)	Michigan	39	–23	–200	+51	+20	n/a
King and Goldblatt (43)	Virginia	30	–24	–181	+34	+18	–16
King and Goldblatt (43)	Michigan	33	–8	–84	+45	n/a	–236
NYS DOT (44)	New York	39	+7	+21	+13	–11	–13
Hammer (45)	California	170	+21	–90	+76	+32	+14
Clyde (46)	Michigan	52	–34	–98	+45	–11	–66
Short et al. (47)	Milwaukee	31	+2	–37	+34	–6	n/a
Vey (48)	22 cities	599	+20	–37	+56	n/a	n/a
Schoene and Michael (49)	Illinois	30	–16	–221	+48	–26	

In the studies cited in Table 16, pedestrian accidents either were not reported or were so few that the results were inconclusive. In the study of 31 installations by Short et al. (47), pedestrian accidents decreased from 18 to 12 in 3 years. In the study of 39 intersections by the New York State Department of Transportation (44), accidents increased from 0.1 a year to 0.2 a year after signal installation. Data from Yagar (50) for Metropolitan Toronto suggest that installation of signals at 25 intersections with pedestrian protection decreased the pedestrian accident rate about 40 percent; on the other hand, at the 43 installations with no prior protection, the pedestrian accident rate increased about 20 percent. These data, however, were based on an average of fewer than 30 pedestrian accidents a year. Yagar points out that the 20 percent increase is insignificant.

Recognizing that the overall safety effect of signal installation must depend on a variety of factors, some researchers have attempted to identify the circumstances in which signal installation might enhance safety. The warrant for installing signals implies that they might enhance safety if accidents

exceed some number. However, what evidence there is to support this belief appears to be tainted by statistical shortcomings in the analyses. Information from traffic engineers and from the literature indicates that signals are rarely installed because of a safety warrant, but mainly on the basis of traffic volume. In many cases, no warrants are satisfied, and the findings of many studies have led traffic engineers to the belief that only warranted installations increase safety. Again, most of these studies are fraught with methodological problems that make their findings useless.

It is assumed that once signals are warranted and funds permit, they will be installed. In the following example only the costs and benefits of installing a signal that might be good for safety but does not meet existing volume warrants are considered. Changes in pedestrian accidents are ignored because there are no adequate data on which to base such a discussion.

Suppose that one is contemplating installing signals at a two-way Stop-controlled intersection with a total entering volume of 12,000 vehicles per day that is distributed over time and by approach, so that the signal volume warrants are not met. There are four right-angle accidents (the MUTCD safety warrant requires five) a year, and signal installation is expected to increase this by 30 percent. However, rear-end accidents are less severe, so the increase in these accidents is estimated to cost \$12,000 a year. Annualized costs of installing and maintaining a signal are about \$12,000 a year. Given a requirement for a 2:1 benefit-cost, a further savings of \$11,000 needs to be realized to justify the installation. It is estimated that this can be done if the signals save each entering vehicle an average of about 5 sec. That this is reasonable is not clear.

What this example reveals is that the decision to install a signal for safety reasons is very sensitive to the actual number of target accidents, to the delay savings, and, quite importantly, to the assumed safety effect.

Even though by now there are in the United States about 300,000 signalized intersections, it is not known what the safety of signalization is under specific circumstances. This must reflect the lack of data on the safety repercussions of the decision to install traffic signals. In view of this deficiency, the following recommendation is made:

- Research should be undertaken to enable the professional to estimate for a specific site the expected safety effect of conversion to traffic signal control.

Traffic Signal Control

After a decision has been made to install traffic signal control at an intersection, a series of technical choices follows. These choices are discussed in the following section, including the relative merits of isolated versus coordinated signals; pretimed versus actuated signals; number, type, and duration of signal phase; clearance intervals; and cycle time.

Reaction Time and Walking Speed Preliminary to the discussion of these choices, two characteristics of older persons used as parameters in traffic signal control design need to be addressed, namely, reaction time and walking speed. The assumed driver-reaction time affects the duration of the "inter-green period" (also called the vehicle clearance interval, yellow change and clearance interval, or yellow plus all red).

The issue of the design driver has already been addressed. The assumed speed of walking may affect the amount of green signal time allocated vehicles and, if separate pedestrian signals are provided, also the duration of the clearance interval for pedestrians.

Perception-Reaction Time The yellow signal, which usually lasts from 3 to 6 sec, warns the driver of an impending change to a red signal. Included in this interval is time for the driver to perceive and react (by using the brake) to the yellow signal. Various sources, including the ITE handbook (13), indicate that current practice assumes a perception-reaction time of 1 sec. The adequacy of this interval has been questioned. It is not clear to what percentage of drivers this figure applies or should apply. If, as seems to be currently favored, the 85th-percentile driver is selected, the 1-sec perception-reaction time appears to be inadequate. Wortman and Matthias (51) found that the 85th-percentile value at most intersections approached 2 sec. Gordon et al. (52) estimated a median perception-brake reaction time of 1.23 sec and recommended using the 85th-percentile value of 1.77 sec—both values are quite close to the observations by Wortman and Matthias.

Several studies have measured brake-reaction times in circumstances different from those occurring at the onset of the clearance interval, but it is not known whether these findings are transferable to vehicle clearance intervals. Olson and Sivak (53) estimated reaction time of unalerted drivers to an obstacle in their lane while they were cresting a hill and found a 95th-percentile driver-reaction time of 1.6 sec—a finding obtained for both older (60 to 84 years) and younger (18 to 40 years) drivers. Johansson and Rumar (54) measured brake-reaction time to an audible signal and estimated that, for unanticipated situations, it was 1.5 sec or longer in 10 percent of the cases.

On the basis of this information one would tend to conclude that the perception-reaction time now in use (1 sec) is already too short, and that this shortfall may be particularly hard on older persons. In fairness, one has to make clear that the issue is more complicated than the mechanistic application of a formula. First, the premise of the formula used to calculate the duration of the clearance interval is that the driver should behave legally; he should be able to either stop or clear the intersection without violating the local law. The relationship between the duration of this interval and safety is a different matter. It has less to do with what is assumed to be a proper reaction time and more with how drivers behave at the onset of the yellow signal and how this behavior depends on its duration.

Second, if a longer perception-reaction time was used in the calculation, the duration of the clearance would also be extended, with two consequences. What is added to the clearance interval is taken away from the length of time for the green signal, increasing the frequency of stopping and vehicular delay and affecting safety adversely. In addition, it is widely believed that if long clearance intervals were provided, drivers might gradually begin to encroach on these. Thus, the 1-sec perception-reaction time appears to be used more as a device to get reasonable results than as a serious reflection of actual reaction times. A meaningful discussion of this issue should concern the duration of the clearance interval and its impact on safety, which will be covered under Separate Pedestrian Signals.

Walking Speed The MUTCD (6) is somewhat vague about walking speed. It cites an assumed normal walking speed of 4 ft/sec, but refers to research showing that one-third of all pedestrians cross the street more slowly, with 15 percent crossing at or below 3.5 ft/sec. In the *Traffic Control Devices Handbook* (31), which provides interpretation of the MUTCD, it is stated that "those having slower walking speeds have the moral and legal right to complete the crossing once they have legally entered the intersection."

Some traffic engineers seek guidance from the ITE handbook (13), in which it is stated that some engineers use a walk speed of 4.0 ft/sec, but it is suggested that (13, p. 221) "for relatively slow walkers, speeds of from 3.0 to 3.25 ft/sec would be more appropriate." No reference is made to an ITE Technical Committee estimate of 3.7 ft/sec for mean crossing speed or to the 1965 ITE handbook (55), in which it was estimated that 35 percent of pedestrians were excluded by the 4.0-ft/sec design value. More recently, ITE Committee 4 A-6 conducted a survey in Florida at a location with a large population of elderly pedestrians and recommended (presumably for such locations) a walk speed of 2.5 ft/sec, which provided adequate crossing time for 87 percent of those pedestrians (56).

Elsewhere in the literature, there is conflicting guidance on walk speeds. Sleight (57) reported on a Swedish study by Sjostedt in which the average adult and older person were found to walk at 4.5 ft/sec and distribution curves showed about 20 percent of the older persons crossing at speeds less than 4.0 ft/sec. For that group, the 85th-percentile speed was 3.4 ft/sec. On the basis of these numbers, Sleight suggested that "there would be safety justification for use of speeds around 3 to 3.25 [ft/sec] in order to safeguard the relatively slow walkers." However, Dahlstedt points out (58) that the Swedish study on which Sleight's often-cited numbers are based is not representative of the average pedestrian, dealing only with "pedestrians who have been troubled or interfered by approaching cars." In this regard, Dahlstedt refers to findings by Moore (59) that average walking time was 5 ft/sec if an approaching car was within 3 sec away but 4 ft/sec if approaching cars were not too close. In

Dahlstedt's own study (58), those 70 years or older were instructed to cross an intersection at fast, very fast, or normal speed. Their results show that what is considered fast by about 60 percent of these older pedestrians is slower than 4 ft/sec. At normal, comfortable speed, almost 90 percent crossed at less than 4 ft/sec, and the 85th-percentile speed (15 percent were slower) was about 2.2 ft/sec.

That walk speed depends on a variety of environmental factors and pedestrian characteristics was a highlight of research by Ugge (60). Pedestrian speeds were estimated for two types of nonsignalized crosswalks: (a) marked and signed (protected) and (b) unprotected. The mean crossing speeds were 4.2 and 6.9 ft/sec, respectively. The respective figures for the slowest group (elderly women) were 3.56 and 6 ft/sec. Ugge also found that the closer an approaching vehicle was to the crossing the faster was the mean crossing speed.

Choices and Decisions The main choices and decisions in traffic signal control are discussed singly and in some semblance of the order of importance; however, in practice they are linked and made jointly.

Type of Signal Perhaps the first decision is whether the signal should be timed independently of its neighbors or coordinated with them to allow continuous flow (green wave) as much as possible. Coordination is generally desired on arterial streets and where intersection spacing makes it useful; it can reduce the frequency of stopping and of delay and is thought to be good for safety of both vehicles and pedestrians. Even though the decision of signal coordination may affect safety, the safety repercussions of this choice are not well understood.

Next a decision has to be made on whether the signal phases are to be of fixed duration (fixed-time control) or continuously adjusted on the basis of the instantaneous detection of traffic (traffic-actuated control). Fixed-time control is often chosen when traffic volumes are stable, when a decision has been made to coordinate signals, or when considerations of economy, simplicity, and reliability are important. Traffic-actuated signals are "semiactuated" when confined to minor-road approaches and "full actuated" when detectors are placed on all approaches. Actuated signals require a decision on how far from the stop line to detect traffic. This distance (13, p. 746) "may vary from one car length up to 500 ft." From the point of view of safety, actuated signals have the potential to time the onset of yellow so that no approaching cars are placed in the difficult situation of either having to stop abruptly or of entering the intersection during the clearance interval.

The decisions about whether to have a coordinated signal system and whether signals should be fixed-time or actuated are linked. It stands to reason that these decisions have an important effect on safety. However, this effect seems to be terra incognita. Thus, we cannot explore the question further and

note only that inasmuch as signal coordination and the choice between fixed-time and actuated signals are likely to have important safety repercussions, there is need to find out what these are and to make these findings available to those who make such choices. Only then can safety considerations affect decision making.

Signal Timing Signal timing involves decisions about the duration of the signal cycle, its phases, and the clearance interval. These aspects are detailed in sources such as the ITE handbook (13) and the *Highway Capacity Manual* (HCM) (7), the aim of which is to minimize delay to vehicles. The discussion here will concern the relation between decisions on signal timing and the safety of older drivers and pedestrians.

Long cycle times (100 to 110 sec) tend to be used for intersections at which vehicle flows are near capacity. If a group of intersections is coordinated, the longest cycle time found in the group will be used at all these intersections. Long cycle times necessitate long pedestrian waiting times, which increase the inclination to walk during the red signal phase. It is in this manner that the choice of signal cycle time may affect pedestrian safety.

The duration of green given to an intersection approach has to be long enough for both pedestrians and vehicles, moving forward together at the green light, to have sufficient time. This amount of time is important when the street is wide and the amount of green required by vehicles is short. In other cases the duration of green is governed by vehicular traffic demand. A design walking speed of 4 ft/sec is used. Several sources have suggested that as many as one-third of pedestrians (mainly older persons) walk more slowly. The adoption of a slower design walking speed will increase the minimum duration of green. For example, at a walk speed of 3 ft/sec a pedestrian crosses a 60-ft-wide road in 20 sec compared with 15 sec at 4 ft/sec. Giving an additional 5 sec of green to one approach, where it may not be needed to accommodate vehicles, takes away the 5 sec of green time from another approach, which may already be congested. Thus, the decision to include a larger proportion of the pedestrian population in the design speed may in many cases increase congestion.

The last element of signal timing is the duration of the vehicle clearance interval, which separates the green and the subsequent red signals. Guidelines for computing the duration of vehicle clearance intervals are given in most authoritative sources. The calculation depends on what is legal locally, the approach speed, the intersection width, and the assumed perception-reaction time. Adding 1 sec to the perception-reaction time increases the clearance interval by 1 sec. Generally, a minimum of 3 sec is used, with a maximum of 5 to 6 sec. At the end of the vehicle clearance interval an all-red phase is often used.

A slower design walking speed and a longer design perception-reaction time would have similar effects. Both would diminish the amount of time

available for the movement of vehicles. Nevertheless, a slower walking speed would only affect relatively few approaches, at which it would diminish the vehicular green by a fairly large amount (say, 5 sec). In contrast, were a longer perception reaction time to be universally adopted, a small amount of time (about 1 sec) would be taken away from the green time on every approach.

These considerations carry over to the timing of pedestrian signals. There should be enough time for the pedestrian who starts to cross just as the Walk indication is ending to reach the opposite curb safely. The flashing Don't Walk signal usually provides the necessary time; the duration of this interval again depends on the design walking speed. To accommodate slower walkers, more time would have to be allocated to the flashing Don't Walk aspect, which could be done at the expense of the vehicular green or, more likely, the duration of the Walk aspect, with dubious safety consequences.

Design walking speed and design perception-reaction time feature prominently in various signal-timing decisions. Concern about the safety and mobility of older persons is often tied to the concern that these design parameters are not suited to their abilities. Therefore, it is appropriate to examine the effects of change in these design parameters on safety and the associated costs.

Because considerable space will be devoted to the protection of left-turning traffic, a brief comment about right-turning traffic is in order. In this respect, very little seems to be left to be decided. One can only comment with some bitterness that nowadays allowing right-turn-on-red (RTOR) in the United States is the rule, and disallowing it is the exception. This is the end result of a curious historical development. The practice of allowing RTOR started in the West and for a long time the official position of the ITE was to actively discourage it. However, to allow vehicles to turn right when there is no traffic is common sense and is popular with drivers. Thus, when during the energy crisis jurisdictions would have lost money if they had not switched to RTOR, the practice spread from the West like wildfire. Research consistently showing that with RTOR pedestrians and cyclists are being injured at alarmingly higher rates has been ineffectual in changing this practice. Even the ITE pronouncements have gradually been modified and now a complete reversal of policy has occurred, which is being defended on the basis of a most questionable logic.

Minimum Green

Changing the design walking speed from 4 ft/sec to 3 ft/sec affects minimum green time. While the pedestrian is crossing the main road, the minor road has

a green light. Thus, the time it takes to cross the main road dictates the duration of the minimum green.

Table 17 gives the minimum green times required for various crossing distances. Minimum green requirements are affected in slightly different ways depending on whether a separate pedestrian signal (Walk-Don't Walk) is provided.

TABLE 17 MINIMUM GREEN TIME VERSUS CROSSING DISTANCE AND SPEED OF WALKING

Walking Speed (ft/sec)	Green Time (sec) by Crossing Distance (ft)				
	20	30	40	50	60
5.0	4.0	6.0	8.0	10.0	12.0
4.0	5.0	7.5	10.0	12.5	15.0
3.5	5.7	8.6	11.4	14.3	17.1
3.0	6.7	10.0	13.3	16.7	20.0

No Pedestrian Signal With no pedestrian signal, pedestrians cross the main road when the minor-road vehicles have a green light. In practice, green times are rarely less than 7 sec. Therefore, even pedestrians walking at 3 ft/sec should have no problem crossing a two-lane road. At the other extreme, pedestrians walking at 3 ft/sec can easily cross the main road if it is less than 60 ft wide (about six lanes) and the minor road is getting at least 20 sec of green time.

A problem exists in crossing situations in which the main road is wider than the crossing distances indicated in Table 17 whereas the green time for the minor road is less than the values given for the slowest walking speed. Zegeer (61) believes that these situations are rare. However, information from Metropolitan Toronto indicates that more than half of the semiactuated signals (which account for about 50 percent of the signals in that city) might be thus affected. A semiactuated signal gives a green signal to the minor road when a vehicle on that road triggers the detector. If no more vehicles are detected, the green light returns to the main road. Thus, when a semiactuated signal is used and minor-road traffic is light (a typical circumstance), most pedestrians have to cross the main road at the assumed design walking speed.

Separate Pedestrian Signals The MUTCD (6) requires the Walk message be displayed for at least 7 sec to allow pedestrians time to notice and react. In addition, a pedestrian clearance interval is required, as mentioned earlier. Thus, when a separate pedestrian signal is provided, the green phase for the minor road should be at least 7 sec plus the pedestrian clearance interval. In addition, when a separate pedestrian signal is provided, it is much more likely that the requirements of slower pedestrians are not met if the minor-road

traffic determines the duration of the minor-road green. Therefore, perhaps paradoxically, slow walkers may encounter marginal conditions more often when separate pedestrian signals are provided.

Separate pedestrian signals are discussed in more detail in a later section.

Numerical Example Consider a minor road with a two-way volume of 5,000 vehicles/day that intersects a major road 60 ft wide carrying 20,000 vehicles/day. The intersection is controlled by a two-phase signal with a 70-sec cycle consisting of a 45-sec green phase for the major road, a 15-sec green phase for the minor road, and two 5-sec clearance intervals. The 15-sec interval is just long enough for pedestrians to cross the major road. If the design walking speed were 3 ft/sec instead of 4 ft/sec, the minimum green time required to cross the major road would be 20 sec. If the cycle time remains fixed, the major-road green has to be reduced to 40 sec. This change is estimated to increase delay on the major road by about 3 sec/vehicle and to reduce delay on the minor road by about 2 sec/vehicle. The net annual extra delay is 5,070 vehicle-hr, which, on the basis of costs given by Cottrell (62), translates into about \$10,300/year in extra fuel and travel-time costs.

The target accidents in this example are those occurring to pedestrians at the far end of the crossing. Data from Zegeer et al. (61, Table 22) show about 0.5 pedestrian accident yearly for this type of intersection. Considering that this may occur on any approach and on the entire length of the crossing, it might be assumed that there is $0.5/8 = 0.07$ target accident a year. Even if a pedestrian accident were valued at \$50,000 and the change from 4 ft/sec to 3 ft/sec were to eliminate all target accidents (rather than just reduce the probability of their occurrence), $0.07 \times \$50,000$ is still less than \$10,300. However, an increase in rear-end accidents due to the increased red time on the major road has not been taken into account.

One can debate at length the propriety and morality of this kind of cost accounting. Can one legitimately add a few seconds of delay for a multitude of drivers and compare these with the suffering of seven anonymous pedestrians injured in 100 years? Even if such reasoning is commonly used, it seems a somewhat absurd device for making wise decisions. Surely the problem is not only that people are being injured but also, and perhaps primarily, that they fear being injured. Thus, to confine our thinking to the objective count of corpses might be too narrow a perspective, a scope that disregards the concept that people—and perhaps older persons in particular—wish not only to be safe but also to feel safe. Similarly, one should not plunge into the calculus of costs and effects without pausing to ponder the “balance of rights.” Surely no one would think that what we decide to do for the terminally ill is a matter of weighing costs and benefits. A civilized society is guided on this matter by other considerations as well. Older persons through no fault of their own walk more slowly than young persons and are not as nimble in stepping out of

harm's way. Is it fair to use a design walking speed that causes many of them to feel threatened?

Thus, the cost of giving more green time to the pedestrian (and the minor road) is an increase in vehicle delay on the main road. The benefits might lie in somewhat fewer pedestrian accidents and less pedestrian anxiety and frustration. The balance of costs and benefits depends on the specifics of every case (main-road and minor-road traffic, main-road width, pedestrian volumes, the speed of walking at the site, etc.). It follows that to use one design walking speed for all situations is perhaps convenient but wrong.

The design walking speed of 4 ft/sec should be retained as the maximum. However, when designing signal timing, the engineer should be required to base the minimum green time on a site-specific analysis. This would ensure that 4 ft/sec would be used only where it could be justified and where no better solution can be found.

The following research and actions are recommended:

- A design procedure should be developed to allow the determination of a minimum green time for pedestrian crossings on the basis of site-specific data and explicit analysis.
- Signal installations now in service at which pedestrians have to cross at a speed of at least 4 ft/sec should be identified and it should be determined whether the current timing is justified or better solutions can be found.
- Appropriate guidelines and requirements should be established so that the design and timing of future signal installations are based on the aforementioned design procedure.

Protection for Left Turns

Left-turn protection is important because of accidents involving left-turning vehicles. It has been found (62) that 45 percent of vehicle collisions and 29 percent of collisions with pedestrians at signalized intersections involve a left-turning vehicle, although only 10 to 15 percent of the traffic turns left. Robertson estimates that left-turning vehicles are three times more hazardous to pedestrians than through-moving ones (63). The task of turning left is difficult, especially when the through traffic has the right-of-way and pedestrians are using the crosswalk. For older persons the difficulty of the task is compounded by their slower and less accurate decision making in complex situations as drivers and their diminished nimbleness as pedestrians.

The traffic engineer can elect to restrict left turns or to accommodate the left-turning traffic. If the decision is to allow left turns, three main signal-phasing options arise for signalized intersections: protected, permissive, or protected-permissive. In the first option, a separate left-turn phase is provided (e.g., by a green arrow) during which the left-turner's right-of-way is "protected." In the second option left-turning vehicles are permitted to fend for

themselves by finding gaps in the opposing traffic (a solid green indication). In the third option the first two options are mixed—protection during a part of the green and permission to use gaps in the oncoming traffic during the rest. These three options affect the quality of service for vehicles (in terms of frequency of stopping and delay) and the safety of both vehicles and pedestrians. Accommodating left-turning vehicles during gaps in the oncoming traffic causes the least delay for the through vehicles, whereas protecting left-turning traffic with a green arrow delays the through traffic. According to Fambro and Woods (64), for every left-turn accident during a protected phase, 10 would have occurred without protection. This number may be exaggerated, but it stands to reason that providing a separate left-turn phase reduces accidents in which left-turning vehicles are involved.

Clearly, the decision on the appropriate accommodation of left-turning traffic is a matter of striking a balance between safety and other indexes of service. To this end, it is important to know the safety repercussions of alternative courses of action.

A recent survey of state and local agencies (65) revealed a great diversity of practice in the accommodation and protection of left-turning traffic. One-third of the respondents did not use any warrant or technique to decide when or what protection to provide for left-turning traffic. The criterion for the majority is at least three to five left-turn accidents in a year, a disturbing practice. Perhaps this is because there is no relevant MUTCD warrant. [A corresponding Canadian document (66) provides a numerical warrant based on through, left-turning, and pedestrian traffic.] Accidents involving left-turning vehicles are especially acute for older road users. There are several standard options that the traffic engineer may use to accommodate left-turning vehicles, and these apparently have very different safety consequences. In addition, current practice is marked by great diversity and insufficient guidance. The safety of older persons as drivers and pedestrians may be significantly affected by the choice of left-turn treatment. Detailed examination of the safety facts and the relevant trade-offs is required.

Safety Issues Agent and Deen (67) report an 85 percent reduction in left-turn accidents accompanied by a 33 percent increase in rear-end accidents, producing a 15 percent reduction in total accidents following introduction of separate left-turn phases at 24 intersections. On this basis, one might expect that if some protection were removed (to provide protected-permissive signal phasing), there would be an increase in left-turn accidents. A before-and-after comparison of 17 intersections so altered (68) indicated a sixfold increase in left-turn accidents and a 20 percent increase in other accidents. The same study examined the effect of changing 17 signals from protected-permissive to fully protected status; the number of left-turn accidents decreased by a factor of 7, but the number of other accidents almost doubled. More recently, Agent

(69) found that left-turn accidents increased about fourfold at 11 approaches after conversion from protected to permissive phasing; total accidents, however, did not change. All the studies mentioned so far are the simple before-and-after type. Thus, it seems likely that the reported safety changes might be exaggerated because of a statistical pitfall that plagues this type of study. A few of the studies of the cross-sectional type were reviewed, in which differences in safety at intersections with different types of left-turn protection are assumed to be due to differences in protection. As indicated elsewhere, this assumption is not a good one and will lead to incorrect results.

In conclusion, there does seem to be a consistent indication that the protected signal phasing is the safest, whereas the permissive phasing is the most unsafe. However, numerical estimates of safety cannot be provided until methodologically sound analysis has been performed.

Costs and Benefits: Protected-Permissive to Protected Phasing Cottrell (62) examined the net cost of changing from protected signal phasing to protected-permissive phasing. At a typical arterial intersection with 2,600 left turns a day, the increased delay to left-turning vehicles would cost about \$11,000 a year. If there are 20,000 through vehicles a day, extra annual delay to these vehicles, based on data by Upchurch (70), is estimated to cost \$20,000 a year. Assuming operating and installation costs of \$1,000 a year, one would require a savings of about 2.5 accidents a year at a 2:1 benefit-cost ratio to justify conversion. The data given by Cottrell suggest that left-turn accidents for such an intersection are likely to be reduced by about this much. Thus, the decision appears to be a close one in this case, which emphasizes the need for a careful trade-off of safety benefits with user and vehicle costs.

Costs and Benefits: Protected to Permissive Phasing Consider an intersection similar to that in the foregoing example: two opposing lanes, 2,600 left turns a day, and 20,000 through movements a day. According to Upchurch (70), there would be a negligible change in delay to left-turning vehicles. The extra delay per through vehicle is estimated at 15 sec, giving extra user costs of about \$60,000 a year (62). Extra capital and operating costs are estimated at \$500 a year. Accident savings based on Upchurch's data are about 14 left-turn-related accidents a year. This seems exaggerated, but a net savings of about five such accidents a year would justify the conversion at a 2:1 benefit-cost ratio.

In both examples, it is apparent that the decision is very sensitive to assumptions about the expected safety changes. In previous discussions it was suggested that current information on this issue is sketchy and clouded by uncertainty. Accordingly, the following recommendation is made:

- Rational decisions on changing from one type of left-turn protection to another are strongly dictated by the expected changes in safety. New research to correctly estimate these expected changes is vital.

Separate Pedestrian Signals

The MUTCD (6) recommends the use of pedestrian signals when a traffic signal is warranted because of large pedestrian volumes, when pedestrians cannot see the vehicle signal, and when an exclusive pedestrian phase is to be provided. Robertson et al. estimate that 85 percent of the pedestrian signal indications do not meet the MUTCD warrants (71).

In the past, the MUTCD defined the meaning of Don't Walk and Walk in both the "flashing" and "steady" modes. Readers who were not students of the MUTCD had difficulty guessing what the MUTCD meant by a flashing Walk or Don't Walk. So did most pedestrians, as was shown repeatedly. The MUTCD now recommends not using the flashing Walk and Don't Walk, but practice has not caught up with this recent change.

A recent ITE survey of practice (72) paints the following picture. About half the signals in urban areas have separate pedestrian indications, whereas the majority of reported signals in state jurisdictions do not. Practice in the six districts into which U.S. members of the ITE are divided is diverse. In four districts pedestrian signals are operated as the steady Walk. In two districts the majority are the flashing Walk, although the steady Walk is used also. In one district 18 percent of the indications are the steady Walk and, at the same time, no other traffic is allowed to move across the crosswalk. Two-thirds of the traffic engineers in the ITE survey permit right-turn-on-red at all signalized intersections even when pedestrians have a separate signal indication and an exclusive signal phase. The traffic engineers surveyed believe that only 4 percent of pedestrians understand the meaning of a flashing Walk and that 39 percent understand the meaning of the flashing Don't Walk. Members of the ITE committee that conducted the survey conclude, "It is apparent . . . that most decisions regarding pedestrian control are based on engineering judgment and local preferences."

Pedestrian signal timing influences pedestrian behavior. When pedestrians are asked to wait for long times, when they have to wait at the curb for no apparent reason, and when the Walk signal is displayed for only a few seconds and followed by a long Don't Walk message, pedestrians begin to disregard the signals. This mode of behavior may be contagious; it may render useless those pedestrian indications that are essential.

In short, the safety of pedestrians at signalized intersections may be both positively and negatively affected by the decision to install pedestrian signals and to allow vehicle flow concurrently with conflicting pedestrian flow. Older persons more than others tend to use crosswalks at intersections. They most likely believe that a separate pedestrian signal is there to protect them and perhaps are surprised and frustrated to find vehicles crossing their paths legally. They may develop the "false sense of security" most often blamed for the poor safety showing of pedestrian signals. They are the segment of the

population that is perhaps most harmed by the lack of solid professional criteria on which to base decisions about pedestrian signals and vehicle movements.

The principal reason to have a separate pedestrian signal is that the duration of the minimum green time is calculated on the assumption that the pedestrian begins to cross just as the green signal for the vehicles comes on. Of course, many pedestrians begin to cross later, and the minimum green will not be long enough for them to reach the opposite curb. Nor will many of those who begin to cross late in the green be able reach the curb by the end of the vehicle change interval (yellow plus all red), which is usually 3 to 5 sec long.

There is growing recognition that the provision of pedestrian signals is not always good for pedestrian safety. The lack of uniformity in the devices and in timing strategies, the misunderstanding of the meaning of flashing Walk and Don't Walk messages, and the false sense of security provided to pedestrians are the reasons most often cited for their ineffectiveness. In addition, specific knowledge on when the installation of pedestrian indications is in the interests of safety and when it is not is scarce.

In one of the few studies on this subject, Zegeer et al. (61) found that intersections with standard pedestrian signals had slightly higher pedestrian accident rates than intersections with no pedestrian signals. As they note, a study that compares one set of sites with a different set of sites "does not show cause and effect relationships," so one cannot conclude from these results that pedestrian signals do not improve safety.

It does appear that under some conditions pedestrian signals directly or indirectly improve safety, although Robertson et al. (71) are not specific about what these conditions are. Pedestrian signals are surely necessary when the pedestrian cannot easily see the vehicle signal or when it may be confusing. Robertson et al. estimated that some 85 percent of the pedestrian signals in existence are perhaps not useful. In most cases, however, it is unclear whether the signals are good or bad for safety and by how much safety is affected.

For example, consider a crossing 30 ft wide that now does not have a separate pedestrian indication. The vehicle green time is long enough for those who begin crossing at its onset. The vehicle change interval is 4 sec of yellow plus 2 sec of all red. A pedestrian starting at the last moment of green and walking at 5 ft/sec will reach the opposite curb before the end of the all-red period. Because 5 ft/sec is faster than the design walking speed, the temptation is to consider separate pedestrian signals. Because the vehicle green time is long enough, one could have a steady Walk signal for 7 sec and a flashing Walk for 10 sec—long enough for even those walking at 3 ft/sec to reach safety. The annual cost [based on data from Robertson and Carter (73)] for pedestrian signals is about \$150. It would take only a saving of 0.01 accident a year to justify this cost. Unfortunately, whether pedestrian signals will in fact

increase safety in this situation is unclear. All that can be said is that they will cost some money, they will increase pedestrian delay, they will put more persons in a position in which they will disobey a signal, and some persons may believe that they are getting more protection.

A few cases in which the installation of pedestrian signals might be considered useful are as follows:

1. Left-turning vehicles are given a separate phase (green arrow or equivalent) and pedestrians have to wait until the end of this phase. Pedestrian signals are needed to convey this arrangement to pedestrians. Because there is no choice in this case, the question of costs or benefits does not arise.
2. Pedestrian pushbuttons are installed at a semiactuated signal to improve the efficiency of green time use. In this case, installation is justified strictly for operational reasons, and safety improvement is not the issue. Without a pedestrian signal, every time the minor-road traffic is allowed to proceed, enough green time is provided for pedestrians to cross. Thus, green time is "wasted" for every phase in which only a few vehicles enter the intersection and no pedestrians cross. With a pushbutton pedestrian signal, pedestrian crossing time is provided only when this signal is actuated.

Many competent researchers, notably Robertson et al. (71) and Zegeer et al. (61), have recognized the sorry state of affairs in the area of providing pedestrian signals, their timing, and the message displayed. Similarly, many useful suggestions for improvement have been made. Still, the state of disarray remains. It would be presumptuous for us to make specific recommendations on a subject that many have explored in greater detail. Our impression is that within the context of pedestrian behavior as it now exists, whether pedestrian signals are provided (in those cases in which they are not essential) and what their timing is matters little to safety. The function of these signals seems to be mainly to clarify who is to blame for an accident in what part of the signal cycle.

Still, for the pedestrian, the current state of affairs is of serious concern. Is it true that a false sense of security is created by pedestrian signals (or crosswalk markings)? If so, one should surely insist that unnecessary installations be removed. Not knowing the answer to this question should be a strong impetus for action, not complacency. In conclusion, the following action is recommended:

- Pedestrian signals should be provided to enhance safety. Traffic engineers should be aware of the influence of their professional decisions about the timing of signals and the policies and practices for their provision on behavior of pedestrians.

Crosswalk Markings

There is very little material on cost associated with the marking of a crosswalk. The decision to mark a crosswalk should therefore be based on whether safety will be enhanced. Nevertheless, the literature on this subject is inadequate also.

Hermes (74) has done perhaps the best-known study on this subject. In 5 years of accident experience at 400 unsignalized intersections that had one marked and one unmarked crosswalk, 177 and 31 pedestrians were hit, respectively. After correction for differences in pedestrian volume, approximately twice as many pedestrian accidents occurred in marked crosswalks as in unmarked ones. Hermes attributes the difference to lack of caution by pedestrians when using marked crosswalks. In the largest number of pedestrian accidents, the vehicle struck the pedestrian on the far side of the street that the pedestrian was crossing.

These results might be questioned for two reasons. First, could it be that intersections with marked crosswalks differ from those with unmarked ones? Hermes finds, for example, that between 5:00 and 7:00 p.m. all accidents that occurred were at marked crosswalks. The highest incidence was among pedestrians 70 years or older, who had 35 accidents in marked and 7 accidents in unmarked crosswalks. Second, the assumption was made that because the marked and unmarked crosswalks were on opposite sides of a major street, both had the same vehicle volumes. The decision on which approach was to have the marked and which one the unmarked crosswalk must have been based on some criterion, but it was not given. Was it the accident rate, or could it be that there is relatively more potential for pedestrian-vehicle conflict at marked crosswalks?

A three-year before-and-after study in Vancouver (75) found that pedestrian accidents increased 86 percent at 55 intersections after crosswalks had been marked. Rear-end collisions increased 32 percent. It is unclear whether there were before-and-after differences in pedestrian and vehicle traffic and, if so, whether such differences were accounted for. It was pointed out that marked crosswalks did not give the pedestrian any further legal rights, because they already had the right-of-way over vehicles at unmarked as well as at marked crosswalks. This, it was believed, created confusion among motorists and pedestrian alike.

Contrasting evidence is provided by a few studies. A study cited in the 1965 ITE handbook (55, Chap. 4) found that painted crosswalks reduced violation of the pedestrian's right-of-way and that pedestrians tended to use the painted crosswalk in preference to an unpainted one. (At the two major intersection approaches, one crosswalk was painted, and one was left unpainted.)

Untermann states, without providing supporting evidence, that (76, p. 34) "painted crossings on roadways reduce pedestrian accident risks about 50

percent." He argues, "Many elderly people have difficulty perceiving perpendicularity, and the painted crosswalk helps to keep them from wandering away from the general direction of the other side of the street."

In an extensive study Knoblauch et al. (77) found that unmarked crosswalks had 24.8 percent of exposure for their population of intersections and 61.2 percent of accidents, whereas marked crosswalks had 75.2 percent of the exposure but only 38.8 percent of accidents. [In that study, exposure is taken as the sum of the products of conflicting pedestrian-vehicle flows (*PV*). Although this measure tends to make high-volume sites appear safer, no other reasonable exposure measure would alter the finding that marked crosswalks had more exposure but fewer accidents than unmarked ones. Using the square root of *PV* would indicate that marked crosswalks are three times as safe as unmarked crosswalks.]

In summary, it is unclear at this time whether marked crosswalks are safety-effective. It does appear that under certain (unknown) conditions, marked crosswalks do improve safety. Indeed, even though Herms' study showed that unmarked crosswalks were safer, he concludes that "marked crosswalks will continue to be a useful traffic control device" and recommends limiting such crosswalks to only those locations where they are warranted. These sentiments were echoed by Braaksma (75).

SUMMARY AND RECOMMENDATIONS

From research on older persons and intersection accidents, it appears that the age profile of injuries due to motor vehicle accidents is very malleable. Its shape depends on what is chosen to serve as the denominator of the injury or accident rate of interest. Thus, when the fatality rate is computed "per licensed driver," noticeable overrepresentation begins around 65 to 70; the rate for men is more than twice that for women. However, when the rate is computed on a "per unit of travel" basis, the driver fatality rate begins to climb around the age of 50 and the difference between male and female drivers is small.

The accident data show a mixture of two phenomena: the frequency with which people are involved in a crash and the chance of injury or death as a result (frailty). Older persons have a larger chance of being fatally injured in a crash of fixed severity. When this effect is accounted for, a very different set of age profiles emerges. Not only does the per-licensed-driver rate show no sign of increasing with advancing age, the rate for older persons is dwarfed by that of young men. Similarly, when the frailty effect is eliminated from the data, the plot of the per-unit-of-travel rate also changes: the rate begins to climb only around the age of 70, and its ascent is much slower. A similar line of reasoning applies in the case of the pedestrian fatality rate, which leads to the

conclusion that older pedestrians are not overrepresented in crashes, simply much more vulnerable.

The statistics presented lead to several conclusions. First, for pedestrians in the 64+ age group, about 33 percent of fatalities and 50 percent of injuries occur at intersections. For drivers in the same age group, 40 percent of fatalities and 60 percent of injuries occur at intersections. It follows that roughly half of the safety problem for older persons involves intersections.

Second, a relatively large number of pedestrians over 64 are killed at intersections (some 500 per year compared with approximately 800 in all other age groups).

Third, for "overrepresentation" to lead to countermeasure identification, it is important to separate "involvement rate" from "frailty" (the likelihood of injury or death as a result of an accident). It appears that much of what is seen as overrepresentation in age profiles of accident rates is due to "frailty." Older persons seem to be able to adapt to the traffic environment so as to keep nearly constant the probability of being involved in an accident; they do not seem to be able to adapt sufficiently to keep constant the probability of injury or death.

Many of the intersections we use now did not exist a generation ago. Our grandchildren will likely make the same observation. Therefore, the intersection safety problem must be viewed within the dynamics of the process by which intersections are created and the transformations that they undergo. Review of this process indicates that important decisions affecting safety are made in the early stages of development or redevelopment. These are the decisions by which the density and hierarchy of intersections are set. In making them, as a rule, no explicit professional attention is being given to safety. Yet it is these early choices that build future accidents into the transport network. Unfortunately, explicit authoritative guidance on this matter is not available in standard professional literature.

Inasmuch as older persons are active mainly close to their residence, their safety is particularly strongly affected by these early choices. Accordingly, the safety of older persons at intersections could be increased if alternative road designs were explicitly evaluated at the planning stage in terms of their future safety repercussions. The professionals and institutions in charge of planning and approving plans for development and redevelopment should assume the responsibility for the creation of the tools needed for the safety evaluation of street networks and for the training of professionals in their use.

A number of specific design elements are reviewed for their potential effects on safety and cost. The first is the decision to provide a left-turn lane. These are known to reduce rear-end accidents and also delays. However, there is no officially sanctioned procedure for engineering design or analysis by which the practitioner can reach a rational decision on when to provide a left-turn lane. This lack of guidance may lead professionals to overlook opportunities to enhance both the safety and the level of service at some intersections. Several recommendations, both for research and action, are made.

The question of sight distance at intersections is explored next. On the whole, research results reinforce the commonsense belief that longer sight distances enhance safety. However, there is very little knowledge about the extent of the safety improvement that can be expected.

When the design standards are examined in detail, it appears that the assumptions used for perception-reaction time matter little. What governs the design outcome (that is, whether the sight distance is long or short) is the design vehicle. If the design vehicle chosen is an automobile, not a truck, sight distances will be too short for those who are slow to make up their minds or to turn their heads. Again, research and actions are recommended to improve design practice and rectify problems when it is cost-effective.

Once an intersection has been designed and constructed, short of reconstruction, one must look to changes in intersection operation to improve safety. It is somewhat surprising to find that there is no consensus on the safety effect of changing the level of traffic control from none to a Yield sign and from that to a Stop sign. Converting two-way Stop control to multiway Stop control reduces accidents by about 40 percent, but delay and stops by motorists are substantially increased. It appears that there is no economic justification for the use of the multiway Stop. Research is recommended to obtain more factual data on which to base decisions about level of traffic control.

The decision on when and where to use traffic signals raises similar problems. Even though in the United States about 300,000 signals have been installed, it is not known what safety effect to expect and under what circumstances. Research on this topic is in order.

The decision to protect left-turning traffic has important safety repercussions. Knowledge of the safety implications associated with providing one type of protection or the other is sketchy. Nevertheless, traffic engineers must make decisions based on expected safety changes. Thus, new research to correctly estimate these expected changes is vital.

The economic comparison of accidents saved by designing for a walking speed of 3 ft/sec instead of 4 ft/sec is examined. It appears that the delay to main-road traffic usually swamps savings in pedestrian accidents. However, were one to impute a cost for the anxiety of those pedestrians who walk at less than 4 ft/sec, the outcome of the economic analysis could be reversed.

The balance of costs and benefits depends on many local factors: main-road and minor-road traffic, volume of pedestrians, road width, distribution of walking speeds, and so on. Therefore, the use of a universal design walking speed is perhaps convenient but certainly leads to inferior design in many cases and does not appear to be fair to the large elderly portion of the population. It is recommended that 4 ft/sec be retained as the maximum allowable design speed, but that the signal timing be designed on the basis of a site-specific analysis.

On the provision of separate pedestrian signals, it is noted that pedestrians may not know what the flashing signals mean. A bewildering variety of practice among localities as to what indications are used, the circumstances in which pedestrian signals are installed, and what vehicular traffic is allowed to move concurrently with the pedestrian compounds the problem. There is also a belief that in many cases pedestrian observance of these signals is very poor and that this is due in part to the preceding questionable practices. It is recommended that pedestrian signals be provided and that traffic engineers be aware of the influence of their professional decisions about the timing of signals and the policies and practices for their provision on the behavior of pedestrians.

Some general issues emerge from the detailed findings in this discussion. In many cases, perhaps most, we find that to increase safety one has to make sacrifices, which are measured not only in money but also in delay to road users. Who is to decide what the right balance is? Even though a great deal of thought has been given to the estimation of "value of time" and "cost of accidents," basic questions remain. The questions are not mainly about whether the values assigned to life or time are correct; they are also about the attitude that once such estimates have been published, they can be added, multiplied, compared, and otherwise manipulated as if one were dealing with measured properties of inanimate matter. Society has put on the shoulders of the highway and traffic engineer a task not commonly given to them—that of making decisions about the road user's time and about his health. Highway and traffic engineers have very little background or training that would allow them to discharge these responsibilities particularly well.

The safety consequences of many design decisions are not well known. Recommendations in this paper aim to bring about an engineering practice in which safety is an explicit element of design. Only then will one have a "safety-conscious design" and only then will action that shapes the safety of intersections be based on factual knowledge.

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Potential Improvements in Roadway Delineation for Older Drivers

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Safe driving requires that the moving vehicle follow a proper path on the roadway. Inadvertent excursions can lead to disaster: head-on collision with an approaching vehicle, sideswipe of a passing vehicle, or an overturn or collision with a hazardous roadside object. To avoid such disasters, the driver must be able to (a) sense in advance required changes in direction resulting from horizontal curvature or an intersection turn and (b) accurately follow the desired path, thus maintaining safe edge-of-pavement and intervehicle clearances. Each of these tasks—identified herein as guidance and tracking, respectively—relies extensively on visual stimuli. The kinds of stimuli that are most important differ between intersection and nonintersection locations.

Guidance through intersections is accomplished almost exclusively with traffic control devices such as route markers and direction and street signs. With the intended movement chosen and attention properly directed, the driver steers toward the appropriate departure leg. Tracking on the approach and departure legs is largely based on the location of lane boundaries, usually defined by the physical edge of the pavement or the curb or gutter line; by pavement stripings, including centerlines, lane lines, and edgelines; and by channelizing devices. Within the intersection proper, the driver gains useful tracking clues by following leading vehicles, by the location of channelization, and occasionally by a dashed lane line extending through the intersection.

At nonintersection locations, guidance comes largely from the visual perspective of the road ahead and the location of parallel elements such as lines of trees, fencing, utility poles, parked cars, lighting standards, and bridgerail or guardrail. Traffic control devices such as chevron alignment markers, post-mounted delineators, raised or recessed pavement markers, curve warning signs, and centerline, lane-line, and edgeline markings are also important, often critically so at night and during other periods of restricted visibility and when speeds are high. For tracking, the driver relies on nearby features; contrasts in color, texture, and shape between pavement and shoulder; curb and barrier edges; and pavement striping. Under high traffic volumes, car following is likely a dominant tracking and guidance aid. The vibration and noise of an inadvertent excursion onto a properly textured shoulder also serve to alert the inattentive driver to potential danger and redirect attention to the tracking task.

The purpose of this paper is to identify special difficulties of the older driver in performing these guidance and tracking tasks at nonintersection locations, to determine whether these difficulties can be eased by the installation or enhancement of delineation devices, and to identify conditions in which such installation or enhancement appears warranted. Intersections and signing are treated by Hauer and Mace in other papers in this volume.

The discussion in the following sections draws heavily on the material presented in Chapter 3, *Safety of Older Persons in Traffic*, of Volume 1 and on other papers in this volume by Mortimer, McKnight, Hauer, Mace, Bailey and Sheedy, Kanouse, and Schieber.

THE OLDER DRIVER

The typical aging person suffers a deterioration in at least three functions important to safe and carefree driving: sensory (visual), cognitive, and psychomotor. Unlike more complex driving tasks such as emergency maneuvering or freeway merging, guidance and tracking at nonintersection locations probably place critical demands only on vision; the cognitive function becomes important only for complex guidance tasks and high-speed travel. Typically, though, the changes in direction necessary for guidance and tracking are small and continuous; they do not demand quick thinking and fast and strong response.

Specific visual capabilities essential to guidance and tracking have not been accurately identified. However, for travel on two-lane roadways at night, resistance to glare and quick recovery from its effects are obviously essential to both tasks. Visual acuity (the ability to see details clearly) and contrast sensitivity (the ability to discriminate small-contrast differences in larger objects or features) are probably the most critical visual elements for identifying distant features essential to the guidance task. Tracking requires the

identification of more closely located features, typically outside the point of visual fixation, and as a consequence relies heavily on peripheral vision. Unfortunately, deterioration of each of these vital visual functions is a frequent consequence of the aging process (1). The deterioration is often dramatic and, with exception of visual acuity, largely uncorrectable.

One anticipated consequence of visual deterioration in aging drivers is certainly an increase in the rate of their involvement in guidance- and tracking-related crashes, in the context of this paper at nonintersection locations. For two-lane highways, these include both head-on and single-vehicle run-off-roadway crashes; for multilane highways, sideswipe and single-vehicle run-off-roadway crashes. Nighttime would be expected to exacerbate the consequences of impaired vision.

Past research establishes a conclusive association between driver age and crash measures such as the number of fatalities per mile of travel: crash rates have been positively associated with age for older drivers. Other research has shown the deleterious effect of visual impairment on crash rates (2). However, crash research has not been sufficiently refined to attempt direct correlations between the rates of guidance- and tracking-related crashes and age or vision. At the same time, the typical types of crashes in which the older driver is involved are clearly known. They occur in urban areas during the daylight hours. They are multivehicle crashes involving turning, merging, pulling into traffic, lane changing, backing up, and the like. Not infrequently, the older driver fails to yield the right-of-way or to observe traffic signs or signals. The typical older-driver crash is obviously not of the type expected from failures in the guidance and tracking tasks.

The absence of a clearly defined link between the patterns of guidance- and tracking-associated crashes and driver age or vision may stem from inadequacies of crash and exposure data bases or by lack of a concerted attempt to seek such a link. However, it is almost certainly related to adaptive and compensatory behavior of the aging driver. As a consequence of visual deterioration, older drivers are expected to find guidance and tracking tasks becoming increasingly difficult with time. As a result, they alter their patterns of behavior, driving less at night, avoiding unfamiliar routes, venturing less frequently into unaccustomed territory, and avoiding peak traffic conditions. In short, aging drivers may selectively avoid driving situations that they believe will be difficult and dangerous.

DELINEATION

A "bare" roadway—one devoid of traffic control devices—is seldom adequate for supplying essential input for guidance and tracking tasks, even for the most competent motorists. A striped centerline is considered essential for

almost all two-lane roadways (3). It provides essential delineation, acts to assure adequate separation between opposing or passing vehicles, and provides a convenient mechanism for identifying no-passing zones. In addition, the horizontal curve, hidden from view by the roadway geometry, is the genesis of one of the more common signs along rural secondary roadways—the diamond-shaped curve warning sign. Such signs—long considered essential to proper guidance—are frequently supplemented by delineation devices such as post-mounted delineators or chevron alignment markers. Interestingly, roadways of the highest standards, Interstate highways and other freeways, make most extensive use of delineation devices: centerlines, lane lines, and edgelines (all reflectorized for enhanced nighttime visibility); raised or recessed pavement markers for enhanced wet-weather visibility; post-mounted delineators at roadside for use when other devices are obscured by ice or snow and for general advance direction; and, as necessary, the chevron alignment marker at critical locations.

The extensive use of such devices reflects not only the common belief that enhanced delineation is essential to safe and comfortable driving at night and during other periods of impaired visibility but also an expanding body of research that has validated its operational and safety benefits (4, 5–8). The Federal Highway Administration's study of delineation techniques, conducted in the mid-1970s, provides an indication of crash benefits (7, 9):

- Highways with centerlines had lower crash rates than those without delineation treatment. For example, application of a painted centerline to two-lane sections without prior delineation was found to reduce the overall crash rate by up to 1.5 crashes per million vehicle miles. The reduction was approximately 30 percent for the entire sample of highways.
- Highways with raised pavement marker centerlines had lower crash rates than those with painted centerlines. The average reduction in crash rates was approximately 0.5 crash per million vehicle miles.
- Installation of post-mounted delineators lowered crash rates for sections with or without edgelines. The reduction in crash rate resulting from the installation of these delineators averaged 1.0 crash per million vehicle miles.
- The application of edgelines generally resulted in a decrease in crash rates. The reduction was greatest for tangent sections, averaging approximately 0.7 crash per million vehicle miles.

The significance of the foregoing estimates is demonstrated by a cost-effectiveness analysis that justifies the application of striping and post-mounted delineators for a wide range of conditions including minimum traffic volumes of 1,000 vehicles per day or even less in some cases. Raised pavement markers, as a substitute for painted centerlines, become cost-effective at larger volumes, 3,000 or more vehicles per day.

Because of the difficulty of performing investigations that rely on crash data, much delineation research has been based on observations of its operational effects, including such measures as speed, speed change, lateral placement, and frequency of out-of-lane excursions. Although there is limited evidence of correlation between such measures and crash experience (4, 5), definitive relationships have yet to be developed, and researchers sometimes disagree as to the appropriateness of specific measures. At the same time, the controlled nature of operational experiments contributes to more reproducible and sensitive results, and researchers who have applied such methods generally agree on the merits of improved delineation.

Possible effects of enhanced delineation on the operational behavior and crash patterns of older drivers have not been objectively studied. Research currently under way may eventually yield significant new insights on the kinds of delineation enhancements likely to most greatly benefit the older driver (1). For the moment, however, some reasoned speculation is necessary. The greatest crash savings from improved delineation are expected when the vision or visibility is least. Certainly, for example, crash savings are greater at night than during daylight, and a few investigations suggest more beneficial effects for the driver whose vision has been impaired by alcohol consumption (10–12). It seems reasonable to conclude, therefore, that enhanced delineation would more favorably affect the older driver than possibly more average segments of the driving population. Present research supports this view by postulating that older drivers suffer greater degradation in the ability to detect pavement markings and other horizontal targets than younger drivers, especially in poor visibility conditions (1). Yet to be tested, however, is whether unsafe driving behavior is induced by the sense of security stemming from enhanced delineation—the selection of speeds too fast for conditions and driving ability, tracking too close to (or too far from) a conspicuous edgeline, increased travel during periods of reduced visibility, and so on.

ENHANCEMENT OF DELINEATION

For the Older Driver

Given that the typical older driver has diminished ability for safe and comfortable steering, and that enhanced delineation has proven beneficial to vehicle guidance and tracking tasks, it is logical (a) to seek to identify circumstances in which delineation improvements might be justified, largely on the basis of benefits accruing to the population of older drivers and, in such circumstances, (b) to specify the nature of improvements likely to be cost-effective. An objective analysis of this type requires quantification of the lifetime costs of the delineation improvements as well as the safety benefits likely to be realized by the population of drivers, including the subset of older drivers. The

latter requires not only an estimate of the reduction in crash rate but also an estimate of the exposure to crash risk. Although quantification of lifetime costs of delineation devices is a task that can be accomplished with relative ease, the scientific basis for quantification of crash rate improvements is limited, and little is known about exposure of older drivers to delineation-related risk.

Although a quantitative evaluation is thus not feasible, a qualitative assessment can indeed be made. Older drivers typically travel at reduced speeds and drive at times (daytime and better weather) and in places (urban streets instead of rural highways) not demanding greatly enhanced delineation for safe driving. Like other drivers, their rural travel is probably concentrated on Interstate highways and other freeways, facilities for which existing delineation treatments are most advanced and therefore in need of little, if any, enhancement. Furthermore, the established patterns of older-driver crashes and violations are not of a type thought to be correctable by enhanced delineation, at least not at nonintersection locations. On the basis of such considerations, it seems unnecessary to attempt to give priority to delineation improvements on the basis of special needs of the older driver.

Travel patterns of the older driver will almost certainly change in the future, and the aging population can be expected to seek to maintain the high level of mobility achieved during their middle years. Fewer self-imposed restrictions on personal travel can be expected: the older driver is likely to travel more at night, take more long-distance trips, more frequently select unfamiliar routes, and travel more often during adverse weather. In short, older drivers will be more frequently exposed to the kinds of conditions for which enhanced delineation is beneficial. Fortunately, the installation of delineation devices is relatively quick and inexpensive; thus, future enhancements to better accommodate the changing population of drivers can easily be made.

For All Drivers

As has been noted, centerline striping is applied to most paved, two-lane highways. The first enhancement to this basic delineation pattern is usually the addition of edgelines. Painted edgelines are relatively inexpensive and have been found to be cost-effective from a safety perspective when daily volumes exceed 1,000 vehicles. Their use has been recommended for all major roads wider than 20 ft (9). Recent interest has focused on the use of edgelines wider than the standard, 4-in. width (13). These wide edgelines offer the potential for extensive cost-effective application (14).

Unfortunately, published crash studies have not produced conclusive findings on the incremental safety effect of wider-than-standard edgelines (see Appendix). A joint study by FHWA and seven participating states is designed to rectify this situation when its findings are published in early 1989. In the

interim, a tentative assessment can be made based on existing knowledge of the safety effects of standard edgelines, results from operational studies of wide edgelines, and the crash studies that have examined wide edgelines. The current state of knowledge is summarized as follows.

1. The presence of edgelines has a small but measurable effect on traffic operations (5, 6, 10–12, 15–17). On horizontal curves, for example, edgelines

- Reduce the disparity between daytime and nighttime operating speeds and generally increase nighttime speeds,
- Reduce the frequency of excessive turning curvature,
- Move vehicles away from the pavement edge toward more central positions within the lane of travel,
- Reduce the frequency of shoulder encroachments, and
- Reduce the variability in vehicle position and speed. Operational effects are more pronounced at night than during the day.

2. When applied to centerline-marked roadways, the addition of standard edgelines reduces crash risk (5, 7, 11, 18–20). Although reductions in the frequency of all types of crashes as large as 60 percent have been reported (11), a more likely expectation for the normal roadway would be within the range of 10 to 15 percent. Reported reductions in excess of this range most probably reflect experimental deficiencies—such as regression-to-the-mean effects common in before-and-after studies—or applications to highways having greater than normal incidence of delineation-related crashes, or both.

3. Studies of the effects of edgelines on crash severity have yielded mixed findings (11, 18, 19, 21). However, beneficial effects, if any, are likely due to changes in the mix of crash types rather than an attenuation of the consequences of specific crash events. Such effects could be countered, however, by the increased nighttime speeds induced by edgelining.

4. Although there is some indication that relative benefits of edgelines on straight or gently curving roads may exceed those on more demanding sections (7, 19), research has not been sufficiently refined to pinpoint the confounding effects of many roadway and roadside variables. Edgelines are likely to have maximum beneficial impact in these situations: following

- Poor existing demarcation between pavement and shoulder surfaces;
- Hazardous shoulder or roadside conditions, or both;
- Hazardous horizontal curves, particularly when preceded by straight or gently curving sections;
- Sudden changes in pavement width and the approaches to narrow bridges;
- Large nighttime traffic volumes and high speeds;
- Frequent occurrence of fog or mist; and
- Frequent and severe glare from opposing headlights.

5. Prior research has not defined conditions in which the application of edgelines may have harmful effects. However, these are likely to include narrow roadways, particularly those without centerline markings. Although edgeline applications on 20-ft pavements have not been found to result in safety decrements, most states have prohibited their use on pavements narrower than 22 ft (4), a precaution likely to be a prudent one. Narrower roadways with an abnormally high incidence of delineation-related crashes can likely be better treated by widening or by the installation of raised or recessed pavement markers on the centerline or, possibly, post-mounted delimiters off the shoulders.

6. Although one study has documented an increase in crashes following the application of 8-in. edgelines on some types of highways, accompanied by a decrease on others (22), there seems to be no logical basis for arguing that, under normal circumstances, wide edgelines are more hazardous than narrow ones. No such claim has been found in the literature. To the contrary, operational and safety effects of edgelines would logically appear to be continuous functions of their widths, although the incremental effect of each inch of width would likely diminish as width increased. Studies showing a reduction in crash risk following wide edgelineing generally support such an assertion (23; R. Kelly, Spokane County, Washington, unpublished data; N. D. Nedas, letter to W. Hoversten, California Department of Transportation, July 18, 1985). Reductions are expected to be quite small, however—almost certainly less than 5 percent for typical highways. Although research under way may more accurately assess the quantitative benefit, changes as small as those anticipated are difficult to quantify from records of crash history.

7. The performance of drivers suffering from alcohol impairment is improved by the presence of edgelines (10–12). Although the effects of edgelines on older-driver performance have not been directly tested, an improvement is, by inference, expected.

8. For 8-in. edgelines to be a cost-effective replacement for 4-in. edgelines when the daily traffic exceeds 1,000 vehicles, crashes need only be reduced by an amount of 0.7 percent or less (14). Such a small reduction seems to be well within the expected range, and 8-in. edgelines appear to be a cost-effective application on all two-lane, rural highways warranting such delineation. However, applications on lanes narrower than 11 ft should be considered experimental and carefully monitored.

In view of the foregoing findings and at least until more conclusive crash data become available, 8-in. edgelines should be used in lieu of standard, 4-in. edgelines on two-lane, rural highways. Although this finding is not based on benefits accruing specifically to older drivers, older drivers will share—probably proportionally more—the safety benefits with others who travel these highways during periods of impaired visibility.

RECOMMENDED RESEARCH

Findings of this study suggest that only minor gains in the safety of older drivers are likely to be realized through the widespread adoption of enhanced delineation techniques. Accordingly, motivation for the refinement and extension of knowledge on this subject is not as compelling as it is for others. Two matters however, do warrant additional investigation. The first is the travel and crash patterns of older drivers. A critical study should search for situations in which the older driver is most in need of help that can be rendered by changes to the design and operation of the street and highway system. In the context of delineation, validation would be sought of the finding reached herein that major safety gains are unlikely through the enhancement of delineation. The second is the response of older drivers to a variety of delineation treatments. The primary objective of such a study would be simply to confirm that enhanced delineation improves the performance of older drivers and that abnormally conspicuous delineation does not induce unsafe driving behavior. Effects of lane width and shoulder and roadside conditions as measures of risk in improper tracking should be included in the investigation.

CONCLUSIONS AND RECOMMENDATIONS

Ample evidence suggests that harmful effects of visual degeneration typical in older drivers can be alleviated by the installation or improvement of pavement striping and other delineation devices. At the same time, available evidence is not sufficiently precise to quantify the safety gains that older drivers can expect from enhanced delineation. It does appear, however, that the typical trip made by the older driver is taken on streets and at times when any benefits of improved delineation would be marginal. Furthermore, crash and violation histories of older drivers do not suggest predominant patterns of unsafe behavior of a type correctable by improved delineation.

Nevertheless, the older driver—along with all others—derives some benefit from improved delineation. It is incumbent upon those who operate and maintain the nation's streets and highways to provide delineation treatments in accord with the highest standards of accepted practice (3, 24, 25) and to assure that such treatments are satisfactorily maintained and replaced as necessary. One promising enhancement for two-lane rural highways having pavement widths of 22 ft or more is to replace standard edgelines with wider, 8-in. ones. Where older drivers make up an unusually large portion of the traffic stream, additional consideration should be given to the incremental enhancement of delineation treatments, either at spot locations—such as sharp curves, narrow bridges, construction zones, lane drops, and sudden changes in pavement width—or on extended highway segments.

APPENDIX

Studies in New Mexico (22) and Virginia (23) are among the most recent and probably the most frequently cited in connection with the safety effects of wide edgelines. Both studies concluded that wide edgelines were not beneficial. The researchers recommended, respectively, that "this treatment be discontinued on rural highways" and that "wide edgelines not be considered as a countermeasure." Actually, in Virginia wide edgelines were associated with a reduced frequency of run-off-road crashes; however, the reduction was not statistically significant. In New Mexico, although there was an overall negative effect of wide edgelines on run-off-road crashes, a favorable experience was found on the federal-aid primary subset of the sampled mileage. Unfortunately, statistical testing procedures were not used to evaluate the significance of the New Mexico findings.

In both New Mexico and Virginia the sampled mileage of treatment and control highways was quite limited; neither study addressed the sample size that would likely be necessary to detect, with acceptable risk for error, any beneficial effect of edgelines. Because that effect is likely to be a small one and because highway crash data are so highly variable, it is likely that sample sizes considerably in excess of those used in New Mexico and Virginia would be necessary. The purpose of this Appendix is to examine the sample sizes necessary to keep the risk of error within satisfactory bounds for studies such as these.

For simplicity, the experimental plan selected for investigation was a before-and-after design with both treatment and control sites. Further, it was assumed that the treatment and control sites would be individually matched so that paired comparisons could be made. The following quantities would be observed in such a study.

- TB_i = number of crashes at treatment site i in the before period,
- TA_i = number of crashes at treatment site i in the after period,
- CB_i = number of crashes at paired control site i in the before period, and
- CA_i = number of crashes at paired control site i in the after period.

Computed quantities would include the following:

- $\delta T_i = TB_i - TA_i$, the reduction in crashes at treatment site i ,
- $\delta C_i = CB_i - CA_i$, the reduction in crashes at control site i , and
- $\delta_i = \delta T_i - \delta C_i$, the improvement observed with site pair i due to treatment.

For such an experiment, the required number (n) of site pairs in the sample can be determined as follows (26):

$$n = \frac{(z_{1-\alpha} + z_{1-\beta})^2}{d^2}$$

where

- z = normal variate,
- α = level of significance,
- β = probability of committing an error of the second kind, and
- d = $(m_T - m_C)/\sigma$, in which the first term is the value of the positive average difference that is desired to be detected and σ is the standard deviation of the population of signed differences, δ_i .

$$\begin{aligned} m_T &= \text{Exp}\{\delta T\} \\ &= \text{Exp}\{TB - TA\} \\ &= \text{Exp}\{TB\} - \text{Exp}\{TA\} \end{aligned}$$

where $\text{Exp}\{ \}$ is the expected value of the quantity in braces. The difference in crash frequency due to wide edgelines is expected to be quite small. A 1 percent difference is chosen because that is the approximate level at which wide edgelines are cost-effective. Accordingly,

$$m_T = 0.01 \text{Exp}\{TB\}$$

Because no change in crash frequency is expected at the control sites,

$$\begin{aligned} m_C &= \text{Exp}\{\delta C\} \\ &= \text{Exp}\{CB - CA\} \\ &= 0 \end{aligned}$$

For maximum accuracy, σ should be estimated from results of actual crash studies. However, the following is considered to be a reasonable approximation. First, the variances in the crash frequencies are assumed to be identical, that is, $\text{Var}\{TB\} = \text{Var}\{TA\} = \text{Var}\{CB\} = \text{Var}\{CA\}$, where $\text{Var}\{ \}$ represents the variance of the braced quantity. Then

$$\begin{aligned} \text{Var}\{\delta T\} &= \text{Var}\{TB - TA\} = \text{Var}\{TB\} + \text{Var}\{TA\} - 2 \text{Cov}\{TB, TA\} \\ &= 2 \text{Var}\{TB\} (1 - r_1) \\ \text{Var}\{\delta C\} &= \text{Var}\{CB - CA\} = \text{Var}\{CB\} + \text{Var}\{CA\} - 2 \text{Cov}\{CB, CA\} \\ &= 2 \text{Var}\{TB\} (1 - r_1) \end{aligned}$$

$$\begin{aligned}
 \text{Var}\{\delta\} &= \text{Var}\{\delta T - \delta C\} = \text{Var}\{\delta T\} + \text{Var}\{\delta C\} - 2 \text{Cov}\{\delta T, \delta C\} \\
 &= 2 \text{Var}\{\delta T\} (1 - r_2) \\
 &= 4 \text{Var}\{TB\} (1 - r_1) (1 - r_2)
 \end{aligned}$$

where $\text{Cov}\{\}$ is the covariance of the braced quantities and r_1 and r_2 are correlation coefficients. In the absence of actual data, the correlation coefficient r_1 is assumed to equal 0.50 and r_2 , 0.25. Thus,

$$\text{Var}\{\delta\} = 1.5 \text{Var}\{TB\}$$

and

$$\sigma = (\text{Var}\{\delta\})^{0.5} = 1.22 (\text{Var}\{TB\})^{0.5}$$

Although $\text{Var}\{TB\}$ is not known, it can be treated parametrically by expressing it as a fraction of the mean as follows:

$$\text{Var}\{TB\} = k \text{Exp}\{TB\}$$

where k is some constant fraction. Then

$$\sigma = 1.22 (k \text{Exp}\{TB\})^{0.5}$$

and, finally,

$$d = \frac{0.01 \text{Exp}\{TB\}}{1.22 (k \text{Exp}\{TB\})^{0.5}}$$

As stated earlier, the experiment being considered in this investigation is a before-and-after experiment with paired treatment and control sites. For purposes of estimating the required sample size, the following assumptions are made:

- Extent of crash data: 2 years before and 2 years after treatment;
- Length of each site: 5 mi;
- Traffic volume: 2,000 vehicles per day;
- Crash rate: 5 crashes per million vehicle miles; and
- Mean and variance of accidents: Based on the above, the mean number of crashes in the 2-year before period is 36.5; the variance is largely unknown but might be expected to be about one-fourth the mean, yielding a standard deviation of about 3.0 crashes; the crash frequency in a 2-year period at virtually all sites would thus range from 28 to 46 (mean $\pm$ 3 times the standard deviation).

The typical crash investigation of a feature such as wide edgelines might involve 10 to 30 test pairs (100 to 300 mi of roadway in the context of the

foregoing example). The level of significance is commonly 0.05. Given the assumptions just made, the probability of not being able to detect a real 1 percent crash effect for this typical experiment is very large, about 87 to 91 percent (Figure A-1). Therefore, the researcher is almost assured in advance of being unable to detect a beneficial effect as small as 1 percent with such limited mileages of treatment and control sections. In fact, if the effect sought is a small one such as 1 percent, no purpose would be served in performing the study unless the sample size were much larger.

Figure A-2 extends the analysis to much larger numbers of test pairs and to a wide range in variances. The probabilities of not detecting 1-percent effects remain quite large except for large sample sizes and unrealistically low crash variances. Some improvement is possible by increasing the level of significance, that is, the risk of committing an error of the first kind. Figures A-3 and A-4 demonstrate the effects of increasing the level of significance to 0.20. These illustrations also demonstrate that trade-offs are necessary in realistic experiments between the risks of committing each of the two types of errors on one hand and sample size on the other.

Of more specific interest to the current investigation, required sample sizes for levels of significance ranging from 0.05 to 0.20 and for a 40 percent

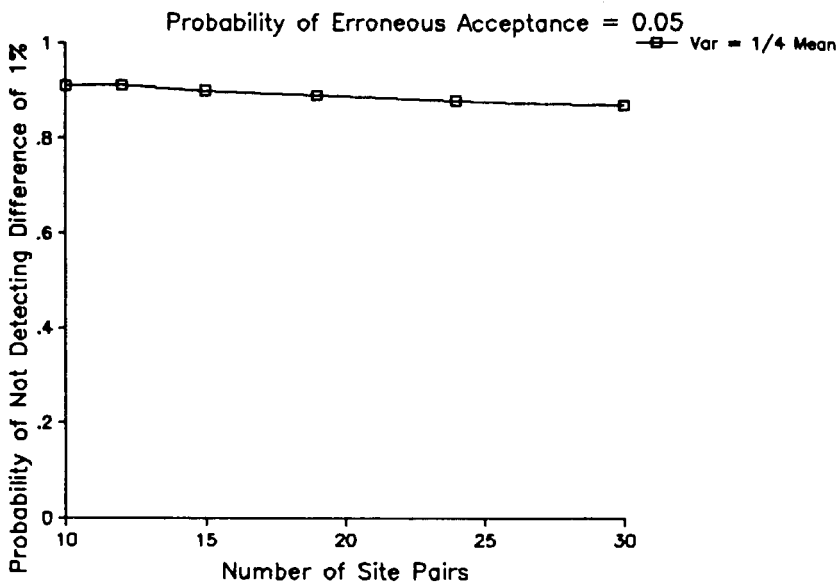


FIGURE A-1 Large probability of failing to detect a significant crash improvement with small sample size.

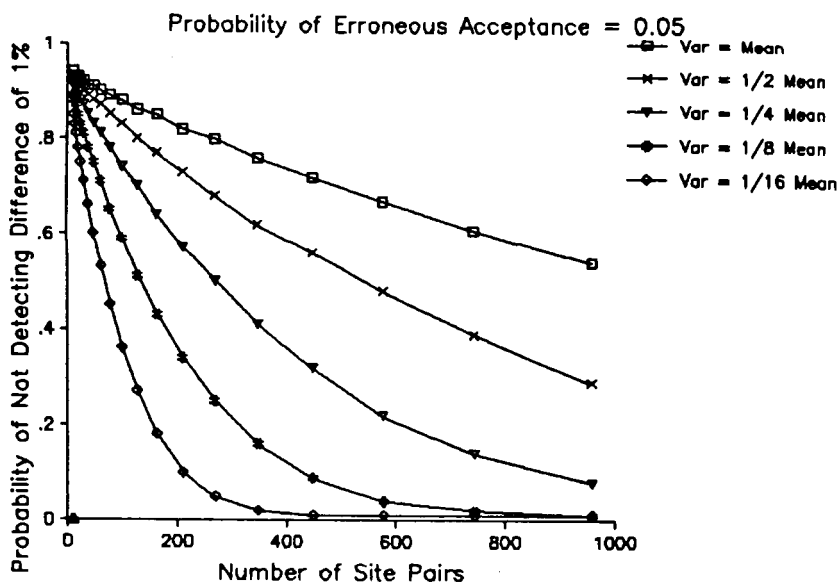


FIGURE A-2 Significance of sample variability and sample size on the experimental plan.

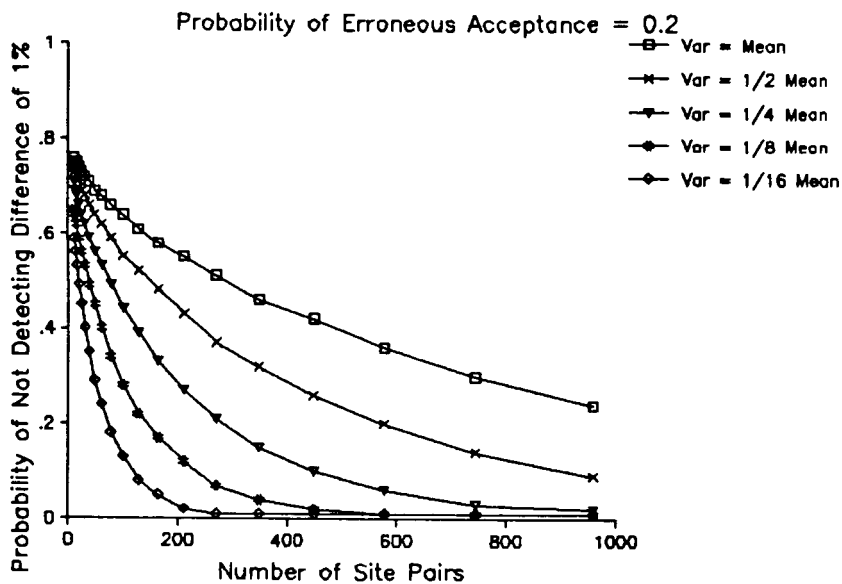


FIGURE A-3 Reduction in required sample size for a larger level of significance.

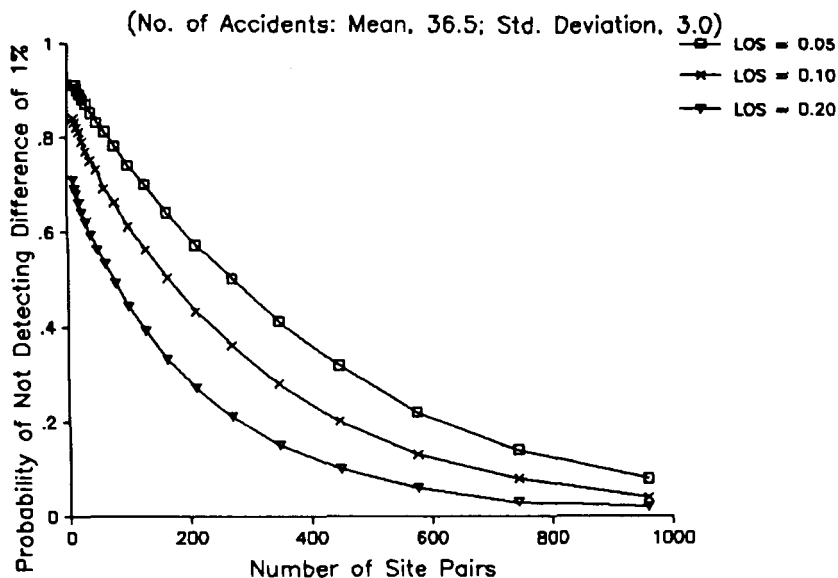


FIGURE A-4 Comparative effects of level of significance on sample size.

probability of not detecting a significant crash reduction effect at the 1 percent level are as follows:

	<i>Level of Significance</i>		
	<i>0.20</i>	<i>0.10</i>	<i>0.05</i>
No. of site pairs	125	240	360
Total no. of miles	1,250	2,400	3,600

Even at a level of significance as large as 20 percent, the required sample size greatly exceeds that used in the New Mexico and Virginia studies.

In summary, wide edgelines were found to have had a beneficial effect on run-off-road crash experience on federal-aid primary highways in New Mexico and, although not significant in the statistical sense, on Virginia highways. On other New Mexico highways, the observed effect of wide edgelines was detrimental to highway safety. Most important, however, neither the New Mexico nor the Virginia study seems to have been designed to detect small crash effects of the magnitude sufficient for cost-effective application of wide edgelines. Therefore, the findings of these studies, although adding valuable information to the rapidly accumulating bank of evidence, must be considered inconclusive.

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Sign Legibility and Conspicuity

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Back in the early days, in New England, they didn't have any tractors or big cranes. They used oxen. And when they got a great big log on the ground and they couldn't budge it, they did not grow a bigger ox—they used two oxen.

Grace Hopper (1)

There are two perspectives from which to argue the importance of designing traffic signs to meet the needs of older drivers. The first, and perhaps more convincing, argument is contained in demographic data that document the growth in older age groups relative to other age groups. The second argument is derived from consideration of accident data and the overinvolvement of older drivers in accidents and fatalities. Both lead to the conclusion stated by Staplin (2) in a review of age-related diminished capabilities that "it is prudent to anticipate ways in which the present system of traffic control devices may fail to accommodate the special needs of this group of motorists."

Demographic projections for the older population are presented by Rosenbloom elsewhere in this volume. A review of these projections and their associated data leads to several unambiguous conclusions. However one defines older drivers, their representation in the driving population is rapidly increasing. Also, the older population varies in physical abilities and their use of motor vehicles. The classification of older people by Neugarten (3) into the young-old and old-old is most useful. The over-75, or old-old, group is growing faster than any other (4). However, the young-old group is more dependent than the old-old group on personal use of motor vehicles, and it is their needs that are addressed in this paper.

It has been observed that the rapidly expanding mobility of older drivers has not brought about responsive change in the interrelated vehicle-highway-driver system (5). This transportation system is of fundamental importance to the life-style of older persons in the United States, just as it is for all other Americans. It is therefore logical to attend to all components of automobile travel if the mobility and safety of older persons is to be improved. These components include vehicle design, driver education, and highway construction and maintenance.

To downplay the problem, it is sometimes suggested that older drivers take compensatory actions that improve safety. First, the nature of their trips changes, particularly after retirement, so that much of their travel is during daylight and off-peak hours (6). Retirement, however, encourages vacation travel and driving in unfamiliar surroundings, which increase the dependency of older drivers on signs. Also, older persons drive more slowly and tend to stay in the right lane on multilane highways. Although it is true that driving is often regarded as a self-paced task, this style of driving may itself be hazardous in the heavy volume of daytime urban travel.

The demographic changes already discussed suggest that many more dramatic changes in the life-style and highway use of older drivers may be forthcoming. As life span increases and older people become a larger percentage of the total population, pressures may arise to force retirement to occur later in life, changing current driving patterns. It is easier to imagine people working while in their seventies than to imagine that worker productivity can be increased to support the social cost of a rapidly increasing retirement group.

Although elderly drivers are known to be overrepresented in traffic fatalities, the reasons behind this are far from certain (7, 8). Attempts to relate driver performance (measured by either accidents or violations) to age-related impairments or signing deficiencies do not suggest any single obvious course of remediation.

Maleck and Hummer (8) observed that in rural settings older drivers are less likely to be the cause of accidents. Staplin (2) observed that the principal problems of older drivers, as measured by accidents and violations, appear to involve left turns, yields, and merges. Harrington and McBride (9), comparing violation rates on a mileage basis, noted that older drivers are most likely to fail to yield right-of-way and to disobey traffic signs.

Although visibility of existing signs may contribute to these documented driving errors, there may be other contributing causes: cognitive processing problems, missing signs, and unclear and confusing information. A recent survey by Yee (10) found that 25 percent of elderly drivers experienced problems reading traffic signs. Of these, the most frequently reported problem (42 percent) was sign placement. Other problems, reported equally often, were

size, clarity of lettering, and clarity of message. In addition, difficulty with signs occurred more often in or around cities.

The focus of this paper is on improving the highway transportation system for older drivers through the maintenance of adequate sign legibility and conspicuity. The need for standards is suggested by reports of increasing costs arising from tort liability cases. Signing deficiencies were cited as the primary factor in 20 percent of sampled tort actions (11), second only to pavement deformities (22 percent). When only those accidents involving a fatality or serious injury are considered, signing deficiency is the primary factor.

The overrepresentation of nighttime accidents has been the basis of arguments to implement standards to maintain sign reflectivity at necessary levels. The tendency of older drivers to drive less at night is somewhat negated by the exposure-adjusted nighttime accident rate of older drivers coupled with the demographic and life-style changes already mentioned. These factors argue for consideration of both daytime and nighttime conspicuity and legibility.

Mace et al. (12) developed an analytic framework for evaluating the adequacy of any sign. The framework reflects the principles of supply and demand and is based on the simple observation that drivers demand a minimum time and therefore distance to process and respond to information and that the characteristics of signs, headlamps, and the highway determine how much distance and therefore time are supplied to the driver. This discussion will cover driver requirements (i.e., demand for conspicuity and legibility) and how they are affected by driver age, supply of conspicuity and legibility under current design practice, and alternative methods of implementing conspicuity and legibility requirements.

REQUIREMENTS OF OLDER DRIVERS

Research has shown that drivers require a minimum amount of luminance contrast for both conspicuity and legibility. Signs must first be detected (sometimes on a visually complex background) and then the information must be processed and understood. This should all happen before a sign has been passed, and sometimes (e.g., at a Stop sign) with enough distance remaining to permit a vehicle maneuver (e.g., deceleration to a stop) before the sign has been reached.

Although it cannot be proved that insufficient sign legibility and conspicuity contribute to the driving problems of older drivers, the verbal reports in studies such as that by Yee (10), the role of signing in accidents, and the involvement of older drivers in accidents suggest that it does. More basic is the fact that both analytical and empirical studies show increasing luminance thresholds for sign legibility and conspicuity with age.

It is important, however, to recognize that one cannot discuss a visual requirement applicable to all signs. Mace et al. (12) discussed the influence of

factors such as motivation, uncertainty, use of symbols and purpose of sign message, and so forth, on conspicuity and legibility requirements. Because these factors are affected by age, it is important that they be considered in determining the specific requirements of older drivers.

Information Distance

Safe driving is heavily dependent on control, guidance, and navigation sub-tasks, as discussed by Alexander and Lunenfeld (13). Guidance and navigation require having the time necessary to process information and execute an appropriate response. The basic visibility requirement model for signs is based on the Decision Sight Distance (DSD) model presented by McGee et al. (14). In this model it is assumed that the driver needs time to detect a sign, comprehend its message, make a decision, initiate a response, and implement or complete a vehicle maneuver before reaching the sign.

When the DSD was automated, Mace (12) built a Sign Dictionary that classifies all signs in the *Manual on Uniform Traffic Control Devices* (MUTCD) on the basis of components of the model that are relevant to that sign. Depending on which components are necessary, the model (assuming serial processing) combines the time estimates and applies the estimated time to the operational speed to compute the DSD.

The model, now the Minimum Required Visibility Distance (MRVD) model (15), is being revised under a current FHWA contract to account for differences resulting from driver age. The MRVD for older drivers can be considerably longer than that for younger drivers because of diminished cognitive abilities and changes in motivation and risk-taking behaviors. Signs that require most or all of the DSD components will therefore potentially be more affected by driver age than those that only need to be detected and read. MRVD is a reasonable model for estimating legibility and detection distance requirements of signs in general.

Without reference to MRVD one might think that the special needs of older drivers for conspicuity and legibility are based solely on visual impairment. The concept of MRVD makes it obvious that factors such as reaction time, decision making, and problem solving increase the distance needed by the older driver to detect and read signs, and that these factors can create visibility problems for the older driver even when visual impairment is not added. In general, older drivers not only have problems seeing what younger drivers can see at a given distance but also need to recognize and be able to read signs at greater distances to provide them with the additional time needed to respond in a safe manner.

Age-Related Impairment

It is well known that age is associated with diminished capacities in sensory-perceptual, cognitive, and psychomotor skills that are all related to safe driving performance. Less clear, perhaps, is which diminished capabilities make a difference. Several reviews (2; 16, pp. 131–159; 17, pp. 121–130) substantiate that as people age, visual acuity and contrast sensitivity decline, the visual field contracts, and depth perception diminishes. As a result, older drivers experience a decline in peripheral vision, glare resistance, glare recovery, and the ability to focus. Lindholm et al. (18) report a number of basic research studies on the effects of aging on perceptual and cognitive processes and generalize to the highway environment. Their principal findings relate to the interaction between sign attributes and task characteristics and the increased processing time required by older drivers. Milone (19) summarizes cognitive changes as follows:

While long-term memory loss and learning skills seem not to deteriorate, a decline in short-term memory causes problems, especially in organizing information coming from a variety of sources. Decision-making in traffic is less acute. There is some decline in the ability to estimate the passage of time and to judge the speed of other motor vehicles. The traffic environment may produce too many cues at one time, thus causing confusion or erratic driving behavior.

Yanik has conducted a literature review on the effects of aging (20) and reached the conclusion that the aging process does affect a driver's ability to perceive and process information from road signs. He observes that older drivers need large sign messages with high contrast, that they would be expected to take more time to find signs in cluttered backgrounds, and that they take longer to respond.

It is most difficult to make predictions about driving performance from tests of driver impairment, whether in the laboratory or in the field. The relative importance of this impairment under actual driving conditions will vary enormously depending on driving conditions, which include volume, road geometries, weather, and complexity of the visual field. Signing alternatives that do not produce significant effects in a research study may do so when observed under the higher demands of city driving. Alternatives that produce significant performance differences in the laboratory may not be meaningful in terms of real-world driving, which can be, depending on the situation, a self-paced task. This may explain the difficulty in identifying valid predictors of driving performance.

As mentioned earlier, decrements in cognitive and psychomotor functions may increase the time required by the elderly driver and therefore the distance at which the sign must be legible. Decrements in sensory and visual performance will change the level of visual thresholds and may also increase the time and distance requirements for processing traffic signs.

Effects of Age on MRVD

To determine the effect on visual requirements of increases in required detection and legibility distance, it is necessary to examine the effects of impairment on the perception-reaction time (PRT) component of the MRVD model. Research shows that older drivers spend more time looking at irrelevant stimuli, which suggests that a longer time for the detection component of MRVD may be necessary. Although older drivers do not appear to require more time to read sign messages (2), additional time for recognition may be necessary for specific signs whose message is not clear. Studies of symbol recognition suggest that clear graphic symbols may decrease the recognition-time component of MRVD (21) and reduce recognition distance as well (22).

Decision time is the component of MRVD most likely to show differential age effects. Staplin reviewed several studies that show age-related decrements in tasks associated with higher-order cognitive processing. He concluded that "as decision making becomes more complex and problem solving requires more steps, speed and efficiency are diminished in older adults." Older drivers need more information and take more time to select an appropriate response. Decision time is often site specific: the characteristics of the sign location often increase the level of complexity. This may explain the problems of older drivers at some intersections.

Simple reaction time and brake reaction time increase with age, but the increase is a modest 10 percent, or about 50 msec (18). Olson and Sivak (23) came to the same conclusion based on the PRT data mentioned earlier. A recent study (6) supports this finding, indicating that when tasks are more complex, imposing greater cognitive demand, the older person's reaction time increases by more than 30 percent.

Sign Conspicuity

The issue of sign conspicuity has been addressed by several authors. Cole and Jenkins (24) operationally define a conspicuous object as one that will, for a given background, be seen with certainty (greater than 90 percent probability of detection) within a short observation time (250 msec) regardless of its location in the visual field. Mace et al. (12) have suggested that driver motivation and expectancy should also be considered in any definition of a conspicuous object. This distinction allows for manipulation of conspicuity by changing the driver's "set" so that changes in a sign or its location are not always necessary. Guide signs are more conspicuous to drivers looking for them (i.e., motivated) and Stop signs following a Stop Ahead sign are more conspicuous to everyone (i.e., there is high expectancy). Conspicuity may therefore be aided by multiple or advance signing as well as changes in size, luminance, and placement of signs.

Criterion

To satisfy the need for conspicuity, detection should not be confused with threshold size or brightness. The criterion for the study of visual thresholds is frequently set at 50 percent accuracy, far too low for traffic sign conspicuity. Also, in the experimental paradigm observers usually know what the target is and either when or where it will appear. Threshold luminance for detection under these circumstances is far below that required for traffic sign conspicuity. Less than 0.1 candela (cd)/ft² is required for detection of a 30-in. traffic sign at a distance of 1,740 ft where the visual angle subtended is about 5 arc min. Threshold detection for typical traffic signs is over 3,000 ft (25). Although detectable, signs at this distance are not conspicuous objects.

Visual Complexity of Highway Scenes

The role of visual complexity in the conspicuity of traffic signs has been studied in nighttime scenes by Mace (26, 27) and in the daytime by Jenkins (28). Both studies found scene complexity to be a significant determinant in sign detection. In general, rural scenes may be thought of as low in complexity and urban scenes as high in complexity; however, the reports of both Mace and Jenkins show that scene complexity is not undimensional and that simple measures such as visual clutter are poor predictors of detection performance. Specifically, complex nighttime scenes are those that place high demands on driving (e.g., multiple lanes, other traffic, signals) and in which there is a significant amount of reflective or light sources in the area searched for signs (26). Similar measures are not available for daytime complexity. It is reasonable to hypothesize that visual complexity would have a significant effect on older drivers because they are more likely to be distracted by irrelevant stimuli (2). Evidence that an age effect does not exist when visual search is not required suggests that advance warning and sign placement may be very effective in improving sign conspicuity for older drivers.

Size and Luminance

Data do not exist from which to prepare a set of contrast modulation curves for sign conspicuity. What is known about conspicuity suggests that separate curves would be required for levels of visual complexity, target eccentricity, and driver attention and uncertainty. Cole and Jenkins (24, 29) determined that during daylight, size and visual complexity of the scene are more important determinants of conspicuity than target brightness. Many authors have shown the importance of contrast to sign conspicuity, but the effect of contrast diminishes at high levels of visual complexity (26).

Under real-world driving conditions a shoulder-mounted 30-in. yellow diamond was recognized at distances ranging from 600 ft (14 arc min) to

1,400 ft (6 arc min), depending on its luminance and the visual complexity of the surround (26). Signs measuring 1.5 cd/m² provided detection distances greater than 500 ft for 30-in. signs when visual complexity was low. When visual complexity was high, signs with luminance of 0.3 cd/m² were inadequate to provide 500-ft detection distances.

Other Factors

The alertness of the driver and his degree of knowledge about what he is looking for and where are also primary determinants of conspicuity (12). This hypothesis is supported by others. Roper and Howard found that detection distances for darkly clothed pedestrians averaged 50 percent less when drivers were not alerted (30). A similar difference was observed in PRT by Olson and Sivak (23) when data from a reaction to an unexpected obstacle were compared with reaction to a brake light when there was no uncertainty about what and where the target would be. The effect of alertness and lack of surprise will be larger for targets not on the road, which require peripheral vision to be conspicuous. Eccentricity has not been researched for the unalerted, low-certainty condition. How these variables might interact with age also needs to be studied. Differences in glare sensitivity, restricted peripheral vision, and the process of selective attention may cause higher conspicuity thresholds for older drivers.

The use of color on highway signs has been studied both as an aid in conveying information and as an aid in detection. Although the MUTCD provides that green be used for guidance, red for prohibition, and so on, a study of the ability of the color code to convey information produced generally negative results (31). Studies of color as an aid to conspicuity have been inconclusive. At least two studies (32, 33) have suggested that color has potential as an aid in detection, but Jenkins and Cole (34) provide conflicting data. The discrepancies are likely to be the result of differences in the experimental task, but may also be due to differences in background that would limit the generalizability of color as a useful code. Color is obviously not a requirement for conspicuity, but its role as an aid in detection, particularly for older drivers, needs further study.

Legibility

Legibility has been more heavily researched than any other factor related to signing. The primary variables affecting legibility are letter height, stroke width, letter width, spacing, direction of contrast, amount of contrast or reflectorization, and surround brightness. The principal methods used to improve legibility are increasing sign size (which may be used to increase

letter height) and increasing reflectance (which may be used to change contrast or increase luminance). Changes in stroke width (for nighttime legibility) and modest changes in color saturation or lightness (for daytime legibility) may also be used to the extent allowed by the MUTCD requirements for standardization.

Sivak and Olson (35) and Mace et al. (12) have reviewed much of the research on sign legibility and have drawn attention to the variability in recommended luminance levels. Research on luminance requirements of traffic signs has focused on establishing both minimum and optimum levels for legibility. When a sign is fully reflectorized, the luminance requirements are described in terms of both brightness and contrast of the brightest component (typically the letters) against the background. Signs with only one reflectorized component are measured with respect to luminance of the reflectorized material.

Effects of Aging on Luminance

The validity of high-luminance static visual acuity as the primary vision standard for driver licensing is discussed elsewhere in this volume. Whatever the validity of static acuity for measuring driver safety, recent studies show static acuity to be a poor predictor of nighttime legibility. When older and younger drivers were matched on high-luminance acuity, older drivers were found to perform substantially more poorly than younger drivers (36). This finding was verified by Sivak et al. (37). These authors also found low-luminance static acuity to be uncorrelated with detection distance, leaving unresolved the question of what causes the underperformance of older drivers.

Evans and Ginsburg (38) report studies that demonstrate Snellan acuity to be a poor real-world predictor of vision performance. Research by these authors has shown that an individual's ability to identify a target of one size under one contrast condition does not predict performance with another size of target under a different contrast condition. The hypothesis that contrast sensitivity measurements can be used to predict age-related differences in the legibility of traffic signs was supported. Again, no significant relationship existed between Snellen acuity and discrimination distance.

With regard to the effect of aging on legibility, the following generalizations were noted by Olson et al. (39):

- Older drivers require more contrast between the message and the background of a sign than younger drivers to achieve the same level of performance.
- Legibility losses with age are greater at low levels of background luminance. A reduction in legibility distance of 10 to 20 percent should be assumed when signs are not fully reflectorized.

- Signs are more likely to suffer a loss in legibility for older drivers when luminance is increased beyond the optimum level on a partially reflectorized sign.
- Surround luminance improved the legibility of signs more for older drivers and reduced the negative effects of excessive contrast.

Optimum Luminance

Sivak and Olson (40) provide optimum and replacement values for partially reflectorized signs on dark surrounds on the basis of their literature review. Legibility is generally an inverted U-shaped function similar to those shown in Figure 1. The optimum value is the crest of a curve such as those shown in Figure 1. The problem is that a large number of curves exist for different colors, surround luminance, driver age, and, for fully reflectorized signs, background luminance. The crest forms at different locations and sometimes not at all.

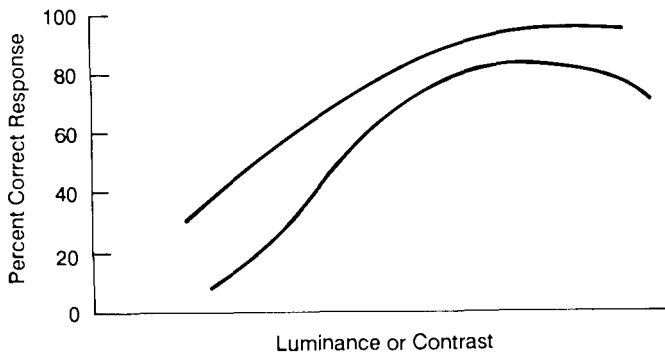


FIGURE 1 Generalized legibility function.

The optimum value of 75 cd/m² provided by Sivak and Olson is the geometric mean of six studies with recommendations ranging from 24 to 343 cd/m². For fully reflectorized signs they recommend a contrast ratio of 12:1. For example, if the luminance of the green background was 5 cd/m², the luminance of the legend should be 60 cd/m². The optimum value is primarily relevant to the goal of increasing sign brightness to enhance conspicuity.

Unless conspicuity is of primary concern, brightness and contrast should be kept below their optimum values to ensure that legibility is not sacrificed. Excessive contrast (or luminance on partially reflectorized signs) is more

likely to degrade legibility for older drivers (39). In the following section on luminance supply, it is shown that available materials are unlikely to reach 75 cd/m². However, several studies suggest lower optimal values for some situations. Highly reflective materials, particularly prismatic button copy, could provide a legibility problem, but they are typically used on fully reflectorized signs where contrast is kept below optimum levels. On dark roads, signs above the optimal luminance are thought to have poor legibility because of irradiation. However, in brightly lit areas, where conspicuity may be a problem, research by Allen (40) indicates that highly reflective signs should not create a legibility problem.

Minimum Luminance

Establishing minimum or replacement luminance standards requires an estimate of driver requirements. Unfortunately, a consensus does not exist with regard to minimum requirements. Forbes and Holmes (41) used a legibility index (distance in feet at which a letter is legible per inch of letter height) to describe the relative legibility of different letter styles (ratio of height to stroke width). Under daytime conditions, Series B, C, and D letters were reported to have indexes of 33, 42.5, and 50. Forbes et al. (42) found Series E letters, which are wider than Series D, to have an index of 55. Over time the value of 50 ft per inch of letter height has become a nominative, though arbitrary and disputed, requirement. The most valid estimate of legibility requirements for traffic signs is the MRVD. Either letter size or legibility index may be manipulated to satisfy this basic distance requirement. Therefore the following relationships should be noted:

Required letter size = MRVD / legibility index

or

Required legibility index = MRVD / letter size

From the standpoint of sign maintenance management, luminance and contrast cannot be expected to compensate for inadequate size. Therefore, it is important that the required size be determined at the time of installation.

The minimum luminance for traffic sign replacement should provide the required legibility index, given a letter size and MRVD. Sivak and Olson (35) provide an estimate of 2.4 cd/m² (0.22 cd/ft²) for the 50th-percentile legibility requirement on the basis of their literature review. This estimate represents ideal conditions and requires adjustment for the effects of age, misalignment, glare, and so forth. However, 2.4 cd/m² is not adequate for conspicuity at high levels of background complexity (26), and it is questionable that it is representative of the needs of older drivers.

At low levels of background luminance, legibility is determined by the luminance of the message alone. As luminance of the background increases, the required amount of contrast between message and background decreases. In general, a contrast range of 4:1 to 15:1 is appropriate for most conditions. Lower contrast is not acceptable, and contrast as high as 50:1 is typically not a problem. Like conspicuity, the luminance requirements for traffic signs vary with the brightness of the surround. Older drivers require more luminance from partially reflective signs and more contrast from fully reflective signs than younger drivers to achieve the same level of performance.

Olson and Bernstein (36) suggest that older drivers should not be expected to achieve a legibility index of 6 m/cm under most nighttime circumstances and that even 4.8 m/cm should be expected only with fully reflectorized signs. The data provided by Olson et al. (39) give some expectation that 4.8 m/cm is a reasonable goal under most conditions. Their data compare young and old drivers on luminance and contrast requirements for different legibility criteria, different colors, background, and surround luminance. A 4.8-m/cm standard can generally be achieved by older drivers with contrast ratios greater than 5:1 (slightly higher for guide signs) and luminance greater than 10 cd/m² for partially reflectorized signs.

CURRENT DESIGN PRACTICE

The standards relative to the visibility of traffic signs are those that determine sign design (including color, shape, legend, stroke width, etc.) as well as sign size and brightness. Size and brightness are the dimensions generally considered in attempts to improve sign visibility because the other dimensions are more strictly controlled by the MUTCD. In practice, size is established by the MUTCD and adjusted in response to level of service and design speed, not MRVD requirements. Because color is the major determinant of daytime internal sign contrast, daytime legibility is primarily manipulated by size. For a specified color, nighttime contrast is determined by the reflectivity of the material chosen.

The federal standards for luminance of retroreflective materials are acceptance standards defined in terms of specific intensity per unit area (SIA) and provide no differentiation based on driver need. Standard FP-85 provides minimum values of SIA for materials made from different manufactured processes, for example, Type II enclosed lens engineering grade and Type III encapsulated high-intensity sheeting.

Requirements are specified for two observation angles (0.2 and 0.5 degree) and two entrance angles (-4 and 30 degrees). The observation angle is that between the light beam going from headlamp to sign and the reflected light beam seen by the driver, in other words, the line of sight. The entrance angle is

that between the light beam striking the sign surface and a perpendicular line coming straight from the surface. The specifications for different observation and entrance angles are necessitated by the decrease in sign reflectivity as these angles increase and the general increase as a vehicle approaches a sign. The specifications attempt to guarantee minimum performance at short distances.

The MUTCD specifies simply that all warning and regulatory signs be reflectorized or illuminated to show the same color and shape by day and night unless specifically excepted in the standards. There are no minimum initial or replacement standards for retroreflective signs. New signs are installed with reflectivity depending on the material chosen. This choice and guidelines for replacement are left to practices that vary between the states and levels of government.

The federal standards suffer from three major inadequacies. First, as noted earlier, they are acceptance standards and do not guarantee that the sign, as used, will meet user requirements when new. The MRVDs of different signs (or the same sign in different locations) are dramatically different and therefore the range of relevant observation and entrance angles is not the same for every sign. Critical detail is different and therefore luminance and contrast requirements differ.

Second, the standards address the issue of accelerated wear as another acceptance test, and do not address the more critical issue of when a sign ceases to perform its intended function.

Finally, the standards apply only to the materials from which signs are made and not to the sign fabrication process or sign placement.

Many signs [approximately 80 percent of those of the Pennsylvania Department of Transportation (PennDot)] are made using a reverse-screen process. The federal standard for red sheeting, for example, does not apply to the performance of Stop signs or any other red sign when the red is silk-screened onto a white sheeting. The luminance of the message may be controlled by the standard for white sheeting, but the contrast of a sign made by the reverse-screen process is not determined by the federal standards.

PennDOT has established standards for their reverse-screen colors that are generally lower than the federal standards for the same colors of the same material. The contrast ratio for signs with a reverse-screen process is higher than that for cutout letters on a colored sheeting. Adding to the confusion is the existence of some state standards. PennDOT's standard for federal Type II material is about 30 percent higher for white; the same is true for other colors. Differences among the standards for various colors and other materials are not so predictable. Some values are higher in Standard FP-85; others are higher in PennDOT standards. Some differ only at some observation or entrance angles.

Table 1 compares contrast ratios available using FP-85 standards and those provided by PennDOT standards for three types of retroreflective material.

TABLE 1 CONTRAST RATIOS OF FULLY REFLECTORIZED SIGNS

	White on Red	White on Green	White on Blue
FP-85 Standards			
Type II	5	8	17
Type IIa	5	5	14
Type IIIa	6	6	13
PennDOT Standards			
Type II	11 ^a	10	NA
Type IIa	5 ^a	5	16 ^a
Type III	8 ^a	6	12

^aReverse-screen standard.

The most notable differences are that PennDOT standards achieve higher contrast ratios with Type II sheeting (because of their higher specification for the reflectivity of white), and a higher contrast ratio for white-on-red Type III sheeting (because the reflectance of a reverse-screen red is about 70 percent that of red sheeting).

IMPLEMENTATION OF CONSPICUITY AND LEGIBILITY REQUIREMENTS

To provide a basis for substantive improvements in sign design and replacement strategies, problems found in current design practice will be examined. As mentioned earlier, the comparison of supply and demand provides a convenient paradigm for conducting this analysis. The problems created by inadequate supply of luminance may be rectified by increasing luminance or contrast or by decreasing the demand for luminance, that is, increasing sign size or reducing MRVD. If the information needs of older drivers are to be addressed, both techniques must be openly considered.

Optimum and Replacement Luminance

Recommendations for sign standards should not make it necessary to have complex sign inventories. It is reasonable to require several sign sizes and to stock signs of different materials. However, it is not reasonable to stock different materials made into all the possible sizes of the same sign. Management decisions made to simplify inventory should err on the side of safety and provide more size and reflectance than may be needed.

As mentioned earlier, care should be taken to install signs of adequate size so that daytime performance is maintained and luminance requirements are

kept realistic. If signs are to provide adequate visibility for older drivers, the size of Series D and E letters should be based on an assumed legibility of 40 ft/in. (4.8 m/cm) of letter height and not 50 ft/in. (6.0 m/cm) (36, 39). For example, if the MRVD is 600 ft, the minimum letter size should be 15 in., not 12 in. At distances of 300 ft, 8-in. letters should be used in place of 6-in. letters to accommodate older drivers.

With regard to legibility of fully reflectorized signs, any of the materials reviewed earlier provide adequate contrast when new, assuming a criterion of 40 ft/in. of letter height. Materials should be chosen on the basis of cost, durability, and need for conspicuity. Sign maintenance practice should provide more frequent inspection of signs with 5:1 ratios to be certain that they do not deteriorate to unacceptable contrast levels.

Determining which materials provide adequate luminance for legibility on partially reflectorized signs is more difficult. For a given required luminance, the required retroreflectance varies with sign distance and placement. Sivak and Olson provide a table that can be used to determine the retroreflectance needed to provide a specified luminance at 600 ft for right, left, and overhead placement. Table 2 gives the estimated coefficients of retroreflection (also referred to as SIA) for Sivak and Olson's suggested optimum luminance (75 cd/m²) their 50th-percentile requirement (2.4 cd/m²) as well as the author's more conservative estimate of 10 cd/m². To allow for a 25 percent deterioration factor, new signs should have at least 33 percent more reflectance than the minimum values indicated.

TABLE 2 COEFFICIENTS OF RETROREFLECTION
USING U.S. TYPE LOW-BEAM HEADLAMPS

Sign Placement	Luminance (cd/m ²)		
	2.4	10.0	75
Left shoulder	90 ^a	360	2,806
Overhead	114 ^a	460	3,547
Right shoulder	24 ^a	100 ^a	736

NOTE: 1 cd = 10.76 lx.

^aMay be satisfied by reflective sheeting.

Table 2, applicable to signs requiring 40 ft/in. of legibility at distances of 600 ft (e.g., guide signs), suggests that only the requirements of the 50th-percentile (2.4 cd/m²) right-shoulder signs can be satisfied by retroreflective sheeting. The data in Table 2 imply that to be legible by older drivers all other signs requiring a minimal luminance of 10 cd/m² and a legibility distance of 600 ft should have button copy or should be fully reflectorized.

Most regulatory and warning signs do not require a 600-ft legibility distance and many do not require 40 ft/in. of legibility. It is quite possible that

retroreflective sheeting can meet the requirements of older drivers in many situations. Relevant data should be forthcoming from a current FHWA study. Mace (12) found that the 2.4-cd/m² estimate corresponded very well with the subjective evaluation of signs requiring replacement by those experienced in traffic signing, but whether these meet the needs of older drivers must still be determined.

One reason why many of these signs may function well with retroreflective sheeting is that the critical detail of signs with symbols (or those whose shape conveys adequate information) subtends an excess of visual angle so that they do not require 40 ft/in. of legibility. These same signs often have simple messages with short PRTs, which reduces the MRVD.

A short MRVD, however, does not necessarily produce a more legible sign. As a vehicle approaches a sign the luminance increases because more illumination from each headlamp reaches the sign (i.e., the inverse-square law); however, as the entrance angle widens, luminance decreases because of the performance of the retroreflective sheeting and headlamp aiming. The result is that sign brightness typically peaks at a distance greater than 300 ft. This will vary with headlamp variations, sheeting material, and sign placement.

Although the minimum luminance requirements of warning, regulatory, and other traffic control devices can often be met by retroreflective sheeting, a simple set of minimum standards has not been defined. Some general guidelines can be made. The No Passing Zone pennant and any other left-mounted sign should be constructed with Type III high-intensity sheeting. Overhead regulatory signs should probably be either Type IIa or Type III sheeting; overhead warning signs should be Type III. Roadside yellow diamond signs should generally be Type IIa or Type III to guarantee conspicuity because they are unexpected. These requirements may be relaxed at low operating speeds or in areas with low visual complexity.

Trade-offs Between Legibility and Conspicuity

One way of increasing conspicuity is to use materials of higher reflectivity. The limitations to this approach are the higher material cost and the reduction in legibility from irradiation. Increasing luminance increases legibility up to a point, after which overglow or irradiation begins to degrade it. The loss of legibility is difficult to document. Allen (40) reports the loss to be quite small and to occur only at very high levels of luminance. Others have shown irradiation to be more of a problem, particularly for older drivers (39). When contrast is maintained within reasonable levels, irradiation should not be a problem; therefore, the luminance of fully reflectorized signs may be increased to aid conspicuity without sacrificing legibility. On partially reflectorized signs at high levels of luminance, the stroke width of white letters on

black backgrounds should be decreased and the stroke width of black letters should be increased to offset the effects of irradiation (39).

The luminance requirements for legibility and those for conspicuity are not always in agreement. A verbal sign may require more luminance for its legibility than for its conspicuity, because it requires a long MRVD. However, a symbol sign may require more luminance for its conspicuity because it subtends a larger visual angle than is necessary for legibility at the distance required. The 18-in. hazard marker with its 2.5-sec PRT is an example of a traffic control device whose luminance requirement should be responsive to the need for conspicuity.

Reduction of MRVD

Although attention should be given to providing adequate legibility at a distance through increased size and luminance of signs, other factors militate against using long MRVDs. Road design and geometry often reduce the visibility distance, so the sign must be very conspicuous and recognizable with a short MRVD. Also, long distances give older drivers the opportunity to become distracted and forget what action they are to take.

The use of multiple signs may reduce the MRVD requirement as well as the luminance threshold for conspicuity. Some signs and signing situations require that information be divided among two or more signs in order to reduce the time required for either recognition or decision making. Advanced directional signing facilitates an early decision concerning the exit a driver wants and its approximate location. The decision component, and therefore PRT, of subsequent signs is therefore shorter. Multiple signs have the added advantage of creating driver expectancies, which improve sign conspicuity.

Reducing the MRVD requirement may also be accomplished by redesigning a sign to make better use of symbols. Additional research relevant to symbols versus words and their relative effects on older drivers will be needed. Several studies suggest that the use of symbols may require more time by older drivers not familiar with them. Lindholm et al. (18) report that pattern goodness and spatial frequency interact with age to make generalization difficult. It may be that symbols reduce the MRVD for younger drivers and increase it for older drivers. Redundant symbol and word coding might be the best solution. This research is difficult to accomplish because the results of one sign message or symbol are not generalizable to others and individual differences are large.

Other Methods

As already mentioned, the easiest way to lower the perceptual threshold for conspicuity is to use advance warning signs. The brightness threshold for

conspicuity is much less for drivers who know what to look for or where to look, or both. Although advance warning is useful, perhaps essential in some situations, multiple signing must not be allowed to create excess clutter.

The perceptual threshold for conspicuity may also be reduced by attention to sign placement. Although placement of signs in visually complex scenes cannot be avoided, sign placement has been mentioned as a factor that determines conspicuity. Attention should be given to the possibility of standardizing sign locations so that they are more readily seen. To some extent this is already being done on divided highways. The consistent use of advance guide signs and exit signing creates expectancies that should improve conspicuity. The use of a single sign to organize multiple service advertisements is a further step in this direction.

Lindholm et al. (18) suggest that standards for sign spacing and placement be based on information-processing speed and short-term memory capacity. They point out that the location of signs must give older drivers enough time to process the information and respond, but also that the information should not be presented so early that older drivers forget what they are to do. Another conclusion by Lindholm et al., which is consistent with our thesis that signs vary, is that driver requirements differ with the format and message of the sign and that optimal placement of a sign "may be both situation and sign specific." They conclude that "sign spacing and placement should be optimized with respect to the elderly driver's capacities."

Within the color coordinate values for signs there is room for variation that could be used to improve daytime contrast. Increasing saturation and decreasing lightness for a given hue will increase luminance and may result in more visible colors. The effect this has on nighttime luminance and color depends on the manufacturing process.

It is important to realize that many sign deficiencies are not the result of insufficient size, luminance, or contrast. Signs may be missing, bent, fallen, vandalized, and so on, and these problems can only be addressed by a formal system of review and inspection. It is not sufficient to simply erect adequate signs and forget about them. Better sign maintenance is essential to maintain safety for all drivers.

IMPLEMENTATION ISSUES

If the requirements of older drivers for sign legibility and conspicuity are to be met, change is required in a number of areas, including public policy, financing, and research.

Public Policy

The most serious public policy issues related to highway signing are licensing and definition of the design driver. Signing practice should be adequate to

meet the needs of those licensed to drive. Although the needs of older drivers are addressed here, age is not the real issue. It is the need for a clear definition of the minimum skill and ability required to drive and of when this is impaired by reduced perceptual and cognitive skills. To determine impairment, a valid and efficient test must be developed to screen drivers and discriminate among safety-related driving behaviors. Such a test is not available now, and decisions must be made using the tests available.

Age is not an efficient predictor of driving performance. To avoid age discrimination, the cutoff level must be set too high to be effective. Aging is a gradual process. Impairments do not occur at once or at the same rate in different individuals; thus, signing should focus on impaired drivers and not a specific age group.

The practices of various states with regard to vision testing are discussed by Schieber and by Bailey and Sheedy elsewhere in this volume. The typical practice is to license drivers with 20/40 high-luminance acuity, which is roughly equivalent to 30 ft/in. of sign letter height. Given that many states do not retest, it is safe to assume that there are many drivers who are limited to reading signs at distances less than that.

There are alternatives to upgrading signs and revoking licenses. One is to restrict the time or location (or both) of driving for the impaired driver. Drivers could be given restricted licenses to discourage driving at night or on roads with poor signing and high volume. Another alternative that does not require testing and might be politically more acceptable is to post warnings on roads with insufficient signing.

In the final analysis the safety of all drivers can best be served by a combination of policies. Signing should be upgraded to meet the needs of as many drivers as possible. Licensing and other restrictions should be explored to deal with problems that signing cannot resolve.

Improved signing for older drivers would affect other drivers as well. Because the signing would be intended to compensate for impairment, all impaired drivers (including those temporarily impaired from the use of alcohol or drugs) would derive an immediate benefit. To the extent that safety is promoted, everyone shares in an indirect benefit from the improvements.

Solutions that require additional signing run the risk of conflicting with those concerned with the environment. Certainly a more cluttered highway is not desirable from the standpoint of beautification, cost, or information load on the driver. It is therefore important to attempt a comprehensive set of improvements. Such a program should result in the elimination of unnecessary signs and the grouping of other signs as well as the creation of some redundant and multiple signing. The concern should be the net effect of any sign improvement program on both safety and the environment.

The judicious use of placement and size may make more signs as attractive as fewer large signs. The collection of multiple service notices on single signs

near Interstate exits enhances the appearance of the highway while continuing to serve the interests of motorists and merchants.

Cost Considerations

Several of the signing improvements mentioned in this paper would raise the cost of signing.

First, increasing sign size to maintain the legibility index at 40 ft/in. will increase sign costs because larger sign areas would often be required. Many signs, particularly those that use symbols, arrows, shapes, and so on, are of adequate size in current practice and would not need to be increased. However, it must be understood that increasing letter size by as little as a third may result in a 60 to 80 percent increase in the area of the sign needed to accommodate the larger letters.

Second, upgrading sign materials to provide greater reflectivity would increase costs. High-performance Type III sheeting costs about three times more than Type II sheeting. When the fixed costs of substrate, fabrication, hardware, transportation, and labor are considered, the cost ratio of Type III to Type II sheeting is about 1.5:1. When durability is considered in the comparison of life-cycle costs, Type III sheeting has been shown to be less expensive. Given the variability in durability reported by different states, life-cycle cost comparisons may have limited generalizability.

The third source of cost increase is the additional signing to achieve redundancy and advance warning. It must be remembered that this practice enables the use of smaller signs and also that a relatively small number of signs would be affected. After a careful analysis of signing requirements and placement, some signs will be found unnecessary and may be removed, offsetting to some extent the cost of additional signing.

The greatest expense in meeting the requirements of older drivers may be in sign maintenance. Inspection, washing, remounting, and replacement need to be given higher priority. Raising the priority of these activities will significantly raise the cost beyond the modest maintenance budgets normally allocated. Even if accident costs are unaffected by sign upgrades, the solution is likely to be cost-effective because of the reduction of tort liability awards.

The issue of tort liability needs to be explored and new legislation may be needed. It is hoped that the legal system could be used to encourage better signing and sign maintenance management. Administrators should be allowed to begin the process of upgrading signing without having to admit that the present system is unsafe and the consequential increase in liability. Agencies that do not have an effective sign maintenance management program should be more at risk than those that do.

Research Needs

It should be recognized that as the population ages, the problems of impaired drivers will intensify. This means that a long-term commitment is needed, not just a quick short-term response.

Research is needed to determine valid methods for measuring which visual, cognitive, and psychomotor impairments are associated with unsafe driving. Once the measurement methods have been developed, attention can be given to determining criteria for licensing.

Because factors that have no effect on younger drivers may have an effect on older drivers, research undertaken with young drivers as subjects should be reexamined with regard to the interactive effects of age.

The effect of signing methods needs to be tested on groups with different visual and cognitive functions and not on groups that differ in the amount they drive or when they drive. The results of such studies can then be projected to a highway system with any mix of driver characteristics, and generalizability to future driving patterns will be more direct.

Research is needed to derive an equivalent legibility index for specific symbols. Although much is known about the dimensions of symbols that improve recognition and discrimination, a firm understanding is needed of the visibility of the symbols currently in use. How does the recognition distance of any symbol compare with the legibility of an equivalent-size Series E letter?

As new manufacturing processes become available it may be possible to build signs with a border made of very high-intensity, narrow-angle sheeting intended for conspicuity and the sign background and message composed of wide-angle materials directed at legibility requirements. Research will be needed to test the effectiveness of this approach.

Research should be directed at the manipulation of color saturation and lightness to aid daytime visibility.

The MRVD model needs improvement and validation. The goal should be to make this model available to management so that they can use it to determine the distances at which signs in their inventory should be recognized.

Further research is needed on conspicuity. This research is difficult because of the effect of driver alertness on performance. What has been done should be redone with age as a factor. Critical variables to be studied include color, shape, contrast, visual complexity, driver expectancy, and eccentricity. The work must be repeated under daytime and nighttime conditions. The underlying dimensions of daytime visual complexity also need to be defined and the interaction of visual complexity with age should be explored.

A research program should begin that is directed at identifying those signing situations most in need of remediation. A special emphasis should be

given to situations requiring short PRTs because of limited sight distances. Alternative solutions, including the use of symbols, placement, and multiple signing, should be explored. These solutions should be compared with regard to the reduction of PRT and then weighed against the alternative of providing greater visibility to satisfy the longer PRT.

CONCLUSIONS AND RECOMMENDATIONS

There appears to be a consensus in the literature that although basic visibility requirements must be met by providing signs of necessary size and luminance, the sign-related problems of older drivers require the highway community to do more than erect bigger and brighter signs. Improvements in sign management, multiple signing, placement, and other new approaches are critical.

The effects of age on visual processes suggest that signs should be installed with sufficient size to require no more than 40 ft/in. of legibility. Signs should be inspected to ensure that the physical condition of the sign and the mounting is maintained and that required contrast is retained. Sheeting of higher reflectivity should be used to achieve adequate conspicuity for critical purposes and where sign placement reduces luminance because of high observation and entrance angles.

The effects of age on information-processing time and short-term memory suggest that an effort be made to reduce the MRVD and specifically the PRT required for certain signing situations. This can be done through the use of symbols, color and shape codes, multiple signing, and placement.

The focus of most signing research has been on legibility and to some extent conspicuity. Although this research has been valuable, it should not be overlooked that such research is relatively easy to do. Research aimed at finding ways of reducing the MRVD through placement, multiple signing, and symbol messages is far more difficult to conduct and places more demands on the creativity of the research staff.

Standards and specifications should be reviewed to eliminate unjustifiable restrictions that may interfere with valid performance improvements. One example is the requirement of wide entrance angle performance for traffic control devices that must function only at narrow entrance angles. Another example is the need to reevaluate color coordinate values for highway signs to improve visibility.

Leadership is needed to ensure that the needed research is conducted, and the procurement process should be evaluated. The use of college students as subjects lowers costs and makes for more competitive bidding, but the answers needed to improve the safety of older people are not obtained. Changes should be made that would favor research plans including adequate testing of the effects on older drivers of any signing or other highway improvement.

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Vision Screening for Driver Licensure

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In the past 40 years the percentage of drivers who are 60 or older has increased from 5 to 15 percent (1). Improvements in medical technology and health care delivery along with the aging of the post-World War II Baby Boom population will certainly cause this percentage to increase in the coming years. Those over 75 make up our nation's fastest-growing age group; their numbers are expected to double by the end of this century.

The elderly driver has more traffic safety difficulties than the younger driver. Staplin et al. (2) report that those 65 and older represent 12 percent of the population and have 13 percent of the accidents. At first glance this does not seem to be a disproportionate accident rate. However, as a group the elderly drive fewer miles, and many do not drive at all. When expressed in terms of accidents per miles driven, the accident rate of the elderly is the highest of any age group except teenagers. Burg (3, 4) showed that there is a slight increase in accident rate beginning at age 55, but when the increase at age 55 is expressed in terms of accidents per miles driven, it becomes striking. Koltnow (5) found that although U.S. traffic fatalities dropped 14 percent between 1980 and 1982, there was no decrease for drivers over 65 and women over 65 experienced a 14 percent increase. Koltnow also points out that the elderly are more physically vulnerable and are more likely to be killed or injured in a crash that would not cause such serious injury to a younger individual.

Although there are many aspects of human performance that are related to driving ability, vision is the primary sensory input on which the driver

depends. It is commonly estimated that 90 percent of the input that a driver receives is visual. A decrease in visual skills with age could be an important causal or contributory factor in the driving difficulties experienced by the older driver.

Several authors (2, 6–10) have reviewed the visual characteristics of the elderly, and it is clear that nearly every aspect of visual performance decreases in old age.

The crystalline lens within the eye shows functionally significant changes with age. It progressively and predictably loses its elasticity, causing a decrease in the ability of the eye to accommodate, or change focus. This loss begins to impair performance of common near-point tasks around the age of 40; typically, compensation must be obtained through reading glasses or bifocals. The loss of accommodation is complete by the age of 60 to 65. The lens also loses its transparency and becomes yellowish with age. This contributes to changes in color vision, decreased light sensitivity, and decreased visual acuity. It also increases light scatter within the eye, resulting in increased susceptibility to disability glare such as that created by oncoming headlights. Cataracts, opacities that develop in the lens of the eye, are usually age related. They obstruct and scatter light and should be removed when the reduction in vision begins to impair performance of normal tasks. After a cataract extraction, the optical power of the lens must be replaced by means of strong spectacles, contact lenses, or intraocular lens implants.

The pupil of the eye becomes smaller with age and loses its ability to dilate in dim light. Consequently, the elderly eye admits less light. This relative deficit is most pronounced in darker conditions. The area of the typical 20-year-old pupil is 12 times larger than that of an 80-year-old pupil (11); thus the illumination on the older retina is only 8 percent as intense as that on a younger retina.

Many disorders of the retina are associated with age. Degeneration of the macular or central retina is more common in the elderly and is referred to as age-related maculopathy (ARM). Central vision is affected by impairments in visual acuity and night vision. Retinal detachments are more common in older eyes and result in the loss of portions of the visual field. Peripheral retinal degenerations are common in the elderly and may cause loss of peripheral vision. Other progressive conditions producing visual degradation include retinitis pigmentosa, degenerative myopia, diabetic retinopathy, hypertensive retinopathy, arteriosclerotic retinopathies, and glaucoma.

Most tests of visual function and performance show functional decreases in visual capabilities with age. In the absence of disease, corrected visual acuity remains relatively constant from ages 20 to 50. After 50, corrected acuity begins to decrease, with a rapid decline after 60 (12). The critical flicker frequency (CFF), the flicker rate beyond which flickering of light cannot be

detected; dynamic visual acuity; and color discrimination show age-related declines (9). Studies of dark adaptation (13) show that the elderly have reduced sensitivity to light. Visual field has also been shown to exhibit age-related losses.

Higher-level functions showing age-related decline have recently been reviewed (2). There is evidence of diminished cognitive capabilities, visual spatial judgments, and visually based motor responses. The elderly find it more difficult to give selective attention, especially within a complex array of information. Visual spatial and organization skills show deficits with age. The elderly tend to show deficiency in recalling recently acquired information even though they tend to be proficient at remembering more remote events. Complex problem-solving abilities tend to diminish with age. The elderly may have difficulty in ignoring redundant or superfluous information. All of these higher-level skills are used in driving.

Staplin also presents data from the American Automobile Association that show a 4 percent increase in reaction time for every decade of adult life. Thus, a 70-year-old driver takes 20 percent longer to react than a 20-year-old driver.

The decreasing visual abilities of the elderly may be a significant contributing factor to the decreasing driving ability associated with age. The purpose of this paper is to examine whether current vision standards and screening procedures for drivers are appropriate for identifying those with significant visual disabilities that are unsafe for driving.

CURRENT STATE OF THE ART

Visual Acuity and Visual Field

The primary vision screening test in the 50 states is static visual acuity. The National Highway Traffic Safety Administration (NHTSA) surveyed state visual acuity standards for driving (14). For the best corrected vision and with both eyes open, standards range from 20/30 to 20/60; 41 states use the 20/40 standard (15). Some states have lower acuity standards if the applicant is wearing optical correction or higher standards if there is blindness in one eye.

Many states have a visual field requirement [27 states according to Keltner and Johnson (15) and 17 according to NHTSA (14)]. The requirements always relate to a measurement of the extent of the horizontal meridian of the visual field, and the required minimum field size ranges from 70 to 140 degrees.

Several states impose stricter visual acuity or visual field standards, or both, for bus or truck driver's licenses. Ten states do not allow individuals with one blind eye to obtain such licenses. A few states also specifically do not allow individuals with bioptic telescope systems to obtain such special class licenses.

Keltner and Johnson (15) report that 41 states require visual testing for license renewal.

Visual acuity standards used in other countries are generally similar to the U.S. standards, but the between-country variations are greater than the between-state variations within the United States (16). Some countries use a license plate reading task as the principal visual criterion, following a practice that originated in Great Britain. An acuity level of about 20/33 is required to perform this task. Most countries have a visual field requirement, and many test color vision and some aspects of binocularity.

The American Optometric Association (AOA) and the American Association of Motor Vehicle Administrators (AAMVA), in a joint 1974 publication (17), recommended that a visual acuity of 20/40 be required, either with or without optical correction. They recommended that drivers with two functioning eyes be required to have a binocular visual field at least 150 degrees wide in the horizontal meridian and that drivers with one eye have a visual acuity of at least 20/30 and a visual field of 40 degrees nasally to 75 degrees temporally in the horizontal meridian. Color vision testing was recommended for professional or commercial drivers but not for drivers of private or personal vehicles.

The U.S. Department of Transportation (DOT), NHTSA, and AAMVA also offered in a joint publication (18) recommendations for vision standards and testing for drivers. They established six categories of visual acuity, three levels of binocular visual field, two levels of monocular visual field, two levels of ocular motility, and two levels of color discrimination. They recommended that eligibility for license type (passenger, commercial, etc.), the need for periodic reevaluation, and various constraints or restrictions depend on the level of visual ability in each of the specified visual function categories.

The AOA in 1965 adopted a policy that favored stipulating a desired standard of 20/20 or better in each eye, normal binocular vision, no field restriction, no muscular anomalies, and no color vision deficiency. However, their recommended minimum visual standards were 20/40 or better in at least one eye, no double vision, and an intact field of vision of at least 70 degrees to one side and 45 degrees to the other. A driver unable to meet these minimum requirements should not be licensed without a thorough evaluation of his driving skills.

Sign Design

A rational connection may be made between visual acuity and driving performance, because the identification of detail is necessary for making many driving decisions. One visual task that is common and quantifiable is the recognition or reading of signs. Forbes (20) reviewed sign design, and Gordon et al. (1) cite common sign design standards. A current design rule is that 1 in. of letter height be provided for every 50 ft of recognition distance. This

translates to a visual acuity requirement of 20/23. At least 13 percent of the current driving population (who are principally screened for 20/40 vision) will not have the 20/23 vision for which the signs are designed (21).

Older drivers are more likely to have visual acuity less than 20/23, and furthermore, as a group, they have slower reaction times. Halpern (22) presents evidence that the elderly take relatively more time to process signs with symbols than with alphanumerics, suggesting that it may be preferable to use signs with verbal messages for the elderly.

Sign design standards are intended to ensure that displayed information is received in time to allow drivers to make the appropriate response safely. They are based on assumptions involving factors such as expected travel speed, processing time, and reaction time. A significant proportion (about one-sixth) of the driving population has a visual acuity that diminishes this safety margin, and the elderly are disproportionately represented within this group.

Other Visual Measurements

Static visual acuity is the only visual ability specified as a prerequisite for driving by all U.S. states and Western countries, and in all authoritative recommendations. There is strong, but not unanimous, preference for an acuity requirement of 20/40 among the 50 states. Beyond the visual acuity requirement, the various states show a considerable range of differences in their requirements relating to optical correction, visual field, monocularly, color vision, depth perception, diplopia, and the use of bioptic telescope systems and in the provisions for special license categories and for relicensure. As summarized in the NHTSA report (14), seven states have a color vision requirement, three states have a depth perception requirement, one measures eye coordination for lateral and vertical imbalance, and apparently none uses dynamic visual acuity.

RELATIONSHIP OF VISION AND DRIVING PERFORMANCE

The most comprehensive study of the relationship between vision and driving performance was conducted by Burg on over 17,500 California drivers during a 3-year period (3, 4, 23). The age and sex of drivers and annual number of miles driven were recorded. Visual attributes measured on each subject included static visual acuity, horizontal heterophoria, low-light recognition threshold, glare recovery, horizontal visual field, and dynamic visual acuity. The visual data were analyzed in relation to traffic convictions, all reported accidents, accidents recorded by the Department of Motor Vehicles (DMV), accidents excluding those caused by obvious nonvisual factors, daytime

accidents, and nighttime accidents. The significant correlations found between vision and the driving performance metrics were very weak.

A later analysis of the Burg data (24) drew some interesting conclusions. No meaningful relationships were found between the accident rates and any of the visual test results for persons under the age of 54. For those over 54, however, both dynamic and static visual acuity showed relationships to accident rates, even though the correlation coefficients were quite small. The horizontal extent of the visual field was not found to be related to accident rates. No significant relationship was found between driving and low-light recognition threshold or glare recovery for any age group, although the glare recovery test was judged to have a marginally significant relationship with driving performance for those over 54.

Following their review of the prior literature and the analysis of the Burg data, Henderson and Burg (25) assigned weights to various aspects of driving behaviors and also to each visual function according to its judged importance to each behavior. Their overall weightings suggested that the visual attributes most important in driving are, in ascending order, detection of angular movement, detection of movement in depth, the extent of the useful visual field, static visual acuity, saccadic fixation, and dynamic visual acuity.

Hofstetter (26) correlated visual acuity test scores with self-reported accidents of 13,786 drivers. Accident rates for persons with acuity in the lower quartile of the measurements were compared with those for persons with acuity above the median. Drivers in the poorer visual acuity group were twice as likely to have had three accidents in the previous 12 months and 50 percent more likely to have had two accidents. The two visual acuity groups showed no significant differences in their likelihood of having had one accident. These trends persisted across ages. By using records of multiple accidents to identify the accident-prone, Hofstetter has provided the strongest evidence yet available to show a connection between poorer visual acuity and increased propensity for accidents.

Shinar (27) also reviewed the literature on the relationship of vision to driving performance. He used an instrument called the Mark II Vision Tester, which was an expanded version of the testing equipment developed by Burg and his coworkers. It measured the following parameters: static visual acuity under standard photopic conditions; dynamic visual acuity; detection-acquisition-interpretation skills; static visual acuity under low-light levels; detection thresholds for movement in depth, angular movement centrally, and angular movement peripherally; the horizontal extent of the visual field; and static visual acuity with glare. This test battery was administered to 890 licensed drivers, and for each driver the accident history was recorded. Static visual acuity under low illumination and dynamic visual acuity were the two attributes most consistently related to accidents. Poor static visual acuity under

low illumination conditions was particularly related to involvement in night-time accidents. Detection of central angular movement was third in the strength of relationship to accident involvement. Correlation coefficients were calculated separately for daytime and nighttime accidents and also for the different age groupings for each of the nine categories of visual performance. All of the attributes tested were found to be significantly correlated with accident rates in at least one of the subtests, and none of the vision tests correlated in all of the subtests.

Hills (28) suggested that the poor correlations found between vision measurements and driver accident rates could be attributed to many factors, including compensatory behavior by drivers. He presents the view that higher-level perceptual errors or misjudgments as related to factors such as inattentiveness, overconfidence, and fatigue are the major cause of accidents.

Davison (29) studied vision in relation to the reported accident records of 1,000 randomly stopped British drivers. Reported accident rates were found to have significant correlations with monocular visual acuity, binocular acuity, and hyperphoria. The number of miles driven was not reported; thus the more meaningful measurement of accident rate was not available. Visual acuity was more strongly associated with accident rates for drivers 55 and over, and the association was stronger for the right-eye visual acuity than for the left. A study of U.S. drivers (30) showed that the left-eye visual acuity was more strongly associated with accident rates. This suggests that the visual acuity of the roadside eye is most important. However, it is difficult to provide a convincing rational explanation for this proposition. The roadside roof-support pillar does obstruct vision, with the obstructed regions being different for the right and left eyes. Consequently, within the field of the front windshield, there is a region (often about 5 degrees wide and located about 25 to 35 degrees off center) that can only be seen by the nonroadside eye. A similar small region within the side window and just behind the roof-support pillar is only visible to the roadside eye. If poor visual acuity in the roadside eye does indeed create a significant hazard, then it might suggest that discernment of detail within the region near the roof-support pillar is of high importance. A more likely explanation is that profound losses of vision in the roadside eye may effectively reduce the roadside visual field for object detection, in which case the association should be thought of as resulting from a functional field deficit rather than from a simple difference in resolution between the roadside eye and the other eye.

Standard visual acuity measurements are made with high-contrast targets. Studies by vision scientists and clinicians indicate that such high-contrast visual acuity scores are not highly reliable predictors of the sensitivity to lower-contrast targets (31). Contrast sensitivity may be measured by a number of means, some of which involve the detection of striped patterns of various

contrasts and spacings presented on either video or printed displays, whereas other tests require the reading of low-contrast visual acuity charts. A *prima facie* case can be made that many of the detection and recognition tasks associated with driving are strongly dependent on the ability to discriminate small contrast differences in larger objects or features. Contrast sensitivity is arguably more important than high-contrast visual acuity for tasks such as detecting pedestrians and other vehicles, seeing the edges of the roadway, and recognizing undulations or irregularity in the road surface and many other features. It is known that contrast sensitivity decreases with age (32), but there is no direct evidence associating reduced contrast sensitivity with traffic accidents.

Burg (3, 4, 23) found dynamic visual acuity to be more strongly related to accident rates than static visual acuity. Dynamic visual acuity involves the discrimination or recognition of detail on a moving target and might be expected to be more relevant to the driving task than the identification of detail on a stationary target as measured in static visual acuity tests. Dynamic visual acuity is also known to decrease with age (10).

Because identification of objects within the peripheral visual field is a necessary task for a driver, it might be expected that deficits in peripheral vision would correlate with driving performance. However, the majority of the published studies show no such correlation (33). Most of these studies involved nonstandard perimetric techniques and inadequate controls over the subjects' fixation; furthermore, only the extent of the horizontal meridian of the visual field was considered. A notable exception is a study by Johnson and Keltner (34), who used an automatic visual field screener (Field Master model 10-PR) to gather data on 10,000 volunteer subjects (20,000 eyes). Drivers with binocular visual field loss had accident and traffic violation rates that were twice as high as those for drivers with normal visual fields. Drivers who only had monocular visual field loss showed driving records similar to those considered normal. Their screening procedure presented 78 stimuli located at sites between 5 and 60 degrees within the visual field, and their testing was performed on each eye separately. The incidence of visual field loss was 3.3 percent, in general agreement with the 1 to 8 percent found in other studies (33). More than half of the subjects with visual field losses had been unaware of their deficits. Johnson and Keltner (34) reported that the average testing time per eye was under 2 min, including setup time.

Visual field reductions can be caused by age-related decreases in retinal illumination and perhaps some contribution from a reduction in retinal sensitivity. Visual disorders such as glaucoma, degenerative myopia, diabetic retinopathy, and retinal detachment may affect the visual field and are more prevalent in older persons.

Individuals with one functional eye have a restricted visual field. In normal binocular vision, the horizontal visual field is between 170 and 200 degrees

wide, whereas the monocular horizontal visual field is only 130 to 160 degrees wide. The more important field constraints imposed by monocular vision are the limitations of the visual field to about 50 degrees (instead of 90 degrees) on the side of the blind eye and the enlargement of the regions obscured by roof pillars, dangling ornaments, and other hardware features of the vehicle. In binocular vision each eye compensates for the physiological blind spot of the other, whereas the monocular driver experiences a true loss.

In a group of drivers with high accident rates Keeney (35) found that 8 percent were monocular. Surveys of patients from private optometric practices found only a 2 percent incidence of one-eyed individuals. Liesmaa (36) considered a group of drivers who had been observed showing dangerous driving behaviors as judged by observers from a patrol car. A control group of apparently good drivers was similarly selected. The incidence of monocular vision was three times higher in the group driving dangerously than in the control group. In addition to the visual field restriction, monocular drivers also suffer from a loss of stereopsis or binocular depth perception. Keeney and Garvey (37) recommend that monocular individuals not be licensed for professional or commercial driving. Both the Keeney and the Liesmaa studies have substantial design or reporting limitations, or both.

Less light falls on the retina in the older eye because of the smaller pupil and the decrease in transparency of the ocular medium. Consequently, there is a decrease in relative light sensitivity with age. Although night driving is essentially a mesopic task, age-dependent differences in night driving performance must be expected on the basis of studies of the dark adaptation process. For detection tests on the dark-adapted eye, 10 times the light is needed by a 60-year-old compared with a 20-year-old (13). MacFarland's data indicate that between the seventh and ninth decades there is a further 10-fold decrease in the absolute threshold for the dark-adapted eye.

Kline (10) reported that older drivers believe that low illumination causes functional difficulties. Older drivers are more likely to judge their dashboard instruments inadequately illuminated and are also more likely to avoid nighttime driving if they have the option. Steward et al. (38) surveyed 2,000 persons seen for optometric examinations and found that the proportion of drivers reporting visual difficulty with nighttime driving was virtually independent of age. However, they also found that after age 70 there was a substantial increase in the proportion of drivers electing not to drive at night for vision-related reasons.

It has been argued (39) that protanopic and protanomalous drivers are at some disadvantage because they are relatively insensitive to red light. Consequently, they would be more likely to have poorer responsiveness to red signal lights, tail lights, and brake lights. However, color vision defects have not been shown to be associated with higher accident rates.

Older persons are also more susceptible to intraocular light scatter and consequently have more difficulty with disability glare. This is a particular problem when driving into the sun or at night with oncoming headlights. The bright light is scattered across the retina and produces an effective veiling luminance that decreases the visibility of other objects in the field. Pulling et al. (40) showed that the glare threshold substantially worsens with age. However, the relationship of disability glare sensitivity to accident rates remains largely uninvestigated.

The ability to properly judge distances and the speed and distance of an approaching car could appear to be related to driving performance. Stereoscopic depth perception, however, has not been shown to correlate with accident rates (27). Kline (10) reviewed studies that showed that the ability to judge depth declines with age as does a driver's ability to judge the speed and distance of an approaching car.

Vision is obviously important in driving, because it is the primary sensory input used for the task. The visual skills required to perform particular driving tasks are numerous and varied. However, statistical relationships between visual measures and driving performance measures such as citations and accident rates are weak. Other factors such as windshield dirt, windshield damage, dangling toys, distractions, camouflage, solar glare, obstructed signs, worn lane lines, and traps are likely contributory or causative agents. Accidents are relatively rare occurrences and result from a combination of circumstances and factors. It is not surprising that correlations between vision measurements and accident rates are weak. Most individuals with very poor vision have already been denied licensure, so they are not represented in these studies, which dilutes the correlations. Until and unless it can be convincingly shown that a particular measure of the more exotic visual abilities bears a strong correlation to safe driving performance, it is the common clinical measures of vision that are likely to remain as the bases for driver's licensure criteria.

BASES FOR VISUAL STANDARDS AND SCREENING PROCEDURES

The primary goal of setting vision standards for drivers and establishing vision-screening programs is to improve safety and driving efficiency and, in particular, to reduce accidents, injuries, and deaths. A subsidiary benefit of vision-screening programs is that individuals in need of vision or eye care may be identified, and with proper professional attention their problems may be treated or rectified so that they may optimize visual performance for driving and other tasks.

For most people in today's society, driving is almost essential for work, social and recreational activities, and the daily needs of life. This is equally

true for the elderly. License denial cannot be taken lightly; it can be a severe restriction on a person's ability to participate in society. The setting of standards is necessarily a balancing process, weighing the risk to public safety against the individual's freedom to drive. In the establishment of visual standards for driving and the procedures for applying those standards, there are several major issues that require consideration.

First, the impairment of what visual attributes is associated with unsafe driving performance? Ideally the visual attributes that are specifically demanded for driving licensure should be irrefutably associated with accident rates or some other index of driving performance. However, even if there is no clearly demonstrable association, a strong *prima facie* case can be made for the claimed relationship. It is not essential that the relationship always be shown to be a causal one. A causal relationship should be required for denial of licensure, whereas an associational relationship may only justify referral for a professional opinion. For example, there is evidence (34) that visual field defects are associated with reduced driving safety. A substantial proportion of the visual field defects are a result of glaucoma, in which not only losses of visual field occur, but also of contrast sensitivity, night vision, and glare sensitivity. It is conceivable that these other visual characteristics may be more relevant to accident causation than are visual field defects. Nevertheless, this possibility does not dilute the value of visual field testing to identify drivers who are at risk because of impaired visual function due to glaucoma.

Second, at what level should the visual criterion be set? It is almost inevitable that some arbitrary judgments will be made about the most suitable level of performance at which to set the minimum criterion required for driving. Regardless of the strength of the evidence that might support the chosen minimum standard, it is virtually certain that there will not be sufficient justification for a single and absolute cutoff point. If, for example, there were a 20/40 standard, it would be unfair to allow a debilitated, inattentive person with 20/40 to drive and deny licensure to a fit and alert person whose visual acuity is only marginally below 20/40. Any practical and rational vision-screening program should allow individual consideration for persons whose visual capabilities fail to meet the required standards.

Third, what vision-screening tests should be used? For any visual attribute for which a standard has been set, there should be a reliable and valid means of measurement that will clearly establish whether the standard has been met. For example, Cole (41) points out that measurements of the rate and extent of dark adaptation are not reliable because one individual can show variations similar in magnitude to the variations among individuals. The chosen vision-screening tests should be well established and accepted, give repeatable results, and provide a means of consistently identifying individuals whose visual capabilities fall short of the required standard.

Fourth, will the imposition of the standard cause a real change in the driver population? If the standard is excessively lenient, only the few with very poor vision will be eliminated from driving. It might even be expected that most of those in this category would voluntarily cease driving regardless of any statutory requirements. However, Guest and Jennings (42) in a survey of a clinical population reported that more than 40 percent of those over 60 refused to obtain correction that would improve their vision to a level that would meet or exceed the driver's license standard. If the standard only serves to screen out persons with extremely uncommon vision deficiencies, its impact on the overall population will be very small and the relative cost and benefit of screening the entire driving population to identify merely a few should be examined. The imposition of a required standard for visual acuity can affect the character of the driver population by identifying many whose vision can be significantly improved by proper refractive correction and by eliminating those who, even with the best correction, cannot achieve minimum resolution standards.

Fifth, do the safety benefits justify the costs of administering the standard? There are costs associated with the administration of any visual standard. Records must be kept, equipment with adequate backup provisions must be available, staff must be trained, and the usual overhead costs must be met. There should be certainty that the exclusion of drivers on the basis of vision-screening examinations will cause a significant reduction in costly traffic accidents to justify the whole process on a cost basis. A sometimes overlooked cost in applying vision-screening programs is that of the applicant's time. The time taken by the applicant in waiting for and participating in the vision-screening process should not be excessive, and to this end, the vision-screening stations should be conveniently located.

Sixth, are there other alternatives to the imposition of the standard? Cole (41) illustrates that engineering changes may sometimes be a cost-effective way of compensating for visual deficiencies with this example. Some red, green, and amber signal combinations could present difficulties for persons with inherited red or green color vision defects and possibly justify exclusion of the 8 percent of the male population who have such disorders. However, the color characteristics of the signals have been modified so that they are more distinguishable (43). Adding redundant information such as shape or order differences is another simple, cost-effective way to facilitate signal identification. About one-eighth of the men with color vision disorders have a loss of sensitivity to red light. Increasing the luminance of the red signals in warning signs and in brake and tail lights would reduce the functional disadvantages of this particular type of color vision deficit.

Finally, should failure to meet the standards require immediate exclusion from the driving population, or would it be more appropriate to impose

selected restrictions and constraints? This is particularly applicable to the elderly, who have a greater incidence of vision defects. Persons who fall short of meeting a required standard should be given an opportunity for special consideration. Previous driving experience, anticipated driving needs, previous driving record, other physical or sensory disabilities, stability of the causative pathological condition, opinions from eye care professionals, and driving performance capabilities judged by experienced evaluators are all factors that could be taken into consideration to decide whether a special driver's license could be provided. Such licenses could have a range of constraints or restrictions.

Factors that might influence license denial or restriction:

- Driving tests
- Driving experience
- Driving record
- Driving needs
- Anticipated driving patterns
- Causative visual disorder
- Prognosis of visual disorder
- Variability of vision
- Opinions on visual abilities
- Other visual disabilities
- Other sensory-motor disabilities

Special conditions:

- Monitoring of accidents
- Monitoring of violations
- Renewal frequency
- Vision report frequency
- Driving test frequency
- Mirror requirement

Restrictions:

- Time of day
- Visibility condition
- Route
- Speed
- Purpose
- Distance from home
- Vehicle category
- Bioptic telescope requirement

Restrictions that could possibly apply to all special-consideration licenses might regulate frequency of renewal, of vision evaluation, or of driving

performance evaluation. Constraints that could depend on individual considerations could be restricted times for driving, routes, speeds, and special mirror requirements, passenger limitations, and vehicle type.

IMPLEMENTATION ISSUES

Authorities issuing driver's licenses must keep their policies and practices under review. Careful consideration should be given to the cost and benefit relationships associated with any contemplated changes. On the benefit side of the equation, the overriding broad question is "How will changing the visual standards affect the vision characteristics of the driving population and will this affect the safety or efficiency of driving?" On the cost side, the broad key issues are "What are the equipment, space, personnel, and administrative costs associated with changing standards or practices? And how are these balanced by the costs associated with anticipated changes in accident rate and traffic efficiency and on the personal and societal costs of removing selected individuals from the driving population?" Assigning monetary values to the different components of such a cost-benefit analysis is usually difficult and imprecise, and the costs and benefits associated with implementing changes are highly dependent on the existing practice. In any consideration of changes of screening practices it is important that the range of relevant key issues be identified.

Most states have between 50 and 100 or more examining offices, and most of these have more than one vision-testing station. The cost of new vision-testing equipment would necessarily be a large factor in implementing new screening practices. It would also be necessary to have backup equipment. Most states currently use wall-mounted acuity charts or have Telebinocular, Orthorater, or Keystone vision screeners. It is easiest to implement changes in vision-screening procedures if new tests can be performed on the existing equipment. If the vision-testing procedures require special conditions, such as a darkened room, this could be very costly. Probably the largest costs, however, would be those related to the time required to perform the testing. If additional testing time is required, more office space and more employee time should be acquired. Unless the additional vision tests are simple, there would need to be staff training and upgrading.

If the implementation of additional screening procedures resulted in significant reduction in accidents, the overall savings might be sufficient to offset the increased costs of screening. Although it is difficult to place a dollar value on accidents, especially those involving injury or loss of life, the severity and frequency of accidents are high enough to warrant substantial expenditures to prevent them.

It becomes logical to try to establish a mathematical equation that could be used to determine whether changes in vision screening would be cost-effective. The real costs of administering the screening tests to each driver should be determinable (although reasonable estimates have not been found). The savings achieved by performing the screening could be determined by multiplying the proportion of drivers who would fail the screening, the total number of drivers, the risk factor that those failing would have accidents, and the average cost per accident (estimated at \$800 by the California DMV in 1987). The large unknown in the equation is the risk factor. Such data are not currently available, nor are there prospects for having them in the near future.

However, there is more than just one piece of missing data—an exact equation would be considerably more complex. Some of those who fail the screening may become licensed after professional eye treatment. Is their accident risk rate different from the normal one? Some may be given restricted licenses. What are the effects of restricted licenses on accident risk rates? Some may be denied licensure. What are the societal costs of restricting or denying licensure to a segment of the population, many of whom would not have accidents if they were licensed? These costs involve lost productivity of the individuals as well as inconveniences imposed by lost mobility. It is difficult to assign monetary value to the quality of life. If a group were screened and identified as having an accident risk rate 10 times that of the entire population, they would probably choose to be licensed and take their chances, if given the opportunity.

The principle of vision screening, however, is to identify those who need further testing or who should not be licensed, but with the minimum number of tests. For additional vision testing to be included in licensing procedures, there should be evidence that the function tested is substantially related to driving performance or that it would identify disorders or defects that would warrant license denial or referral for professional opinion.

Vision tests that have been advocated because they show some weak correlation with driver performance often do not give repeatable measurements or are not currently accepted by the clinical eye care community. It would be unreasonable to deny licensure on the basis of such tests, and it certainly would not be defensible in court given the current state of knowledge. A court challenge could be mounted on grounds of discrimination based upon a physical handicap. The burden of proof would be on DMV authorities and experts to show that the measure of vision was related to the driving task and that the applicant was determined unable to drive satisfactorily on the basis of that measure. Current evidence does not provide much support for such arguments. It would be appropriate for the applicant to bear the cost of the special evaluation and the administration of any restrictions or special conditions.

MERITS OF VARIOUS ASPECTS OF VISION SCREENING

Visual Acuity

Visual acuity is the most commonly accepted clinical measure of visual performance. It provides reliable and repeatable results, and standards have been set for its measurement (45–47).

A visual acuity requirement for driving can

- Encourage some individuals to seek an optical correction before appearing for the vision test when applying for their license,
- Identify drivers whose vision is poor (below the prevailing standard) without correction but can be improved to near normal with appropriate correction, and
- Identify those whose vision is below the prevailing standard even when they wear the best optical correction that is currently available to them.

Individuals failing to meet the standard should be referred for optical correction. For most of those referred, an appropriate optical correction can improve visual acuity to 20/20 or better. These individuals then become eligible for a license requiring them to drive with corrective lenses. A small proportion of those referred may have vision not correctable to the standard; for these, special consideration is indicated. This group will be predominantly elderly and have diseases associated with aging such as cataracts, glaucoma, maculopathy, and retinopathy. A license could be issued with or without special restrictions, or it could be denied. Usually, the vision loss is permanent. Only occasionally does medical intervention (e.g., cataract surgery) enable a return to adequate visual status.

The number of people whose driving vision can be improved because of a visual acuity screening program depends on the level at which the standard is set. Data from the U.S. Department of Health, Education, and Welfare (HEW) (21) survey on visual acuity provide a means of estimating the impact of visual acuity standards for driving. Table 1 has been prepared using data from this survey. These figures represent the best binocular visual acuity when the usual visual correction is worn.

The data in Table 1 indicate that 3.5 percent of the adult population would fail a 20/40 visual acuity standard. A tighter standard of 20/30 would fail 6.9 percent, and a looser standard of 20/50 would fail 2 percent. The failure rate increases substantially for the older age groups. Had this survey included the 75-and-over age group, the failure rate would have been even higher and the increase with aging would be even more pronounced.

The principal conclusions derived from the analysis of Table 1 are supported by the results of a study by Rice and Jones (44) on an experimental

TABLE 1 IMPACT OF VISUAL ACUITY STANDARDS

Age Group	Percentage Below by Visual Acuity Level							
	20/20	20/25	20/30	20/40	20/50	20/70	20/100	20/200
18-24	12.5	6.7	3.3	2.4	1.9	1.4	0.8	0.1
25-34	15.7	5.6	2.6	1.5	0.6	—	—	—
35-44	14.7	4.8	2.1	0.8	0.5	0.1	—	—
45-54	28.9	14.0	6.7	3.2	1.9	0.7	0.3	—
55-64	43.9	20.8	10.4	4.5	2.6	0.7	0.5	0.2
65-75	68.0	40.3	26.0	14.1	6.8	3.0	1.4	1.0
Total	26.8	12.9	6.9	3.5	2.0	0.8	0.4	0.1

vision-screening program for driver's license renewal in Oregon. There had not previously been a visual requirement for renewal in that state. This study was conducted at selected DMV offices in which applicants for license renewal had a vision screening that included tests of visual acuity, color vision, depth perception, binocular vision, and visual field. The program was publicized so that those wishing to avoid the vision screening could visit a nonparticipating DMV center. This was an acknowledged source of under-referral in the study. Rice and Jones found that 81 percent of 454 applicants passed the vision-screening test, either without glasses or with glasses if they had been so required by their original driver's license. About one-fourth of those who passed already had a "with corrective lenses" restriction on their original license. Of the 18.9 percent who failed the vision test, the majority (9 out of 10) had a "with corrective lenses" restriction imposed without referral because they had developed a need for and had acquired a refractive correction since receiving their original license. Overall, only 2.4 percent of the sample population was unable to pass the vision screening; these were referred. Of those referred, 88.7 percent failed the visual acuity test, 10.3 percent failed the binocular vision test, and 0.7 percent (one subject) failed the visual field test. The visual acuity standard in Oregon is 20/40 and the 2.4 percent failure rate is reasonably consistent with the 3.5 percent referral rate expected from the HEW survey statistics, especially considering that there was probably an underreferral rate in the Oregon study and that some of the 3.5 percent in the HEW survey would not appear for a driver's license.

In broad terms, one can expect about 60 percent of the driving population to pass a 20/40 standard without corrective lenses. About another 37 percent will pass provided that they use their current glasses or contact lenses, leaving about 3 percent requiring referral. Of those unable to achieve 20/40 in the screening examination, a large proportion (an estimated four-fifths) will be able to obtain a correction that will return them to driving with a visual acuity of 20/20 or better. A more stringent standard of 20/30 would fail almost 7 percent of applicants and most (nine-tenths or more) of these would return to driving with excellent visual acuity.

Hofstetter's analysis (26) provides empirical evidence that reduced visual acuity is associated with repeat accident rates. This supports the *prima facie* case that driving safety would be enhanced if drivers improved their vision through the use of appropriate corrective lenses. In our view, the principal purpose of the visual acuity screening program should be the improvement of visual acuity, not the elimination of relatively a small number of drivers who have irreparably reduced visual acuity.

A rational connection may be made between visual acuity and driving performance, because the identification of detail is necessary for making many driving decisions. One common and quantifiable task is the identification of information on signs. Signs are usually designed for the driver with 20/20 vision, and theoretically a visual acuity of 20/23 is required to read traffic signs at the intended distance.

Dynamic Visual Acuity

Although most studies have shown dynamic visual acuity to be more strongly related to accident rate than other visual attributes, the correlation is not strong enough to justify its inclusion as a driver vision standard given the numerous difficulties in testing.

The dynamic visual acuity task is complex, and a variety of decisions must be made about the selection of test parameters. These include the size and contrast of the test targets, the rates of movement, whether the eyes should be stationary or following the target, whether the target trajectory should be circular or straight, what retinal eccentricities should be tested, and whether target location, trajectory, or speed should be predictable to the subject. Although a considerable amount of research has been performed on dynamic visual acuity, it has not led to standardized testing procedures accepted by eye care professionals. The repeatability of dynamic visual acuity measurements is also poor. Without a standardized data base or broad-based experience with dynamic visual acuity testing, the imposition of a standard cannot be justified. Furthermore, it is not clear whether clinical treatment or training could improve dynamic visual acuity. In our view, it should not be seriously considered until the knowledge base becomes substantially firmer. If an applicant were denied licensure on the basis of a test of dynamic visual acuity and chose to appeal, it would be difficult to provide evidence to justify the denial.

Visual Field

Peripheral vision is obviously relevant to driving. In the driving situation, it is the extent of the visual field when both eyes are open that is of greatest

relevance. Many states apply a vision standard for the horizontal extent of the visual field. In the most common screening test, a large (20- to 40-mm) white test object is presented a short distance away against a dark background. The monocular visual field normally extends 100 degrees temporally and 60 degrees nasally (48). When both eyes are open, the horizontal visual field includes 100 degrees to the right and to the left, a total width of 200 degrees.

Subtle deficiencies or local depressions of sensitivity in the visual field are probably not of major concern in the driving task, but absolute or extensive losses are. The patterns of peripheral visual field loss depend on the underlying visual disorder. When vision is extremely reduced in one eye, regions of the total visual field are functionally inaccessible and this creates a potential driving hazard. If one eye is nonfunctional, the visual field to that side is limited to about 60 degrees. Furthermore, obstructions such as the roof-support column on the driver's side and the rearview mirror become significantly more obtrusive if one eye is sightless. It could be argued that one-eyed drivers should receive advice and instructions on their limitations and should have better mirror systems that would partially compensate for their visual field deficiency.

Some conditions such as retinitis pigmentosa and glaucoma begin to cause visual field losses in the midperipheral region; typically, these blind regions progress to involve most or all of the peripheral field so that later only central "tunnel vision" remains. Retinal detachments and peripheral retinal degenerations also cause visual field loss. Hemianopia is the loss of half of the visual field, most commonly caused by cerebral vascular accidents or other cortical disorders and similar in extent for both right and left eyes.

Some age-related reductions in measured peripheral visual field result from the effect of small pupils, cataract, or perhaps a generalized decrease in retinal sensitivity. Individual variations may be substantial (9). The light sensitivity of the 80-year-old eye relative to that of the 20-year-old eye has been shown to be reduced by more than 2 log units (100-fold) in scotopic conditions and by 1 log unit (10-fold) in photopic conditions (13). This suggests that an 80-year-old may be functionally equivalent to a 20-year-old wearing welding goggles with 1 to 10 percent transmission. (Even very dark sunglasses transmit 15 percent.) This general reduction in light sensitivity can reduce the overall width of the measured visual field as well as create obvious difficulties with night vision.

Defective visual field is related to accident rates. The most important evidence comes from Johnson and Keltner (34), who measured visual sensitivity in multiple locations within the visual field using a standardized clinical instrument. They showed that binocular visual field losses were related to accident rates. Simpler tests that measure only the horizontal extent of the visual field have not yet shown such connections with accident rates.

Johnson and Keltner's evidence indicates that it may be desirable to make more detailed measurements of visual field, but this would involve additional screening and the purchase of relatively expensive equipment. However, the cost factor and the speed and ease of using these instruments have recently improved. Sensitive measurement of the horizontal meridian is simpler and might be sufficient to identify the major field losses discussed above. Until further evidence is available, we recommend screening the visual field in the binocular horizontal meridian.

Monocularity

Individuals who are monocular have a decreased functional field of vision and also lack stereopsis. Both of these losses must be considered potentially detrimental to driving. However, a fairly large number of monocular individuals [2 percent of a clinical population (35)] are currently eligible for a license, and it would require strong evidence to deny licensure to such a large group.

Monocular individuals can be easily identified by testing the horizontal visual field or measuring monocular visual acuity. The cost of identifying these individuals is negligible. Monocular drivers should be advised of their problem and counseled on hazard avoidance, and an outside rearview mirror on the same side of the car as the nonfunctional eye should be required.

Night Vision and Glare Sensitivity

Decreased visual sensitivity associated with aging reduces night vision, making it more difficult to distinguish objects in dim light. Furthermore, glare caused by scattering of light by the lens or other ocular tissues causes a veiling of vision, which makes it more difficult to detect objects or discern detail, especially if the contrast is low. The elderly are particularly vulnerable to glare and they have reduced contrast sensitivity and special difficulties in dim illumination.

Standardized instrumentation is not currently available for the measurement of visual acuity at low-light levels. Although it is easy to put an acuity chart in a room with variable lighting, it can be expensive and inconvenient to set aside a space and to properly control the lighting. For a valid measure of visual performance in dim light to be obtained, the person being tested would need to adapt to the dark conditions for several costly minutes. These costs could be substantial and should probably be borne by the driver.

Individuals who are known to perform poorly on tests of glare or night vision should be considered for night-driving restrictions. However, until more is known about the measurement of glare sensitivity and night vision

and standardized clinically accepted instrumentation becomes available, it is our view that these aspects of vision should not serve as licensure criteria.

Color Vision

Eight percent of the male population and about 0.4 percent of the female population have some form of congenital color vision deficiency. Of the men, three-fourths have a mild form of deficiency in which one of the three cone systems has reduced sensitivity and the ability to identify certain gradations of color is reduced. Two percent of the male population is missing one of the cone systems. One percent is missing the "green" cone system (deuteranopia) and 1 percent is missing the "red" cone system (protanopia). These individuals have more severe color vision difficulties and are unable to distinguish some basic colors such as red, orange, yellow, and green. Protanopes have a significantly decreased sensitivity to light at the red end of the spectrum, so reds appear darker and are more difficult to detect.

Color vision does not appear to be a major factor in accident statistics. Traffic signals have been standardized so that the green signal is a blue-green and therefore distinguishable from the red and yellow signals by the dichromat (43, 49). The protanope's decreased sensitivity to red can reduce the detectability of red traffic signals (50). The color coding of road signs is redundant when meaning is also conveyed by sign shape or location. There is little justification for using color vision to restrict or deny driver's licenses, but colored signs and signals and visual redundancy should be used to assist those with color vision defects. There might be some merit in screening for color vision at the time of initial licensure to advise those who fail of the difficulties that they might experience. However, the cost benefit would be small.

Double Vision

Double vision, or diplopia, is a potential hazard in driving. Diplopia is most commonly caused by strabismus, a misalignment of the two eyes. Most strabismics suppress the vision of one eye and hence do not experience diplopia. There are special problems for intermittent strabismics, who only experience diplopia when tired, after drinking alcohol, or when viewing a scene with poor fusion cues (such as when driving at night). Some troublesome diplopia problems occur in strabismus secondary to trauma. The resultant visual confusion can be very debilitating at first, but individuals usually learn to pay attention to only one of the images and to ignore the other.

Constant diplopia is not common. Those who have a recent onset of diplopia probably voluntarily abstain from driving during their initial adjustment period when confusion is most troublesome. Screening for diplopia is not likely to be cost-effective.

Bioptic Telescope Systems

A bioptic telescope is a small telescope mounted within a spectacle lens so that the wearer may view through it when it is necessary to discern detailed objects such as road signs. In most cases, the bioptic telescope is placed in front of the better eye and mounted high within the spectacle lens to be above the normal view of the roadway. A driver wishing to inspect distant detail (such as a sign) tilts his head forward about 20 degrees in order to direct the telescope toward the object of interest. After viewing through the telescope, the user lets his head resume its usual position during driving, with the telescope up and out of the way. When the driver is observing through the telescope, he keeps the other eye open. The eye using the telescope will inevitably have an annular scotoma, or blind region, as a result of the magnification. However, the region occluded for the eye with the telescope will be visible to the other eye.

The rationale for allowing drivers to wear bioptic telescopes is that higher resolution is important for specific tasks such as the reading of signs. Bioptic telescopes should be recognized as devices that can be engaged intermittently as needed to enable the user to see finer details, such as those in road signs. Driver orientation and the detection of traffic obstacles, pedestrians, other traffic, and roadway markings are all visual tasks that do not directly demand high resolution. Contrast sensitivity and visual field could be more important for many of these navigational tasks.

Bioptic telescope wear is currently permitted in 22 states, but it remains a matter of contention (51, 52). There is evidence that in California the bioptic-wearing driver population has an accident rate higher than the state average, but Kelleher (53) points out that their accident rate is lower than that of other high-risk driver subgroups such as medically impaired drivers (excluding those with visual impairments) and very young drivers. If prescribed and used appropriately, bioptic telescope systems should not present any additional hazard, but they should enable some visually impaired users to perform better at some occasionally encountered visual tasks associated with driving.

Frequency of Screening

Keltner and Johnson (15) reported that 41 of 50 states plus the District of Columbia and Puerto Rico require vision screening for license renewal. The frequency of renewal ranges from 2 to 10 years, with 4 being the most common.

Vision screening should identify those who have impaired capabilities due to correctable or uncorrectable disorders. The most common cause of visual acuity loss is uncorrected refractive error. Many with myopia (nearsightedness) show a slow, continuing increase in the magnitude of the myopia.

Astigmatism tends to change toward an increasing against-the-rule astigmatism with age. For young adults with hyperopia (farsightedness), clear vision can often be achieved by the exertion of accommodative focusing power. But as accommodative function decreases with age, the ability to compensate for hyperopia progressively reduces. After age 50, the likelihood of significant refractive error increases, and, furthermore, this is more likely to be of functional significance because of the lack of accommodative flexibility to compensate.

Periodic vision screening obliges a substantial number of drivers to obtain eye care and to achieve significant improvement in their visual resolution abilities. It could be argued that for younger drivers (for example, below age 45), less frequent vision screening might be justified (perhaps every second license renewal). For older drivers for whom refractive error changes are more likely and eye pathology is more prevalent, it would be prudent to test vision at each driver's license renewal (typically every 4 years) and perhaps even more frequently for those over 70.

Vision screening at renewal becomes more effective for older drivers. However, if vision screening were required at renewal only for those beyond a certain age, this would represent a form of age discrimination that might not be permitted by some state laws.

VISION-SCREENING POLICY DECISIONS

All driver's license authorities administer some vision-screening programs, and they should periodically review the purpose and effect of their programs and consider changes that might be made to achieve more effective and economical outcomes. It should at first be recognized that screening visual acuity is liable to have much more impact on the vision characteristics of the driving population than screening any other visual function.

Tests of dynamic visual acuity, contrast sensitivity, and glare sensitivity can identify individuals with questionable visual fitness for driving. Rarely is there an opportunity to rectify deficiencies in these visual functions and return vision to normal. Refractive error may be a contributing factor to deficits in these functions, but a visual acuity test alone is sufficient to identify such refractive error. There are no adequate epidemiological data on the prevalence of significantly impaired dynamic visual acuity, contrast sensitivity, or glare sensitivity, in the absence of an associated loss of visual acuity. Certainly such a deficit can occur, but until there is respectable evidence of it or opinion to the contrary, it should be considered a rare occurrence. For these three aspects of vision, there is currently insufficient information to justify any particular standard for license denial. There are no well-established and accepted test procedures, and there is inadequate evidence that tests of these functions could

economically identify significant numbers of individuals who should not be eligible for a normal driver's license. Even if there were cost-efficient tests, we would expect that relatively few individuals would actually be denied licensure as a result of substandard performance on these tests, although some might be given a specially restricted license.

In contrast, visual acuity screening can identify many drivers whose vision may be rendered normal by the simple use of corrective glasses or contact lenses. Figures 1 and 2 show models of the screening process for visual acuity and for other visual functions. Most who fail a visual acuity screening can be referred through the "clinical shunt," obtain an optical correction, and return to the driving population with much improved acuity and a license with a simple "with corrective lenses" restriction. This type of screening can also identify individuals with visual acuity loss that is not correctable to normal; such persons should be given individual evaluations and be considered for license denial, a special restriction, or even an unrestricted license.

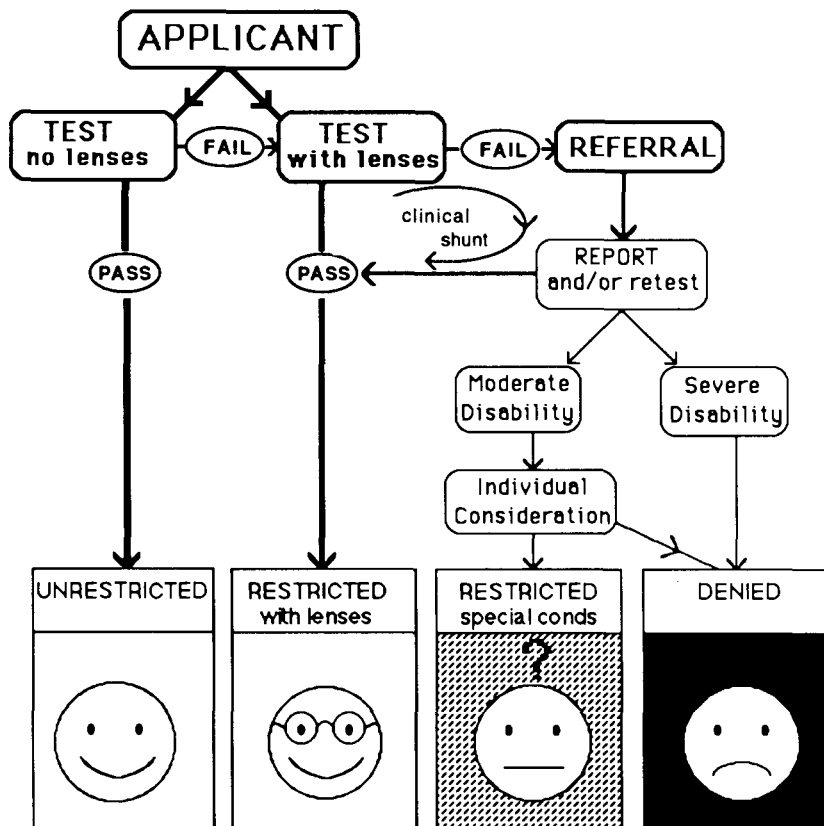


FIGURE 1 Screening visual acuity.

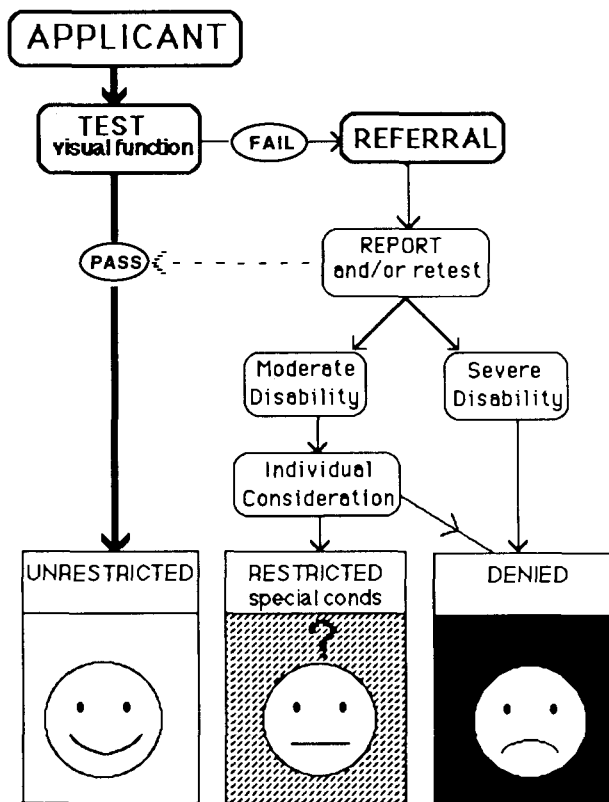


FIGURE 2 Screening other visual functions.

The stringency of standards clearly affects referral rates. Tightening the visual acuity standard of 20/40 to 20/30 would have the effect of doubling the referral rate. Consequently, more individuals would be obliged to obtain corrective lenses and their vision would usually be improved to 20/20 or better. Tightening the standards for any of the other visual functions would cause more individuals to be subjected to the special consideration procedures required in making decisions regarding license denial or restriction. Slackening of standards would reduce referral rates. This would mean that fewer people would be obliged to improve their vision and fewer would be considered for denial or special restriction. For all visual functions that might be included in a screening program, referral rates would be substantially higher for the older age groups. For visual acuity, at least, 70-year-olds are likely to have referral rates that are about 15 times higher than those of young adults (see Table 1).

RECOMMENDED DRIVER VISION SCREENING AND STANDARDS

Visual Acuity

The 20/40 visual acuity standard is the most commonly accepted, and we recommend its retention. Because individuals drive with both eyes open, it is most reasonable to make the standard a binocular one; that is, 20/40 should be obtainable with both eyes open. The driving task remains the same whether the individual is wearing correction or not, so there is no sound basis for having a more lenient standard for the individual with correction. Similarly, there is also no evidence to show that vision in the remaining eye of a monocularly blind individual develops perceptual abilities that compensate for the loss of the eye. Therefore, making the visual acuity requirement more stringent for monocular individuals is not justifiable. Monocular individuals can be identified by visual field screening or, if this type of screening is not used, by measuring visual acuity in each eye. Monocular drivers should receive special instructions and have special mirror requirements.

We consider that it is impossible to establish a single visual acuity standard that would perfectly distinguish between those who should have licenses and those who should not. A single and rigid cutoff point cannot be justified given that there are so many other attributes that contribute to overall safe driving performance. A reasonable approach is to establish a "gray" region. One end of the region will correspond to the criterion for referral (20/40), and the other end to a criterion for automatic denial (this might be an acuity as poor as 20/200). Individuals whose best visual acuity lies in the gray range would be eligible for a special restricted license or for license denial. The stringency of restrictions and denial rates would increase with lower levels of acuity within the gray range. Possible restrictions were listed earlier. It might be expected that individuals in this gray region would be required to take a special test of driving skill, and the tests might be made more extensive for those in the poorer acuity end of the range.

Individuals who at their initial screening do not meet the 20/40 standard should be denied immediate licensure and be referred for an eye examination and proper optical correction. Those who return for reassessment and meet the 20/40 standard would be eligible for licensure.

Application for special restricted licenses would require the applicant's eye doctor to report relevant acuity measurements, refractive data, diagnostic and prognostic opinions, and other relevant findings that could include visual field and night vision evaluations. The applicant could also be required to undergo a driving test by an experienced driver-tester. It would be appropriate for additional costs to be borne by the applicant.

The final decisions regarding licensure and restrictions for gray-zone applicants should be made after the driving test. They involve consultation among

DMV officials, a knowledgeable vision consultant, and the driver-tester who worked with the applicant. Accident and conviction rates of drivers with special restricted licenses should be closely monitored, and the special licenses should be easily revocable by the DMV. More frequent renewals could be considered and new eye examinations and driving tests could be required at each renewal.

Tighter standards or more stringent restrictions, or both, should be considered for drivers of large commercial or passenger vehicles.

Visual Field

The extent of horizontal visual field should be measured with a white object on a dark background. The object should subtend an angle of at least 1 degree. The screening standard should be 70 degrees to either side of fixation. A severe restriction of field (perhaps to a diameter of 20 degrees or less) could be used as a firm criterion for denial. Individuals with field loss between the referral (70 degrees) and denial (20 degrees) criteria should be given special consideration, which could result in denial or special restrictions. Such a procedure would accommodate monocular individuals with one normal eye.

Tighter standards should apply for drivers of large commercial or passenger vehicles.

Bioptic Telescopes

If bioptic telescopes are to be permitted for drivers with reduced acuity, sensible requirements might be that the visual acuity through the telescope at least meet the prevailing visual acuity standard (20/40) and that the binocular acuity (which is relevant when the wearer is not viewing through the telescope) meet a specified standard (this might be in the 20/100 to 20/200 range). In establishing their own standards for binocular acuity without a telescope, DMVs should recognize that individuals whose vision is closer to the extreme limit of the tolerable range are more likely to require special driving tests, to fail driving tests, and to have special conditions imposed on their driver's license. Imposing a tighter standard means that some potentially adequate drivers might be denied the opportunity to demonstrate their driving competence. In contrast, a more lenient standard means that more time will be spent testing drivers who might eventually fail the driving test, and it places more reliance on the driving test as a predictor of the individual's capacity to drive safely.

Bioptic telescopes for driving should be worn in front of one eye only. The other eye should have a specified minimum visual acuity (perhaps 20/200), and the visual field of either eye should meet the driver's license standards.

The bioptic telescope wearer should be skilled at switching between viewing through the telescope and viewing through the carrier lens portion of the device.

The first license issued to a bioptic telescope wearer should require an extensive road test of the applicant's driving abilities. There may be justification for demanding more frequent renewal, more careful monitoring of conviction and accident records, and perhaps more frequent retesting of vision or driving skill. Any restrictions should be decided on individual grounds depending on the causes and the visual consequences as well as a wide range of other personal factors.

Authorities responsible for programs that permit the use of bioptic telescopes may be required to make some difficult judgments. How much poorer than the vision-screening standard should vision be before a bioptic telescope system is recommended or demanded? It is our understanding and experience that most bioptic-wearing drivers have regular visual acuity in the 20/80 to 20/125 range and wear telescopes in the 2.5X to 5X range. Applicants whose vision is closer to meeting the screening standard are less likely to require these devices. A more vexing judgment is how poor visual acuity can be before the individual is considered an unsafe driver, even if a bioptic telescope is used. Many would consider 20/200 or 20/160 to be lenient criteria for this purpose. Were such tolerance permitted with the proviso that the applicant pass an extensive test of driving skills, it could be anticipated that individuals whose vision is at the poorer end of the tolerable range would show higher (perhaps substantially higher) failure rates on the driving test. Clearly it would be prudent for DMVs to carefully monitor the accidents and violations of drivers who are licensed without meeting the vision-screening standard.

Frequency of Screening

We recommend that visual acuity and visual field be screened at the time of license renewal. This is most commonly done every 4 years, which is reasonable. However, an argument could be made for less frequent vision testing (every 8 years) for younger (under 45) drivers.

RESEARCH

Dynamic Visual Acuity

Considerable attention has been given to the possible use of dynamic visual acuity as a visual standard for driving. However, much more research is needed. A standardized test that is relatively quick to administer and gives repeatable measurements is needed. Normalized data on a large population should be developed. Professional eye care for individuals who perform below

normal limits needs to be considered. The effectiveness of treatment on dynamic visual acuity and the improvement in performance of the driving task need to be established.

Night Vision and Glare Sensitivity

The currently used visual acuity and visual field tests do not identify all individuals with night vision difficulties. It is not practical to measure visual acuity at low-light levels during driver licensing because of the time required to adapt to dim light conditions. However, some glare sensitivity measurements could identify those individuals with conditions that cause night driving difficulties. Further study toward developing standardized testing for glare sensitivity could be fruitful.

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Vision Assessment Technology and Screening Older Drivers: Past Practices and Emerging Techniques

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Three topics related to the visual screening of motor vehicle operators are reviewed. First, procedures used to test driver vision in the United States are examined. The most frequently assessed visual functions and the technology typically used to test these functions are summarized.

The second area of inquiry is research efforts to develop a "scientifically valid" technology for testing driver visual function. Coverage is given to the U.S. Department of Transportation's research initiatives, which led to the development of the MARK I and MARK II series of integrated devices for testing driver vision. Conclusions drawn from the review of these programs were used to formulate objectives and guidelines for future research on such testing.

The third, and major, topic covered in this paper is the description and evaluation of emergent technologies that could affect future developments in mass visual screening programs. This review is focused on recent advances in psychophysical data collection procedures as well as advances in visual imaging hardware and clinical testing devices.

Finally, recommendations for implementation of new assessment approaches and critical research needs for driver vision testing are summarized.

Throughout the paper, special emphasis is placed on the interactive influence of human aging and technology and its applications.

CURRENT VISUAL ASSESSMENT TECHNOLOGY

Many stimuli and environmental factors can exert a systematic influence on performance during a visual screening task. Visual acuity level, for example, changes as a function of target luminance, contrast, spectral composition of the light source, and density of the spacing within multiple target arrays. Subject factors, such as the adaptation state of the eye and whether the target is being viewed monocularly or binocularly, strongly influence visual sensitivity scores (1).

Commercial devices known as industrial vision screeners have been developed to provide a self-contained visual environment that controls the stimulus parameters that can alter vision test performance. These screeners ensure that all individuals are screened under fair and equivalent conditions.

Virtually all of the agencies in the United States that administer driver's license applications and renewals employ such commercial vision screeners in their day-to-day assessment of visual function. The major suppliers of this type of equipment include the American Optical, Bausch and Lomb, Keystone Mass, and Tracor and Titmus corporations. These four vendors supply the vision-testing equipment used by the great majority of driver-licensing agencies. Although they differ in some respects, these devices share many common features of basic design and operation.

In general, vision screeners are electromechanical devices that are compact, portable, and totally self-contained. Perhaps the most important feature of these devices is that they isolate the target stimuli from ambient room illumination by means of functionally light-tight enclosures. Backlighting the targets is done entirely by lamps housed within the device itself. All of the screening devices manufactured by the major ophthalmic vendors can accommodate individuals wearing eyeglasses and require no special optical or medical skills to operate.

These commercial vision screeners can be described as precision stereoscopes with built-in illumination sources. They are capable of delivering independent stimulus images to each eye, which makes possible monocular and binocular testing that fully loads the need for visual fusion. Distance vision is assessed with fixed lenses that effectively place the targets at optical infinity (i.e., 6 m or farther). The visual tests performed by the typical commercial screening device include near (25- to 40-cm) and distance binocular acuity, red-green color blindness, depth perception, lateral and vertical phoria, and horizontal visual field. The field test device is usually optional equipment. This battery of tests can be administered in less than 3 min by an experienced examiner (2).

Binocular Distance Acuity

The procedures used in all of the commercially available vision-screening devices to assess acuity are quite similar. Stimulus targets, the correct identification of which requires varying degrees of visual spatial resolution, are presented via backlighted transparencies. Luminance of the acuity targets varies from approximately 30 to 60 cd/m^2 placing the stimuli firmly within the photopic range of visual sensitivity. Stimulus contrast in all cases exceeds 95 percent. The targets are usually arranged hierarchically from largest in spatial detail (easiest to identify) to smallest in detail (most difficult to identify). Typically, the response criteria are defined in such a manner that an observer has only a 20 to 30 percent chance of "passing" a given level of acuity on the basis of chance (i.e., guessing).

The major difference among the screening devices is the type of target (or optotype) they employ. Several families of optotypes are currently used in the screening of driver's license applicants. They include the familiar Snellen and Sloan letters (3), the illiterate-E or Lazy-E, the Landolt-C, square-wave gratings, checkerboard patterns, and a spatially localized dot pattern used on the Keystone tester. It should be noted that several of the commercial vision screeners support more than one family of optotype.

Figure 1 shows examples of three widely used test stimuli that do not belong to the Snellen or Sloan family of optotypes; namely, a checkerboard, the Landolt-C, and the Keystone stimulus. The crucial detail of each of these optotypes can occur at any of four cardinal orientations: top, bottom, left, or right. Hence, the probability of correctly guessing the critical element of each stimulus level is maintained at 25 percent. Although the critical gap of the Landolt-C could also appear at the four diagonal positions, in practice this is avoided because the report of 8 degrees of freedom becomes awkward and difficult to communicate efficiently (i.e., problems with task instructions arise). The magnitude of the critical spatial detail subtended by each optotype is varied by changing the overall size of the target.

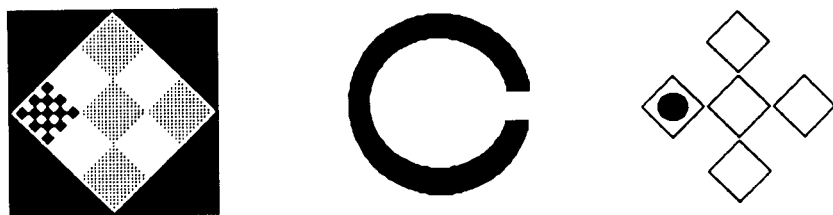


FIGURE 1 Sample optotypes used to assess visual acuity.

Although the acuity measurements yielded by the various vision screeners are highly comparable, small but systematic differences have been noted. For example, the data of Waller et al. (4), which appear in Figure 2, show a systematic difference between acuity measurements made using the Bausch and Lomb Orthorater and the Keystone vision tester. The proportion of license renewal applicants who passed the 20/40 binocular acuity standard was higher when the Orthorater was used. This pattern of results can be attributed to the only major difference between the Orthorater and the Keystone screener, different test targets. The Orthorater unit employs the checkerboard optotype whereas the Keystone tester uses the localized-dot stimulus (Figure 2).

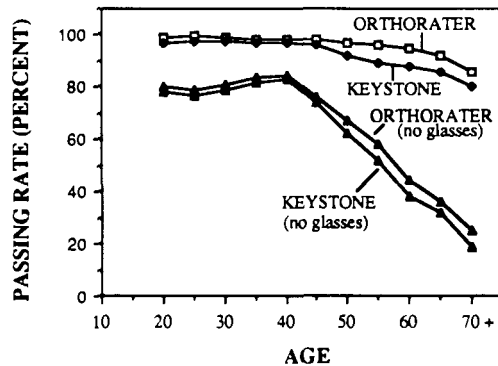


FIGURE 2 Passing rates on the Keystone and Orthorater vision testers as a function of driver age and state of optical correction [after Waller et al. (4)].

Hills and Burg (5) reported a systematic difference in binocular distance acuity of driver's license renewal applicants who were tested using both the Bausch and Lomb checkerboard optotype and the standard Snellen letters. This investigation was based on a re-analysis of a subsample of 4,753 subjects from Burg's (6, 7) earlier studies of driving and vision. It was reported that the correlation between the two acuity measures was only 0.70. Although the acuities generated by the different tests tended to coincide in the normal range of vision (around the 20/20 level), the functions diverged in the range where acuity levels begin to denote suboptimal performance. For example, 20/40 Snellen acuity was found to be equivalent to Orthorater acuity of 20/30. As was the case with the Keystone tester, the Orthorater appeared to be somewhat less conservative (i.e., less stringent). In practical terms, this meant that 46 drivers would have failed the screening test based on the Snellen optotypes

whereas only 18 would have failed had the Orthorater standard been applied. Hills and Burg (5) explained this difference in terms of the checkerboard optotype's lessened sensitivity to astigmatic (cylinder) error in certain orientations. Provisions for eliminating such differences between tests of visual acuity have been proposed by the National Research Council (NRC) Committee on Vision (8). This NRC report establishes comprehensive guidelines for the assessment of both near and far visual acuity. However, these guidelines are too new to have affected the design of mass vision-screening devices such as those employed in the testing of drivers.

Both the Tracor and Keystone vision testers offer "nighttime" visual acuity options. These tests purportedly simulate nighttime driving conditions by using neutral-density filters to attenuate stimulus luminance down to 10 percent of standard levels (approximately 3 to 10 cd/m^2). This luminance is in the low photopic range and is equivalent to the lighting levels that characterize urban roads at night. Two states, Kansas and Tennessee, have incorporated this form of night vision test into their driver-screening programs. Kansas requires the night vision tests only for drivers aged 65 or older. Persons whose scores are less than 20/50 on this test may have their licenses restricted to daylight driving. Tennessee tests the night vision performance of all applicants. Those who score worse than 20/70 are limited to daytime driving (9).

Changes in the eye that accompany normal aging include a reduction in the size of the pupillary aperture and progressive opacification of the crystalline lens (10). These two factors combine to markedly attenuate the amount of light that ultimately reaches the retina of the older adult. For this reason it is probable that older drivers would be affected by the adoption of low-luminance night vision tests. Two recent investigations confirm this.

Rice and Jones (11) examined corrected visual acuity under normal and reduced (i.e., nighttime) illumination using a Tracor integrated vision screener. Of 4,038 drivers who passed the test under standard levels of illuminance, 267 (6.6 percent) were unable to pass the night vision version of the test. Older persons were disproportionately represented in the group that failed the night vision test. The likelihood of failing either the daytime or nighttime version of the acuity test is plotted as a function of age in Figure 3. Reference to this figure reveals that the probability of failing the night vision test remains low for those under age 50. However, the rate of failure for this test climbs to 36 and 68 percent for the 61 to 70 and 81+ age groups, respectively. Similar findings were reported in an earlier study of license renewal applicants using the Keystone vision tester equipped with the night vision option (4). Additional research is warranted before arbitrary cutoffs are established for low-luminance vision.

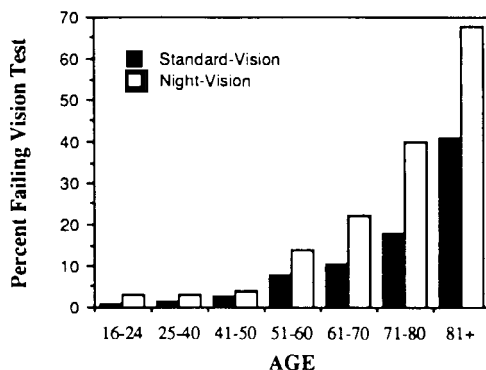


FIGURE 3 Failure rates on regular and night vision screening tests as a function of age of driver [after Rice and Jones (11)].

Visual Field Testing

Two basic schemes for assessing the extent of the horizontal visual field have been used in vision-screening devices, a mechanical approach and an electro-optical approach. The mechanical approach, as optionally implemented in the Bausch and Lomb Orthorater, will be discussed first.

The peripheral field test of the Orthorater consists of a small white ball attached to the end of an L-shaped arm. The arm is mounted on the top of the main body of the screening device with a pivoting joint. The arm can be manually rotated to position the target (a white ball) anywhere along a 360-degree arc surrounding the observer's head. The target is maintained at approximately eye height. By having the observers fixate a stationary target straight ahead and instructing them to report the disappearance and appearance of the target as it rotates about their heads, the administrator can determine the extent of observers' peripheral fields of vision.

Validation studies comparing the Orthorater field test with more rigorous clinical assessment of perimetry have indicated that the Orthorater tends to slightly underestimate field size. For example, Allen et al. (12) collected monocular temporal field estimates from both eyes using the Orthorater and the Clement-Clarke perimeter. When full-field estimates of peripheral vision were compiled by combining the monocular results, the Orthorater fields were found to be more contracted than those obtained for the same individuals using the clinical perimeter (i.e., 173 versus 188 degrees).

The test-retest reliability and the inter-rater reliability of the Orthorater field test have also been investigated. Neil and Johns (13) reported that Orthorater test-retest reliability was good ($r > 0.87$), especially for estimates obtained

while the target changed from being invisible (behind the head) to visible. They also found that inter-rater reliability among experienced driver's license examiners was exceedingly high ($r > 0.96$).

The Orthorater's mechanical field tester is relatively accurate and reliable. Another advantage of the device is that the examiner has an unrestricted view of the observer's eyes and therefore has no difficulty in monitoring the maintenance of central fixation. However, an important disadvantage of the Orthorater visual field test is that it is quite time consuming to administer because of the intense instructional demands that result from the relative unfamiliarity of the task to the observer (14).

The electro-optical approach to assessing horizontal peripheral vision is the technique most commonly employed by driver-licensing agencies. The Tracor, Keystone, and Titmus screeners all use this approach for field tests. Point sources of colored light are placed in a circular perimeter that extends horizontally from the main viewing aperture of the screening device. The target lights are mounted within this perimeter at varying angular displacements from the principal vertical meridian. The examiner must ensure that the observer fixates a centrally located target and maintains firm pressure against the forehead rest mounted above the viewing aperture. If the observer's forehead is not placed against the headrest, the far peripheral targets effectively move toward the center of the visual field and the validity of the test is compromised. It is primarily for this reason that electro-optical field testers have been reported to be less reliable than mechanical tests such as those employed in the Orthorater (4).

In an attempt to control this problem, some models of the Keystone vision tester have an alarm indicator that warns the examiner when ample pressure is not maintained against the headrest. After the observer is properly positioned in the apparatus, the point sources of light that extend between 50 and 85 degrees into the temporal field are briefly flickered. The observer's task is to report the occurrence of such peripheral stimulations. In the typical test protocol, the temporal fields of both eyes are tested in parallel so that the observer's task is to report when and where (left or right) a peripheral target is presented.

The Titmus sector test is representative of the electro-optical approach. Self-illuminated target discs subtending a visual angle of 1 degree are positioned 55, 70, and 85 degrees into the temporal fields of each eye. A single stimulus point appears at 35 degrees into each nasal field. The test administrator manually selects and delivers the briefly presented peripheral stimuli while monitoring the observer's fixation. In practice, test administrators begin with the most extreme temporal target (i.e., 85 degrees) and terminate testing if that target is detected in both eyes (14). The implementation of the electro-optical field test on the Keystone device is similar to the Titmus test [see Waller et al. (4) for a detailed description].

In practice, all of the visual field tests are administered without the use of eyeglasses. This is necessary because spectacle frames can occlude the peripheral field targets. Because the field test is a light detection task and does not require fine spatial resolution, testing without optical correction does not put individuals who suffer from refractive error at a disadvantage.

A final note on electro-optical field tests concerns their apparent insensitivity. Studies involving large numbers of drivers screened with sophisticated clinical perimeters show variability in the extent of individuals' visual fields—especially those of the elderly (15, 16). However, studies of drivers using the more common electro-optical field screeners often fail to detect an age-related decrease in field size. Several large-scale studies could not detect any drivers who failed the field test (4). Rice and Jones (11), for example, screened peripheral vision in 4,544 Oregon drivers and detected only one case with a significant field loss. This pattern of results suggests that apparatus and procedures currently employed to test drivers' visual fields need to be studied further.

Color Blindness

Approximately 4 percent of men and 0.5 percent of women suffer from red-green color blindness (17). The techniques employed by most states to assess this form of color blindness are directly or indirectly based on the Dvorine and Ishihara color plates, the familiar "hidden" color figure test.

The stimuli are composed of multiple dots of varying size and color. They are constructed in such a way that color contours (instead of luminance contours) are used to form alternate pairs of spatial figures.

Typically, the normally sighted individual will report seeing one figure, and the color-deficient individual will report seeing an entirely different figure or object. For example, on one of the Ishihara plates the number 74 is clearly visible to the normally sighted observer; the red-green color-blind observer reports seeing the number 21.

Stereopsis

Binocular depth perception, or stereopsis, is the three-dimensional depth sense mediated through the simultaneous use of both eyes. The most common technique for assessing depth perception in mass screening is the use of stimuli that progressively vary in the degree of retinal disparity that they generate (18). That is, identical images are presented to both eyes through independent optical paths. If properly aligned, these separate retinal images are perceptually "fused" into a single object by the visual system. If a small part of the stimulus presented to one eye is laterally displaced with respect to

the stimulus presented to the other eye, a local region of retinal disparity results. This change in retinal alignment across the eyes is the critical stimulus information needed to perceive binocular depth. The less disparity needed to detect a test object as being "closer" than its retinally aligned surround, the better is the subject's stereoscopic vision.

Stereopsis is objectively assessed by presenting the observer with a series of stimuli of progressively diminishing binocular retinal disparity. The minimum disparity, measured in seconds of arc, at which a subject can correctly discriminate the presence of "apparent depth" yields the stereopsis score.

The stimuli for the stereopsis test implemented on the Bausch and Lomb Orthorater are shown schematically in Figure 4. This test is representative of

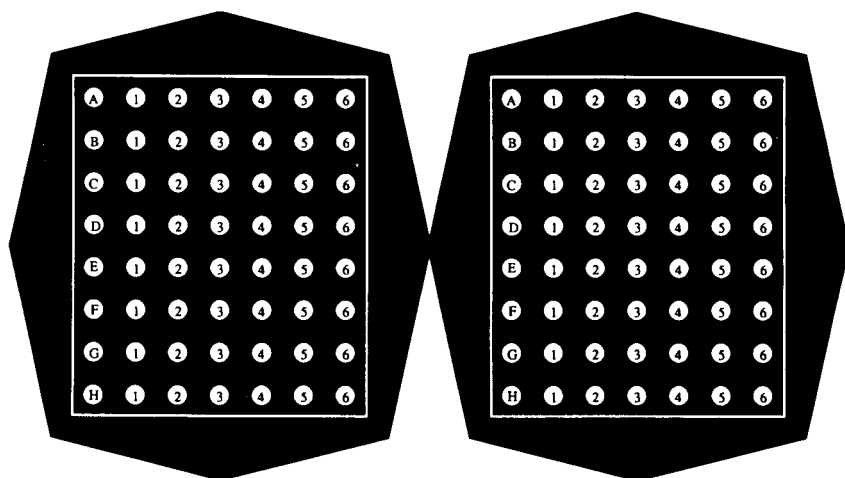


FIGURE 4 A typical "stereo pair" stimulus used to assess binocular depth perception.

the approach used in most mass vision screeners. The two stimuli shown in Figure 4 are presented to the left and right eye, respectively. The two images are identical in all respects except the alignment of a single circular target on each row. The binocular disparity generated by these nonaligned targets provides the information needed to detect depth. The observer's task is to report the stimulus on each row that appears "closer" than the others. The task becomes more difficult as disparity declines from 362 seconds of arc (or 17.8 percent of normal stereopsis on the Fry-Shepard stereopsis scale) on the first row to 9.7 seconds of arc (or 106.5 percent on the Fry-Shepard stereopsis scale) on the bottom row. The discrete test result is applicable to driver screening because depth perception is examined only for advisory purposes and is not used to curtail or limit driving of passenger-car-class vehicles.

SEARCH FOR A SCIENTIFICALLY VALID SCREENING TECHNOLOGY

Throughout the history of driver-licensing programs, it has always been assumed that vision plays an important role in the driving task. The pervasiveness of this assumption is evidenced by the universal requirement of visual screening of driver's license applicants (19, 20). However, before the 1960s there had been no definitive experimental evidence relating visual ability to driving ability or safety. Visual standards adopted by the states had been based on (and for the most part have remained based on) the "expert opinions" of committees of vision specialists. The Federal Highway Safety Act of 1966 mandated that ophthalmologists and other medical professionals take an active role in the development of licensing and screening procedures for driving (21). Because of a lack of scientific data relating vision and driving, visual standards have developed primarily on the basis of input from the clinical community.

Accurate and scientifically derived data were needed to establish more effective visual screening procedures for driver's license applicants. In response to this need, early in 1962 the Institute of Transportation and Traffic Engineering of the University of California at Los Angeles and the California Department of Motor Vehicles initiated a large-scale series of studies that were to form the foundation of a continuing quest to develop a "scientifically valid technology" of driver visual screening (22). In the first phase of these studies, Burg (6, 7) examined the relationship among several measures of visual performance, demographic variables (such as age, sex, and annual mileage), and traffic accident and conviction record.

The visual tests used in this study of more than 17,000 California drivers included static visual acuity; dynamic visual acuity; lateral visual field; lateral phoria; low-illumination contrast threshold (i.e., night vision); glare sensitivity and recovery time; and eye dominance.

These visual functions were selected because of their high "logical" likelihood of being associated with certain types of accidents as well as overall rate of accident involvement (23). Special importance was placed on the dynamic visual acuity (DVA) measure because a major visual requirement of driving is the perception of detail in objects that are moving relative to the observer. Previous research had indicated that measures of static visual acuity and DVA were relatively independent, so Burg and Hulbert (24) hypothesized that DVA might provide a measure of visual ability that was more directly related to driving demands than static acuity. Hence, DVA would be expected to be a better predictor of driving safety record.

Correlational and multiple-regression analyses of the Burg (6, 7) data revealed that driving safety record worsened with increasing mileage, decreasing age, and worsening vision. Mileage and age were the most powerful

predictors of traffic accidents and convictions. Increased mileage resulted in more driving incidents because of a concomitant increase in risk exposure. The reciprocal relationship between age and accident involvement was attributable to dual mechanisms: minimal experience and increased risk-taking behavior of the young and markedly reduced mileage (and, hence, reduced risk exposure) for the aged. Indeed, when accident frequency was corrected for mileage driven (e.g., accidents per 100,000 mi), the older drivers were shown to have accident rates approaching or exceeding the high levels of their 20-year-old counterparts.

Although not as powerful as the age and mileage factors, significant predictive relationships were observed between performance on vision tests and involvement in traffic incidents. Dynamic visual acuity was the visual measure most consistently and strongly related to driving. However, the relationship between DVA and traffic safety interacted with age in a complex manner. On the basis of the overall analyses, DVA was positively related to rate of traffic accidents and convictions. That is, good dynamic acuity was significantly associated with a poor driving record.

However, when separate regression analyses were performed on age-stratified subsamples of the drivers, a more interesting pattern of results emerged. First, DVA declined continuously over the life span. Hence, the best dynamic acuity was confined exclusively to the youngest drivers. These same young drivers, for the reasons noted previously, had the highest frequency of accidents and convictions. Thus, a strong "youth factor" accounted for the overall positive correlational relationship between DVA and driving.

Second, the analyses for drivers over the age of 54 revealed a significant DVA-driving relationship that was in the opposite direction: among older drivers, decreases in DVA ability were significantly associated with increased risk of traffic accidents and convictions [see Hills and Burg (5) for additional age-related re-analysis of the original Burg (6) data].

In addition to DVA, two other visual factors appeared to be systematically related to traffic safety: static visual acuity and glare recovery. Again, decrements in either measure were associated with increased risk of traffic safety incidents for older drivers. Inconclusive results were obtained for the nighttime vision test because of the small number of nighttime accidents encountered in the sample.

Although speculative, the California driving and vision studies (6, 7) suggested strongly that new, more ecologically valid vision tests could be developed to predict increased risk of traffic accident involvement—especially where older drivers were concerned. Also, visual screening technology based on scientifically determined procedures appeared to be feasible given the state of the art of engineering. Burg (6) recommended that a compact, reliable multipurpose vision tester be developed to enable rapid and reliable assessment of driver dynamic visual acuity, static visual acuity, and low-luminance

vision. It was concluded that future research efforts should concentrate on visual tasks that were "perceptual," not merely "sensory," in nature (22).

U.S. DEPARTMENT OF TRANSPORTATION MARK I AND MARK II INTEGRATED VISION TESTER PROGRAMS

On the basis of the pioneering work of Burg (6, 7), the U.S. Department of Transportation (DOT) initiated a series of investigations designed to develop a battery of visual tests that would be more functionally related to driver performance and safety. This initiative was implemented in two phases: the development and testing of the MARK I and the MARK II Integrated Vision Testers. To provide interested scientists and engineers with the mechanical and procedural details of these sophisticated visual work stations, a technical appendix to this paper has been prepared by the author and is available as a separate volume (25). This appendix is a stand-alone document that chronicles the logic behind the development of the MARK I and MARK II systems and offers a critical analysis of the findings of the research programs implemented to assess the reliability and predictive validity of each. Special emphasis has been placed on the role of age-specific factors in the preparation of this auxiliary report. An executive summary of the major contributions of the MARK I and MARK II programs—especially as they relate to future research initiatives—appears in the following paragraphs.

One of the major conclusions to be drawn from the MARK I and MARK II projects was that visual tasks that are dynamic (i.e., temporally modulated) can contribute to the ability to statistically account for group data trends relevant to highway safety indices (i.e., traffic accident and conviction rates). However, this conclusion has been qualified to such an extent that the practical, or applied, significance of this information has been greatly minimized. The relationships found between performance on the innovative MARK II test battery and driving statistics were so weak that they provided less information about the highway safety indices than did knowledge of an individual's age or sex. In other words, the results were significant statistically but not practically.

Regardless of these disappointing results, however, DOT's MARK I and MARK II projects have provided a wealth of information that can serve as an invaluable guide for future research on improved vision-screening techniques. These potential benefits apply to both the theoretical and the practical concerns of any mass vision-screening project.

One of the major theoretical lessons to be learned from the MARK I and II projects is that it is important to establish the reliability of an assessment technique before attempting to establish its predictive validity as a screening

tool. The attempts to develop totally novel assessment techniques and test their reliability and validity in parallel greatly reduced the interpretability of the findings—especially in areas where null findings were obtained. Repeated failures to uncover expected relationships were accompanied by interpretational dilemmas such as: is visual factor- x truly unrelated to driving record or was the failure to observe a relationship due to the inability to reliably assess the magnitude of visual factor- x ? The ambitious attempts to solve all of the problems of developing, verifying, and validating the tests simultaneously necessarily resulted in data that were most difficult, and often impossible, to interpret.

A related problem exposed by the MARK I and II research teams was the inadequacy of traditional correlational and multiple-regression analysis techniques for establishing causal relationships between visual capabilities and highway performance as indexed by accident and traffic violation data. Much of the problem encountered with these techniques stemmed from the highly nonlinear relationship that appeared to characterize the statistical relationship between the vision tests and the highway performance indices.

Nontraditional “graphical analyses” performed on both the MARK I data (26) and the MARK II data (27) attested to this nonlinear relationship and, consequently, indicated that traditional linear statistical techniques would be insensitive to true relationships within such data sets.

A related problem for establishing a causal relationship between visual capacity and accident experience is the multifactor origin of most traffic accidents (28). That is, because many factors interact to cause the typical accident, any statistical attempts to isolate a specific mechanism (e.g., poor vision) will necessarily suffer from markedly limited sensitivity.

Alternative approaches to correlational and multiple-regression analytic techniques should be considered for application in subsequent research projects. Future investigations should have their research designs optimized for analysis by nonlinear causal modeling techniques (29, 30). The “noisy” results obtained during two decades of correlational research on the relationship between vision and driving demand that future studies employ more rigorous experimental alternatives to correlational research designs. An experimental approach would allow scientific controls to be applied that would greatly increase sensitivity to important factors relating driving performance to visual function. One of the experimental techniques that appears to hold much promise for vision-driving research is the simulation approach. The feasibility and cost-effectiveness of simulation techniques for research on visibility and driving have been expertly reviewed by Burg et al. (31).

The DOT vision-testing initiatives also contributed a substantial volume of information on practical issues that affect the implementation of mass-screening programs. Many of these findings related directly to the unique problems

encountered when testing older adult populations. For example, special procedures must be used for testing persons who wear bifocal lenses. Also, luminance levels of the test stimuli must be chosen such that the peak photopic acuity of older observers is not underestimated. Other factors that are critical for efficient administration of tests involving older adults are their diminished response speed and apparently "conservative" response bias, that is, a reluctance to respond when in doubt (32, 33). The potential impact of these and other age-specific population characteristics on the efficiency and reliability of mass-screening systems is noteworthy and discussed more fully elsewhere (25).

Perhaps the most significant outcome of the MARK II vision test program was the demonstrated efficiency that can be attained through the use of computer-controlled vision-screening apparatus. Even though the MARK II tests were implemented using rigid electromechanical stimuli (not the more flexible electro-optic displays available today), they successfully employed computer automation to deliver test instructions, present stimuli, collect responses, and score performance—an outcome that has great implications for future development projects in visual screening. The MARK II project clearly demonstrated that computer automation can be used to implement sophisticated test algorithms (e.g., adaptive psychophysical procedures) in a reliable and efficient manner with little or no manual intervention by department of motor vehicles personnel. Hence, one of the major obstacles to implementing new test programs—the personnel costs associated with administering the tests—could be greatly reduced by the introduction of well-engineered, computer-based automation techniques. Recent improvements in the power and cost-effectiveness of computer and visual display technology offer new opportunities for improving the manner in which driver vision can be evaluated. The emerging visual assessment techniques, which have become realizable through the use of such technological innovation, are the topic of the rest of this paper.

EMERGING VISION ASSESSMENT TECHNIQUES AND THE OLDER DRIVER

Predicting the performance of individuals under adverse viewing conditions represents an important challenge to vision researchers. Traditional assessment techniques have proven to be invaluable for screening and optimizing visual performance under ideal conditions, such as reading high-contrast text or well-illuminated highway signs. However, the predictive validity of these traditional techniques often decreases when visibility conditions are compromised by low levels of illumination (e.g., the highway at night) or inclement weather (rain, fog, etc.). Consequently, individuals who demonstrate "normal" visual capabilities under standard clinical conditions can differ greatly under adverse viewing conditions (34).

There is mounting evidence that this inability to generalize the results of traditional measures of vision to dynamic, nonstandard environments (i.e., the real world) may be exacerbated in the case of older adults. Age-related visual pathologies such as glaucoma, cataract, and retinal disorders (e.g., maculopathy) are often associated with normal scores on standard acuity tests. Yet many of these patients with normal acuity suffer from marked deficits in their ability to function visually under nonstandard conditions such as low illumination, low contrast, and glare.

Laboratory and clinical vision researchers have developed new assessment techniques to bridge the performance gap between high-contrast, optimally illuminated "standard" test environments and the low-contrast, highly variable illumination of the working world. Several of these emerging techniques are potentially useful in the assessment of driver's license applicants. These assessment paradigms and techniques are explored in the subsections that follow and include contrast sensitivity testing, functional glare assessment, use of low-contrast optotypes, and automated peripheral vision testing. These emergent visual assessment techniques were chosen for discussion because they meet the following evaluation criteria: (a) they offer strong potential for identifying correctable vision problems of the aged; (b) the technology for implementing the technique is currently available; (c) sufficient data are available to assess the potential for implementing the techniques in a mass-screening environment; and (d) life-cycle cost (i.e., total costs of development, acquisition, maintenance, training, and personnel and administrative overhead) of the technology needed to implement the technique is not prohibitive.

Contrast Sensitivity

Standard measures of visual acuity assess the spatial resolving power of the visual system in terms of the smallest high-contrast detail that can be perceived at a given distance. Because small amounts of refractive error in the eye yield reliable decrements in acuity, the acuity test has been widely adopted as the basis for correcting optical errors of the eye with spectacle lenses (35). However, the traditional measures of spatial acuity do not fully describe the visual capabilities of an individual. Laboratory and clinical research has revealed that visual sensitivity varies as a function of target size, contrast, and illumination (36, 37). Acuity provides an index of visibility that pertains to only a very narrow band of the size- $\times$ luminance- $\times$ contrast permutations that characterize the driving environment.

Contrast sensitivity testing techniques have been developed to augment acuity measures in the assessment of visual function. At the cost of more sophisticated and time-consuming procedures, currently available clinical

contrast sensitivity measurements yield information about an individual's ability to see low-contrast targets over an extensive range of target size and orientation. Contrast sensitivity tests use sine-wave gratings as targets instead of the letter and checkerboard optotypes used in acuity tests. Sine-wave gratings are used because they are relatively simple to generate and have certain useful mathematical properties (38). Researchers have discovered that early stages of visual processing are optimally sensitive to sine-wave grating targets (39, 40).

Sine-wave gratings can be characterized by three clinically important attributes: spatial frequency, contrast, and orientation. Figures 5 and 6 show

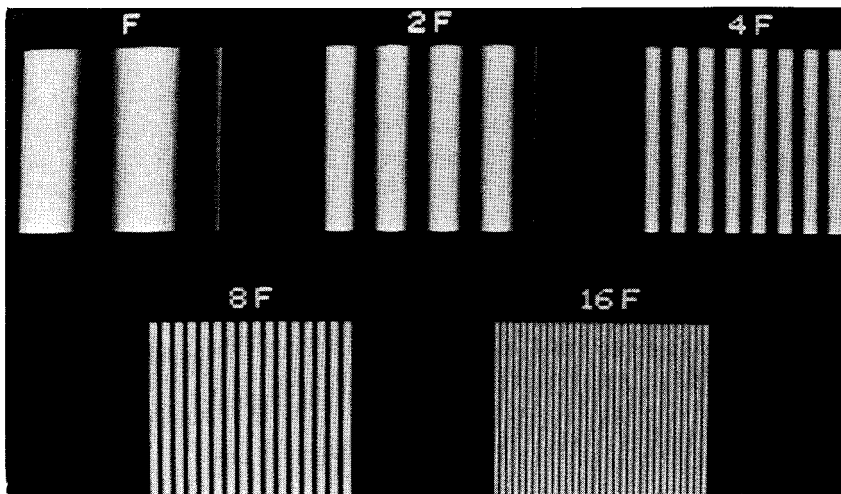


FIGURE 5 Sinusoidal luminance gratings of progressively higher levels of spatial frequency.

some typical sine-wave gratings. When oriented in the vertical position, they appear to consist of a series of fuzzy, alternating light and dark bars of light. In actuality, the luminance of the gratings repeatedly increases and decreases as a sinusoidal function across their horizontal axes. The number of light-dark cycles delineated by a degree of visual angle (or cycles per degree) defines the spatial frequency of a grating. Spatial frequency is an index of the size or width of a grating target: as the width of the bars decreases the spatial frequency of the grating increases. Test gratings varying in spatial frequency are shown in Figure 5.

The contrast of a sine-wave grating is defined by the ratio of the minimum ($L_{\min}$) and maximum ($L_{\max}$) luminance values along the sinusoidally varying axis $[(L_{\max} - L_{\min}) / (L_{\min} + L_{\max})]$. Contrast of a grating target can be varied

from 0.0 to 1.0 without changing the space-average luminance of the stimuli. Hence, a constant state of light adaptation can be maintained during testing. Figure 6 shows a series of sine-wave gratings of constant spatial frequency but progressively diminished contrast.

The final parameter of clinical interest is the orientation or tilt of a grating. Although contrast sensitivity varies as a function of orientation (41), large-scale normative data on the effects of orientation are not available.

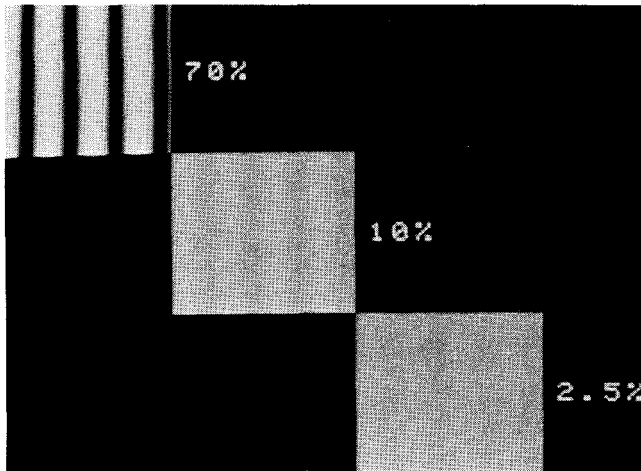


FIGURE 6 Sinusoidal luminance gratings of progressively diminished contrast.

A typical contrast sensitivity assessment procedure is as follows: A vertical sine-wave grating of a given spatial frequency is presented to an observer. The contrast of the grating is reduced until it reaches the threshold of visibility. (The contrast threshold, simply stated, is the minimum contrast at which a sine-wave grating can be distinguished from a uniform field of luminance with some criterion level of accuracy.) The less contrast needed to detect the grating, the more visually sensitive is the observer. Contrast thresholds of this sort are collected for a series of vertically oriented gratings that vary in spatial frequency from 0.5 cycle per degree (c/deg) to approximately 32.0 c/deg, the lower and upper limits of normal spatial vision. Because high levels of visual sensitivity are associated with low contrast thresholds, a reciprocal measure ($1/\text{threshold}$), termed the contrast sensitivity score, is computed. The contrast sensitivity scores collected across the range of spatial frequencies examined during the assessment procedure yield an individual's contrast sensitivity function (CSF).

A typical CSF for a normal, young adult is shown in Figure 7. Spatial frequency is plotted on a logarithmic scale along the horizontal axis of the figure. A logarithmic scale of contrast sensitivity occupies the vertical axis. For normal observers, the CSF (and hence visual sensitivity) peaks in the region between 2.0 and 4.0 c/deg. Visual sensitivity declines rapidly at both higher and lower spatial frequencies.

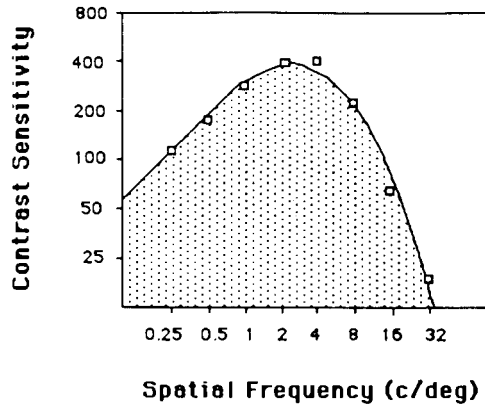


FIGURE 7 A typical contrast sensitivity function.

Origin and Significance of the CSF

The inverted U-shape of the CSF is due to the interacting influences of the optical and neural properties of the eye and the higher-order visual system (42). The progressive loss of visual sensitivity at the higher spatial frequencies (>4.0 c/deg) is a function of the optical quality of the eye. Contrast sensitivity for high spatial frequency gratings is strongly influenced by optical factors such as the refractive state of the eye, the accommodation and clarity of the lens, and the size of the pupil. Contrast sensitivity for low spatial frequency gratings, on the other hand, is not significantly influenced by such optical factors. Instead, the limits of low spatial frequency sensitivity are set by the density and range of the receptive fields of the processing units that compose the visual nervous system; that is, limitations at the level of the retina and primary visual cortex (43).

Extensive laboratory research has revealed that contrast sensitivity is mediated by a series of parallel and independent processors or "channels" in the visual system. Each of these channels is "tuned" to a relatively narrow band of stimulus spatial frequency (44, 39). It is the independent nature of these multiple channels of the visual system that is of particular significance for

visual screening and diagnosis. That is, contrast thresholds for spatial frequencies separated by a factor of two are statistically unrelated to one another. Therefore contrast sensitivity measurements for a 0.5-c/deg grating do not necessarily predict an individual's visual sensitivity at 2.0 c/deg. Likewise, contrast sensitivity measurements taken at 4.0 c/deg fail to predict sensitivity at either 1.0 or 16.0 c/deg (45, 46).

Given the independence of these spatial frequency-specific channels, it should not be surprising that visual acuity measurements (which are related primarily to high spatial frequency sensitivity) cannot predict contrast sensitivity for gratings of low and intermediate spatial frequencies. The clinical literature is replete with cases in which patients with normal visual acuity suffered from losses in contrast sensitivity at low-to-intermediate spatial frequencies and a consequent deficit in the ability to function. The evidence clearly indicates that visual acuity reflects but a small range of spatial visual ability. The contrast sensitivity function offers a much more comprehensive assessment of overall visual capacity.

Temporal modulation of a stimulus grating—whether by drifting at a constant velocity or discrete counterphase flicker—can alter an observer's contrast sensitivity to that grating (47, 36). Again, the difference in contrast sensitivity between a stationary and a temporally modulated grating varies as a function of spatial frequency. Contrast sensitivity is much improved for lower spatial frequencies (<3 c/deg) when temporal modulation is present, but at high spatial frequencies contrast sensitivity is markedly attenuated for temporally modulated gratings. Such spatiotemporal interactions, first systematically demonstrated by Kulikowski and Tolhurst (48), have been attributed to a further specialization of the visual nervous system into sustained and transient processing channels (49). Kline and Schieber (50, p. 181) describe the properties of these sustained and transient channels as follows:

Sustained channels respond primarily to finely patterned targets (that is, those of high spatial frequency) which have been presented for prolonged intervals. The sustained channels are responsible for the mediation of pattern or form perception. As implied by their name, these channels respond slowly and have a relatively long response persistence or integration time. Transient channels, however, are most sensitive to targets of low spatial frequency and respond optimally to rapid stimulus change such as motion or flicker. These transient channels also have very brief response latencies.

The apparent organization of the visual system into sustained and transient channels further constrains the ability to generalize the results of vision tests across targets and environmental conditions experienced while driving an automobile. Just as contrast sensitivity for high spatial frequency targets cannot predict the visibility of low spatial frequency stimuli, it appears that visual sensitivity to stationary targets cannot account for individual differences in visual sensitivity to temporally modulated (i.e., moving) objects.

Moving and stationary stimuli are processed in fundamentally different ways by at least two functionally distinct subdivisions of the visual system: the transient and the sustained channels. Currently implemented driver-screening tests assess only the high spatial frequency, sustained-channel mechanisms that mediate the perception of small, high-contrast optotypes.

Clinical Applications of Contrast Sensitivity Testing

As has the laboratory research reviewed previously, clinical studies have shown that people with identical contrast sensitivities for high spatial frequency targets may have quite different sensitivities at low spatial frequencies (51, 52). Indeed, the dissociation between visual acuity measures and the CSF was first demonstrated in patients with cerebral lesions. For example, Bodis-Wollner and Diamond (53) examined brain-damaged patients who had good acuity (2.0 minarc or better) but complained about severely blurred vision. Contrast sensitivity measures revealed a selective deficit for intermediate spatial frequencies, whereas visibility for higher spatial frequencies remained unimpaired.

Studies of other clinical pathologies (e.g., multiple sclerosis and optic neuritis) have revealed that changes in contrast sensitivity can be confined to narrow bands of spatial frequency. Such selective loss of function in the visual channels responsible for the perception of low and intermediate spatial frequencies often is not detected by traditional acuity-based screening procedures (54). The contrast sensitivity function may also be useful in screening hidden low spatial frequency losses in persons with developing cataract (a pathological clouding of the eye's crystalline lens). Many persons with insidious (undiagnosed) cataract may suffer from blurred vision yet present with normal visual acuity (55). The CSF provides a new means of detecting (screening) and quantifying the diminished visual functioning associated with such cases of insidious cataract (34).

Individuals who wear contact lenses, especially the hydrophilic ("soft") variety, frequently report problems associated with blurred vision even though they retain the ability to resolve the high-contrast, high spatial frequency targets on conventional acuity charts (56). Simple measurements of visual acuity are not sufficient to assess the quality of vision through contact lenses (57). The mechanism of this loss of function, reported as "blurred" vision, appears to be the contrast reduction effects of light scatter introduced by the contact lenses themselves or complications of their use. That is, the lens may become scratched or cloudy, or both, or stimulate deleterious changes in the eye (e.g., corneal edema) that can scatter light and reduce effective retinal contrast. Clinical assessment of the CSF has been found to be useful in detecting heretofore insidious reductions in visual function that result from wearing contact lenses (58).

There is growing evidence that low spatial frequency contrast sensitivity measures may also be useful for detecting insidious age-related diseases of the retina such as glaucoma and maculopathy (a degeneration of the central region of the retina). Glaucoma patients show a 50 percent loss in contrast sensitivity across the whole spatial frequency spectrum. However, the visual loss below 2.0 c/deg is particularly specific to retinal dysfunction because contrast sensitivity in this frequency range is relatively independent of errors in the refractive state of the eye (59).

Comerford (58) describes the CSF as a measure of the integrity of both central and peripheral vision. A loss of function in the visual field resulting from a retinal lesion that is of sufficient magnitude to interfere with visual tasks such as driving will be associated with a general decline in the CSF—especially for low spatial frequency stimuli. This view of low spatial frequency contrast sensitivity as an index of the visual system's ability to integrate spatial information across the entire visual field is consistent with recent clinical findings. For example, contrast sensitivity changes often precede losses in standard visual acuity in cases of age-related maculopathy and glaucoma (60–62).

Contrast Sensitivity and Vehicular Performance

Individual differences in the contrast sensitivity function may potentially serve as the basis for predicting individual differences in performance of complex visual tasks. The research initiative to develop such applications of the CSF has been spearheaded by the U.S. Air Force. Many of the available research results pertain to the piloting of aircraft. Fortunately, however, some of these research findings can be generalized in straightforward fashion to the task of automobile driving.

Ginsburg et al. (63) examined the relationship between the CSF and the ability of Air Force pilots to detect simulated air-to-ground targets (such as another aircraft on a runway). Although all pilots had good visual acuity (i.e., high spatial frequency sensitivity), they varied widely in terms of their peak contrast sensitivity scores. These individual differences in the amplitude (and, perhaps, the spatial frequency) of the CSF peak sensitivity correlated well with individual differences in maximum distance at which target stimuli could be detected. High peak sensitivity predicted high levels of real-world visual detection performance.

In another study of Air Force pilots (64), the relationship between CSF and the ability to detect an approaching aircraft was investigated. Pilots searched for approaching targets under a variety of viewing conditions ranging from clear sky to overcast, rain, and fog. Again, good contrast sensitivity was found to be significantly related to good performance of the detection task. The

pattern of results underscored the need to assess visual function under a variety of stimulus conditions. Contrast sensitivity for high spatial frequencies (>8 c/deg) predicted detection performance under optimal viewing conditions. However, under suboptimal viewing conditions (where the atmosphere would be expected to attenuate the high spatial frequency components of a target) it was found that contrast sensitivity for low (<8 c/deg) rather than high spatial frequencies was capable of predicting detection performance. These results suggest that, unlike acuity measurements, the CSF sampled over a range of spatial frequencies has the potential for predicting real-world detection performance under a variety of visibility conditions. Such a capability would be invaluable in the assessment of driver visual function.

A recent study by Evans and Ginsburg (65) demonstrated a more direct link between contrast sensitivity and the visual skills required for driving. The relationship between the CSF and the ability to discriminate highway traffic signs was examined in young and old observers with good visual acuity (1.0 minarc or better). Age-related declines in the ability to discriminate between highway signs were demonstrated. Furthermore, these declines were predicted by concomitant age-related decreases in contrast sensitivity. The significance of this finding is augmented by the finding of previous studies that age differences in highway sign discrimination could not be accounted for by age differences in standard visual acuity (66).

Aging and Contrast Sensitivity

A number of studies have examined age-related trends in the nature of the CSF. However, the small sample sizes and varying techniques employed in the studies have precluded the accumulation of sufficient data on which age-related CSF norms could be based. The studies employing the two largest sample sizes (37, 67) both used the same assessment technique (the contrast-tracking procedure implemented on the Optronix CS vision tester) and reported similar age-related changes in the CSF: contrast sensitivity for stationary sine-wave gratings above 2.0 c/deg begins to decline after 40 years of age. By age 60, functionally significant attenuation of contrast sensitivity occurs at 8.0 and 16.0 c/deg. Neither study observed an age-related decline in contrast sensitivity for sine-wave gratings below 4.0 c/deg. Figure 8 shows this age difference in contrast sensitivity by superimposing the CSFs typically obtained for groups of young and old observers. Similar age-related increases in the magnitude of the roll-off of contrast sensitivity at high spatial frequencies have been reported in a number of smaller-scale studies (62, 68–70). The agreement in the findings, despite wide variations in the procedures and stimulus parameters employed, indicates that the age-related loss in contrast sensitivity at intermediate and high spatial frequencies is a robust and clearly replicable phenomenon.

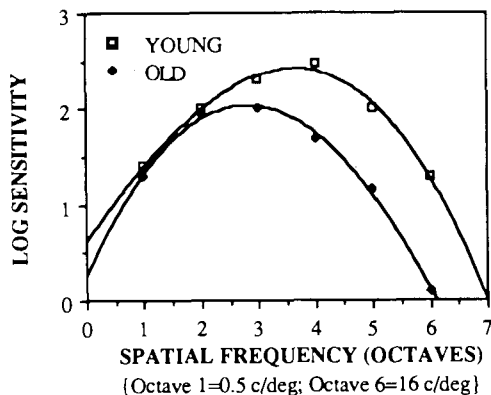


FIGURE 8 Differential contrast sensitivity functions typically demonstrated by young versus old observers [after Kline et al. (69)].

Several studies have noted a progressive downward shift in the spatial frequency of the CSF peak with advancing age (71, 69). Given a standard set of viewing conditions, peak sensitivity appears to shift from approximately 4.0 c/deg at age 20 down to 2.0 c/deg by age 65. This age-related change may be of great functional significance given the predictive role of peak sensitivity for real-world visual performance discussed previously (63).

Several investigators have sought to uncover the specific mechanisms that underlie age-related changes in CSF. The converging evidence generated by these studies suggests that only about one-half of the age-related loss in contrast sensitivity can be attributed to optical factors such as lenticular opacification, refractive error, or restricted pupillary diameter (72–74). Owsley et al. (37) found that age differences in contrast sensitivity at intermediate and high spatial frequencies were not eliminated when young subjects viewed the stimuli under conditions of simulated optical aging (markedly reduced retinal illumination and refractive error induced via a “plus” spherical defocusing lens). These results indicated that the residual age difference in contrast sensitivity most probably was the result of age-related changes in the visual nervous system (i.e., the retina or brain, or both). When Morrison and McGrath (75) bypassed the optics of the eye and directly imaged visual stimuli on the retina using a nonrefractive laser technique, marked age-related losses in contrast sensitivity at intermediate and high spatial frequencies continued to be observed. Taken together, this evidence indicates that both neural and optical mechanisms contribute to the age-related loss in contrast sensitivity.

Finally, there is laboratory evidence that advanced age may also be accompanied by an insidious loss of visual sensitivity to large, moving objects.

When Owsley et al. (37) measured contrast sensitivity with a stationary, low spatial frequency (1.0-c/deg) grating, they observed no age-related differences. However, when this same grating was temporally modulated (i.e., drifted from left to right at a velocity of 4.3 deg/sec) a marked age-related decrement in contrast sensitivity was found. Older subjects failed to demonstrate the motion enhancement of contrast sensitivity for low spatial frequency targets typically observed in younger observers. Similar results were reported by Abusamra et al. (76). Although speculative, these results suggest that visual aging may be accompanied by a diminished capacity to process and detect "transient channel" stimuli (such as large, moving objects like automobiles and pedestrians viewed in motion while driving). Such a loss would not be detected by traditional vision-screening techniques (50).

Potential Significance of Contrast Sensitivity for Driver Screening

The research findings discussed here clearly indicate that the CSF provides information about the quality of vision not generated by standard measures of visual acuity. An important question that remains unanswered is whether the implementation of CSF screening of driver's license applicants would have a significant impact on the safety and mobility of the U.S. population. Given the current state of the art of CSF testing, no definitive scientific answer can be offered to the question. However, the case for the efficiency of CSF screening is strong if the population under consideration is aged drivers.

The CSF has been shown to be useful in the early screening and detection of several visual disorders that often remain "invisible" to standard acuity assessment techniques now universally used on driver's license applicants. These visual disorders include cataract, glaucoma, retinal degeneration (maculopathy), and the insidious loss of visual function under conditions of low contrast or bright illumination that can develop as a consequence of extended contact lens wear. The younger driver population is at risk only with respect to the contact lens syndrome, but the older population is at risk with respect to all of these vision problems that elude detection by mere visual acuity screening.

Epidemiological data (77, 78) indicate that a significant percentage of the older driver population could potentially benefit from the implementation of routine CSF vision screening. These data indicate, for example, that 5 to 7 percent of those aged 65 and older suffer from cataract. On the basis of 1980 census data this figure translates into nearly 2 million individuals. Most of these individuals continue to drive despite markedly diminished visual capacity. Indeed, cataract is often not detected and diagnosed until it has progressed to such an advanced state that even high-contrast acuity is impaired. As a result, the typical older driver with cataract could be expected to experience

several years on the road with significantly impaired vision before diagnosis. Early detection and management of cataracts could result in significant improvements in driver safety, efficiency, and mobility.

It has been estimated that 3 to 5 percent of those aged 65 and older (more than 1.25 million older adults) are afflicted with glaucoma. Glaucoma causes a progressive loss of peripheral vision resulting from the destruction of the optic nerve by the buildup of excessively high pressure within the eye. This loss of vision is permanent and ultimately even central vision is consumed. Total blindness can result if glaucoma is left untreated. Fortunately, the progress of glaucoma can be arrested by medication or surgical intervention, or both. Unfortunately, glaucoma typically develops insidiously. The individual feels no pain and often fails to note the diminished peripheral field of vision until tremendous amounts of visual function have been permanently lost. Early detection of glaucoma could prevent the loss of visual function in many individuals and result in improved highway safety and continued mobility and productivity for high-risk members of the adult population.

The development of debilitating retinal disorders such as maculopathy can be expected to occur in 1 to 3 percent of those over age 65, or 0.75 million persons. Many more older adults suffer from retinal pathology if the complications of diabetes are included in this assessment (79). Until recently, diabetic and age-related maculopathy were entirely untreatable. However, recent developments in laser photocoagulation techniques have been demonstrated to arrest the progress of the disorder in many cases (80). Again, early detection aided by CSF screening procedures could be instrumental in the maintenance of mobility in the population of older adults.

The potential benefit of CSF screening for improved safety and mobility extends beyond the older adult population in the case of detecting diminished visual capacity associated with contact lens wear. The "fogginess" of vision associated with the contact lens syndrome results from accumulated damage to the lenses themselves or to changes in the underlying corneal tissue. Such problems could be quickly reversed if they were detected by contrast sensitivity measurements at low or intermediate, or both, spatial frequencies.

It appears, therefore, that contrast sensitivity measures have a potentially significant role to play in attempts to improve the safety and mobility of the older population. Additional research is required to ascertain the extent to which young and middle-aged drivers could benefit from CSF screening. Work remains to be done on standardizing CSF assessment techniques and generating age-specific performance norms.

Implementation of Contrast Sensitivity Testing for Mass Screening of Drivers

At this time, several systems for assessing contrast sensitivity are commercially available. These include the Arden grating test, the Vistech VCTS 6500

chart, and the Nicolet Optronix CS 2000 vision tester. An analysis of the critical features of these tests reveals many of the important issues that need to be addressed if contrast sensitivity assessments are to be implemented in a mass-screening application such as the testing of millions of driver's license applicants.

The Arden grating test (81) was developed for clinical assessment of patients with anomalous vision and is currently marketed as the American Optical Contrast Sensitivity System. The test consists of a series of five photographic test plates. Each plate depicts a sine-wave grating of a different spatial frequency (0.2, 0.8, 1.6, 3.2, and 6.4 c/deg). The contrast of each stimulus plate varies in a continuous, logarithmic fashion across its vertical extent. That is, the contrast of the grating decreases logarithmically until it reaches zero at the bottom of the plate. The edge of each plate is marked with a scale, each unit of which is equal to a contrast change of 0.08 log unit.

The examiner administers the test by first familiarizing the observer with the target and then covering it completely with a gray occluder card. The occluder is slid upward, exposing the lowest contrast portion of the stimulus first, until the observer reports that a striped rather than a blank pattern can be detected. At this point, the contrast sensitivity score is obtained by reading the value at which the occluder card intersects the contrast scale printed along the vertical margin of the plate. The entire test can be administered in less than 5 min by an experienced technician (59).

The Vistech VCTS 6500 is a wall-mounted chart that consists of a matrix of circular sine-wave grating test patches of variable spatial frequency and contrast. The chart is approximately 100 cm high by 120 cm wide and is viewed from a distance of 200 cm. The chart is organized as a set of six rows of eight stimulus gratings each. Spatial frequency varies across rows and contrast varies across the columns in each row. The first grating in each row is a high-contrast stimulus meant to provide the observer with an unambiguous example of the target spatial frequency for that row. The gratings progressively decrease in contrast as the observer scans left to right across the row. The stimuli in a given row have the same spatial frequency but vary randomly in orientation (75, 90, or 105 degrees). The observer's task is to read across each row and report the orientation of the grating at each position. The contrast of the last correctly identified stimulus in a row yields the contrast sensitivity score for the spatial frequency represented within that row. Experienced administrators can collect a CSF of six data points in less than 6 min—inclusive of instruction time (82). The spatial frequencies sampled by the chart include 1, 2, 4, 8, 16, and 24 c/deg.

The Nicolet Optronix CS 2000 is a computer-controlled, video-based contrast sensitivity tester. Electronically generated sine-wave gratings are presented on a television monitor. The spatial frequency of the target gratings can

be varied continuously. The resolution of the display screen is limited, and, as a result, it must be viewed from a considerable distance (3 m) in order to test spatial frequencies above 12 c/deg. Target contrast can be varied continuously in small, approximately equal steps. In addition to its wide range of spatial frequency and contrast configurations, this television display system is also capable of generating temporally modulated stimuli. The sine-wave gratings can be made to drift from left to right or flicker in counterphase at frequencies of up to 15 Hz.

Because the Optronix tester is controlled by a microprocessor, it has a modest degree of automation for stimulus presentation and test scoring. However, instructions must be given by a trained technician, who must also control session start-up and termination. The device supports several types of psychophysical procedures that take limited advantage of the microcomputer's ability to implement advanced assessment techniques. The procedures for collecting CSF data include continuous contrast tracking, a two-alternative forced-choice task, and a modified ascending method of limits.

The Arden grating test is inexpensive (less than \$200) but entails considerable costs for test time and administration. However, even if these costs were within acceptable limits, other factors preclude its use in a mass-screening application such as the assessment of driver's license applicants. Because of great variations in stimulus conditions (e.g., viewing distance, luminance, rate of stimulus presentation) both the precision and the reliability of the test fall below operational levels necessary to meet the objectives of a mass-screening program.

The Vistech VCTS 6500 system, on the other hand, has several advantages for the mass-screening environment. It is relatively inexpensive (less than \$400) and can be administered with low overhead for instructions and test time. The system samples a wide range of spatial frequencies and requires the observer to make a forced-choice response (when administered properly). This last feature is critical for testing older individuals because of their tendency to adopt a conservative response criterion that tends to decrease the reliability of their contrast sensitivity scores when assessed by techniques that do not implement the forced-choice strategy (59, 83).

The large size of the Vistech CS 6500 chart, however, presents several difficulties for mass screening. Its physical size and large viewing distance limit the ability to test many individuals at the same time. In addition, the charts would have to be mounted in a specially prepared room to adequately control display luminance. Perhaps the most important problem with the Vistech chart is that it comes in only one variety and would be easy to memorize given the public display at the test area.

Vistech has recently introduced alternative implementations of the test that preclude these problems. These tests present the grating targets via slides in a

self-illuminated viewing device. The problem of cheating can thus be controlled through randomization of stimuli across multiple slides. The use of removable stimulus slides also provides the potential for using the same device to test other visual functions such as acuity and color vision. In addition, the self-contained display device eliminates the problems associated with excessive space requirements and controls target luminance more precisely.

The Optronix video tester offers unique advantages such as the ability to temporally modulate the grating display and a degree of automation. However, the poor resolution of its display and the limited processing power of its 6502 8-bit processor do not make it a good choice for mass screening of drivers. The video electronics only display one-dimensional grating stimuli. Hence, alphanumeric optotypes and video-based instructions cannot be generated; this reduces the advantages of a computer-controlled, video-based visual test station, namely, flexibility of stimulus configuration and the ability to incorporate multiple, general-purpose functions. It appears that a much more powerful and sophisticated system could be developed and marketed if the demand existed. A computer-controlled, video-based vision tester that expands on the single-function implementation of the Optronix system offers great promise for test administration and development in a mass-screening environment. In particular, a computer-based system could be designed to fully automate the heretofore labor-intensive process of collecting reliable CSF data. The functional requirements and candidate hardware technologies for implementing such a system are specified in a subsequent section of this paper.

Finally, in addition to stimulus presentation problems, several more basic issues impede the implementation of contrast sensitivity testing as a general-purpose tool for evaluating driver visual function. Legge and Rubin (84, p. 269) have offered an insightful analysis of these problems and have concluded that before the CSF test can be recommended as a practical screening technique the following questions need to be answered:

1. How accurately does the CSF test distinguish subjects with abnormal vision from those with normal vision, either on its own or in conjunction with conventional test measures?
2. How are CSFs to be scored? What criteria are to be used to separate abnormal from normal CSFs?
3. How many measures of contrast sensitivity are necessary to make the test accurate enough to be of use in screening? At what spatial frequencies should these measurements be taken?
4. How robust are measurements of contrast sensitivity to the types of unavoidable variability in testing conditions typical of screening contexts? What sort of repeat reliability is expected of the CSF?

Disability Glare

Disability glare is a reduction in visual efficiency caused by a veiling luminance superimposed on the retinal image. The resulting reduction in the quality of the retinal image is often accompanied by significant decrements in visual performance (85). Not only does visual function per se deteriorate in the presence of glare, prolonged exposure to such effects can result in muscular fatigue and "attitudinal tenseness which can degrade driving skill" (86, p. 103).

The cause of disability glare can be either external or internal in origin. The effective contrast of the retinal image can be decreased by extraneous external luminance sources such as the scattering of light by the dirty windshield of an automobile. Of greater clinical interest, however, are the internal sources of glare that result from the light-scattering properties of opacities within the optic media of the eye. For example, patients with cataract, corneal edema, or cloudiness of the vitreous body can experience excessive reductions in visual function in the presence of unshaded light sources and reflections that are commonly found throughout the driving environment (87). Because standard measures of visual acuity are performed using high-contrast, optimally illuminated stimuli they fail to detect persons who suffer from excessive sensitivity to glare (88, 86).

Laboratory and clinical studies have clearly revealed two driver populations characterized by significant risk of excessive sensitivity to glare: individuals who wear contact lenses and older adults. The light-scattering effects of contact lenses stem from damage to the lenses themselves or changes in the cornea resulting from prolonged contact lens wear. Excessive glare sensitivity resulting from such problems with contact lenses eludes detection by standard clinical tests of acuity (57).

Aging and Disability Glare

All older adults, even those who do not wear contact lenses, are at risk of developing glare sensitivity problems by virtue of the normative age-related decrease in the clarity of the optic media. Between the ages of 10 and 40 there is a steady increase in the amount of light scatter that occurs within the optics of the eye. After age 40, this increase in intraocular light scatter accelerates significantly (89, 90). Numerous studies have shown that such age-related increases in the optical density of the eye are clearly associated with decreased visual performance in the presence of a bright, glare-inducing light source (91-93). This age-related increase in glare susceptibility accelerates after age 40, paralleling the trends observed in objective measures of the optical quality of the eye (88). The finding that the vitreous body remains relatively intact during old age (94) and the observation that sensitivity to glare is markedly

reduced after cataract surgery (92) point to the crystalline lens as the dominant mechanism mediating age-related increases in susceptibility to disability glare.

Excessive sensitivity to the deleterious effects of glare is often one of the criteria used to justify cataract surgery (85). However, surgical removal of the lens does not necessarily eliminate the risk of redeveloping problems with disability glare. Modern cataract surgery is often associated with the implant of a replacement or prosthetic lens. This procedure typically involves anchoring the new lens within the capsule of tissue that formed the exterior layer of the original lens structure. In approximately 10 percent of surgery cases, a clouding of this capsule subsequently develops, which leads to a condition known as "secondary cataract" (87). This condition is associated with a clouding of vision and an increased susceptibility to the effects of disability glare. Finally, the refractive state of the eye after cataract surgery often needs to be corrected with contact lenses. Unfortunately, older adults may be more susceptible to developing the corneal complications of contact lens wear that have been associated with decreased contrast sensitivity and elevated problems with disability glare (95).

Benefits of Driver Glare Sensitivity Testing

Glare sensitivity testing has definite potential for detecting significant but correctable vision problems among two large subpopulations of drivers in the United States: older persons and individuals who wear contact lenses. The aged are increasingly likely to develop cataractous or precataractous ocular opacities that cause marked deficits in the ability to see under transient-illumination or high-illumination conditions (e.g., opposing headlamps during nighttime driving, high-mast roadway lighting, driving toward the brightly illuminated sky at dawn or dusk). Persons suffering from severe lenticular opacities could be routinely screened and treated. Precataractous individuals could potentially benefit from optical aids such as spectacles with special antireflective lens coatings that can attenuate the contrast-reducing effects of glare by a factor of 1.5 to 5 (96). Likewise, persons found to suffer from excessive sensitivity to glare resulting from the complications of contact lens wear could be referred to a vision specialist. The glare problem could then be corrected by replacing the worn or damaged contact lenses or treating corneal inflammation, as appropriate. The potential number of drivers who could benefit from such intervention is undoubtedly large. This potential pool of individuals can only be expected to grow as both the frequency of contact lens use and the number of older persons continue to grow.

Glare Sensitivity Testing in Driver Screening

Few commercial glare sensitivity tests were available at the time of this writing. Of these systems only the Miller-Nadler tester and the newly introduced Vistech MCT 8000 appear compatible with a mass-screening application for older individuals.. Although the MCT 8000 doubles as a contrast sensitivity tester, not enough data are currently available to assess its reliability and operational efficiency.

Several experimental systems that use television-based sine-wave grating targets to test susceptibility to glare using contrast sensitivity techniques have been successfully demonstrated (97, 98). The limitations and potential usefulness of these techniques for mass screening of driver's license applicants are discussed in this subsection.

The Miller-Nadler apparatus consists of a table-top slide projector system with a rear surface viewing screen. The test stimuli are 17 slides of black Landolt-C optotypes centered within a gray circular surround. These stimuli have a Snellen-equivalent critical detail of 20/400 (20 minarc) and vary in contrast from a high of 80 percent to a low of 2.5 percent. The stimuli are presented against an illuminated surround of approximately 6800 cd/m², which serves as a constant glare source. To measure disability glare, the observer is positioned in a forehead and chin rest at a distance of 36 cm from the screen. The stimuli are presented in sequential fashion beginning with the highest contrast slide. The stimulus contrast is reduced until the observer can no longer correctly identify the position of the critical gap in the Landolt-C. The lowest contrast correctly identified provides the glare sensitivity index. The test is conducted separately for each eye.

Studies of normal and cataractous older adults indicate that a glare score of 15 percent contrast or lower is within normal range and that a score of 20 percent contrast or higher is indicative of significant visual loss in the presence of a source of glare (87, 85). The Miller-Nadler test is reliable and yields easy-to-interpret results. However, it possesses several characteristics that limit its usefulness in a mass-screening environment. First, the device is totally manual, requiring the full attention of an administrator to update the stimuli, collect responses, and calculate a final performance score. More problematic, the test assesses only glare sensitivity. Additional equipment and training would be required to implement other measures such as sine-wave contrast sensitivity or standard visual acuity. Finally, the apparatus is not readily amenable to automated administration, which would allow it to be life-cycle cost competitive with a multipurpose, computer-based system.

Prototypes of television-based contrast sensitivity testers of glare sensitivity have seen limited application in the laboratory and clinic. These systems use sine-wave gratings of variable spatial frequency and contrast generated on a computer cathode ray tube (CRT) display or monitor. The display is then

viewed through light from a bright (e.g., 25 000 cd/m²) circular fluorescent lamp that surrounds the stimulus area. Comparisons of contrast sensitivity measures collected with the glare source illuminated and extinguished are used to formulate a glare attenuation ratio at each spatial frequency. Significant reductions of contrast sensitivity in the presence of glare have been found to correlate well with patient reports of glare problems (97, 98) and objective ophthalmic estimates of lens opacification in older precataractous and cataractous patients (98). Paulsson and Sjostrand (97) have presented clinical evidence that contrast sensitivity assessment techniques are both more sensitive and more specific to the detection of cataract when a glare stressor accompanies the sine-wave grating target.

The efficacy of the prototypical CRT-based glare testers strongly suggests that glare sensitivity testing could be incorporated as part of a general-purpose computer-controlled video tester. Such a tester would benefit from advanced automation capabilities and off-load the personnel requirements for administering sophisticated assessments of visual function. The stimulus parameters and procedures required to develop such a video-based glare sensitivity test are reviewed in an exhaustive experimental analysis by Miller et al. (99).

Low-Contrast Acuity Testing

Recent evidence suggests that a new type of vision test may yield much of the same information about visual disability that is provided by the CSF but without many of the costs associated with CSF assessment. This new technique is similar to the familiar Snellen acuity test except that low-contrast optotypes are substituted for the high-contrast letters typically employed in such tests. Clinical data from tests using the Regan contrast sensitivity letter chart (100), a commercially available implementation of the low-contrast acuity test, have indicated extremely promising results. Proponents of the low-contrast acuity test have claimed that it rivals CSF measures in its power to make clinical diagnoses of visual disorders such as cataract, glaucoma, diabetic retinopathy, age-related retinopathy, diffuse visual blur associated with contact lens syndrome, ocular hypertension, glaucoma, and various neurologically mediated losses of visual function (101–104, 83).

The manner in which low-contrast acuity charts can discriminate anomalies in the CSF can be understood by referring to Figure 9. The upper line represents the normal CSF and the lower, more attenuated, line represents an abnormal CSF that might characterize the visual sensitivity of an individual with cataract or corneal edema suffered as a consequence of the contact lens syndrome described previously. Note that the highest spatial frequency that can be resolved by both individuals occurs at 100 percent contrast (as indicated by the dashed lines in the figure). Also note that the two CSF curves

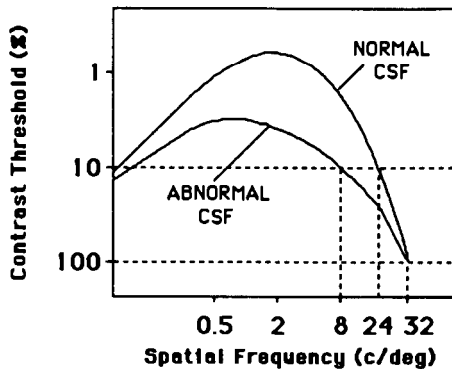


FIGURE 9 Variation in individual differences in spatial sensitivity as a function of stimulus contrast.

virtually overlap at this level of contrast. Both observers could resolve a 32.0-c/deg (1.0-minarc) target presented at 100 percent contrast. That is, both individuals would be able to read the 20/20 line on a high-contrast Snellen chart (ignoring constraints imposed by luminance and viewing distance). These observers could not be discriminated by their scores on a standard acuity test. The situation changes dramatically, however, when visual sensitivity is compared with a 10 percent contrast target instead of one presented at full contrast. At this low level of contrast, the highest spatial frequency that can be resolved drops to approximately 24 c/deg (1.25 minarc) for the person with the normal CSF and all the way down to 8.0 c/deg (3.75 minarc) for the individual with the anomalous CSF. That is, the performance of these two individuals would be markedly different if they were tested using a Snellen acuity chart composed of low-contrast (10 percent) optotypes. The CSF-normal individual would lose one line of Snellen acuity (20/25) on the reduced contrast chart whereas the CSF-abnormal individual could be expected to lose as much as five lines of acuity (20/70) under the low-contrast conditions.

The potential advantages of the low-contrast acuity paradigm for screening drivers are numerous: (a) The technique would be less expensive to implement in terms of the complexity of the instructions to the observer and ease of administration; (b) the scoring criteria would be easier to develop and interpret than in the case of the CSF, largely because of the familiarity of the standard Snellen acuity test; (c) low-contrast optotypes could be easily retrofitted into many of the vision screeners already in use by driver-licensing authorities; and (d) the test is essentially a forced-choice task that would minimize the effects of age-related changes in observer response bias.

The major disadvantages of the low-contrast acuity test include the inability to temporally modulate the stimuli (i.e., add a motion component) and the difficulty of automating a task that has 26 response alternatives (i.e., the letters of the alphabet). However, neither of these problems is insurmountable. The use of Landolt-C optotypes would make the low-contrast acuity test more amenable to automation because only four response categories are needed to code the position of the critical gap (i.e., top, bottom, left, and right). In addition, the production of temporal modulation needed to test the dynamic properties of the visual system would not be precluded if the low-contrast optotypes were presented using a high-resolution, video-based system.

The simplicity of the low-contrast acuity paradigm and its apparent sensitivity in detecting many of the visual anomalies associated with old age suggest that it holds great potential as a technique for routinely screening driver's license applicants. Although low-contrast acuity testing has been known to have relevance for real-world visual performance for many years (105, 38), it has only recently become an area of active research interest. Additional work is required before the full benefits of this emerging technique can be assessed.

Automated Visual Field Testing

The field of vision of an eye is the total area over which effective sight is maintained relative to a constant, straight-ahead fixation point. The extent of the visual field has consequences for everyday activity, such as driving a car. Assessment of the visual field also provides information that is important for the detection and diagnosis of certain visual dysfunctions such as glaucoma, the cortical varieties of cataract, and degenerative retinal disorders (106). The incidence of all of these visual disorders increases markedly with advancing adult age (10). Unfortunately, these disorders typically have insidious onsets and, with the exception of cataract, lead to permanent loss of visual function and mobility if not detected and treated in a timely fashion.

The apparent validity of a causal relationship between the extent of the visual field and driving safety has prompted many state licensing agencies to initiate field testing as part of their routine driver-screening battery. However, as already discussed in the introductory section of this paper, the field testers currently available for mass-screening applications are highly insensitive and often pose severe problems of reliability. Mass field screeners typically test only a few points in the visual field, and these few points fall only along the main horizontal axis of vision. Unfortunately, severe field losses are not confined to the principal horizontal meridian.

Full-field perimetry has been a mainstay of clinical assessment for 50 years. Procedures exist for evaluating the full peripheral extent of the visual field

along many axes of orientation (kinetic perimetry) as well as evaluating functions at representative locations within the bounds of extreme peripheral vision (static perimetry). These techniques provide sensitive tests for glaucoma or the existence of local retinal dysfunctions (scotomas), or both, associated with age-related maculopathy and senescent diabetic retinopathy. Unfortunately, traditional field assessment techniques are labor intensive; it takes at least 15 to 20 min for a highly qualified medical technician to administer them. Recently, however, a host of computerized, highly reliable automated static perimeters have been introduced (e.g., the Humphrey field analyzer, and the Octopus and Fieldmaster automated perimeters). These devices, although expensive at present, point the way to new approaches that could ultimately enable full-field perimetry to be performed in a mass-screening application such as driver vision assessment.

Extensive laboratory and clinical field testing with these automated perimeters indicates that they have high diagnostic sensitivity for glaucoma and localized retinopathy (107, 108), especially when adaptable psychophysical procedures that automatically detect and retest suspicious data points are incorporated into the computer algorithms of the devices (109).

The typical automated perimeter consists of a large, table-mounted hemispheric projection screen at which the observer must gaze. A fixation point and a chin rest and headrest are provided to help maintain fixational stability. Some of the more portable devices require optical aids (i.e., a spherical lens) to allow the short-distance test spots to be optimally focused by presbyopic middle-aged and older adults. The devices use a computer-controlled projector or a two-dimensional array of light-emitting diodes to deliver the test targets at various positions within the field. Fixation maintenance is automatically monitored by dummy probes to the blind spot (which should fail to be detected if the observer is properly fixated) or by monitoring the alignment of an infrared beam reflected off the surface of the cornea.

The observer's task is to maintain rigid central fixation while small illuminated disk targets are randomly presented at strategic points throughout the visual field. The observer presses a button to signal the detection of a test probe. Consistent failure to detect targets at specific locations is indicative of a local loss of retinal sensitivity. Preprogrammed computer algorithms administer the entire testing sequence as well as provide a scored output.

Keltner and Johnson (110) modified the standard clinical test procedure implemented on the Fieldmaster automated perimeter (Model 101-PR) to assess its reliability for mass screening of drivers. The modifications consisted of employing suprathreshold stimulus levels determined by previously established age-norm data instead of trying to determine the increment threshold at each point. Also, because the majority of observers, regardless of age, tends to miss targets presented in the extreme periphery, these targets were dropped

from the test procedure. Because these points yield highly variable results, the overall reliability and sensitivity of the field test were not significantly altered. After making these two changes, Keltner and Johnson (110) found that they could reduce the total testing time for a full-field static assessment to 1.5 to 2.0 min per eye. Data collected from 778 volunteers (1,027 eyes) recruited from driver's license renewal applicants revealed that the test was efficient and reliable.

On the basis of these findings, a follow-up validation study of the technique was conducted on 10,000 driver's license applicants at two California Department of Motor Vehicles branch offices. The average total test time, based on an assessment of approximately 20,000 eyes, was 1 min 54 sec per eye. Results of this mass screening indicated significant field loss in 3.0 to 3.5 percent of all age groups between 16 and 60 years. Frequency of field loss began to accelerate thereafter, reaching a rate of approximately 12 percent for the 65+ age group. More than 4 percent of those aged 65 and older suffered from severe binocular visual field loss indicative of glaucoma or related pathology. These incidence figures were consistent with the results of the preliminary study of more than 1,000 eyes (110) and a second mass-screening study by Bengtsson and Krakau (111).

More than one-half of the subjects with abnormal visual fields (57.6 percent) in the Johnson and Keltner (15) study were previously unaware of any visual problems. This figure was quite similar to the findings of an automated mass visual field testing study by Bengtsson and Krakau (111), which showed that 48 percent of subjects with visual field loss were previously unaware of any visual problem. Follow-up letters to subjects with visual field deficits revealed that the most commonly diagnosed sources of significant field loss were glaucoma, cortical cataracts, and retinopathy. These data are a grim reminder of the insidious nature of glaucoma and retinal disorders and their potential deleterious impact on the mobility and visual functioning of the older population.

Another significant outcome of the application of automated perimetry to the mass screening of drivers was the demonstration of a functional link between visual field deficits and driving accident and conviction rates. Johnson and Keltner (15) found that drivers with visual field loss in both eyes exhibited a traffic accident and conviction rate that was twice as high as that of age- and sex-matched observers with normal vision. This outcome is consistent with previous studies of monocular drivers (112) and patients with visual fields constricted as the result of retinitis pigmentosa (113). The difference between these positive findings and previous studies that failed to demonstrate a relationship between visual field and driving performance (6, 26, 27) was attributed to the use of nonvalidated field test procedures in prior research efforts.

The potential benefits of screening older drivers for visual field deficits are apparent. Because of the insidious nature of visual field losses, hundreds of thousands of persons could be detected and treated in the early stages of dysfunction, thereby preventing permanent loss of visual function and markedly limited mobility. Even age-related maculopathy can be "slowed down" by treatment.

Numerous impediments prohibit immediate implementation of automated field-testing technology, however. Currently available equipment is expensive, and even mass production would not reduce the cost to sufficiently low levels because these devices cannot be used to administer other tests of visual function. Instead, the basic components of automated field assessment need to be translated to a general-purpose visual testing apparatus such as a high-resolution, television-based technology. Such a translation would require substantial effort because of the size of the visual field that must be stimulated. However, this problem could be circumvented through the use of multiple CRT screens deployed at different orientations. Television-based perimetry is not without precedent (114). Additional research on the development of such an automated "glass" (i.e., CRT) perimeter could yield great advances in the safety and mobility of older drivers.

COMPUTERS, IMAGING TECHNOLOGY, AND THE FUTURE OF VISUAL ASSESSMENT

Most of the apparatus currently used for visual testing is based on electromechanical technology and simple display optics. This equipment tends to be rigidly inflexible and quite limited in function. It is often difficult or impossible to upgrade these systems to accommodate advances in visual assessment procedures. Electromechanical systems are labor intensive and not easily converted to automated operation. Recent advances in digital electronics and video-imaging technology have resulted in the availability of computer and display systems capable of presenting traditional and new-generation visual test optotypes in a cost-effective manner.

Computer Technology

During the past several years extremely powerful 16/32-bit microprocessors or central processing units (CPUs) have been developed. Microcomputer systems built around these CPUs have become so powerful that the distinction between "microcomputer" and "computer" has become somewhat of an anachronism. The CPUs that currently dominate the technological niche that has direct implications for new developments in vision testing include the Intel 80286/80386, the Motorola 68000/68020, the Digital Equipment Corporation LSI 11/73, and the National Semiconductor 32000 series. Most of the

currently available graphic workstations, which meet the processing needs of a computerized vision tester, are based on the 80286/80386 and 68000/68020 processors. As a consequence of the resulting economies of scale, these two architectures currently hold the lead in cost-effectiveness in terms of original equipment manufacturer (OEM), hardware pricing, and availability of software development tools such as compilers, graphics support libraries, and operating systems (115).

Modern computer systems built around these new generations of CPUs are powerful and inexpensive. Off-the-shelf systems such as the IBM PC/AT (80286 CPU) and the Apple Macintosh II (68020 CPU) are capable of rapidly accessing and processing millions of pieces of information per second and searching through vast archival records in just a fraction of a minute. This class of small computers can also inexpensively generate high-resolution graphic displays that rival the quality of those produced by workstations costing tens of thousands of dollars.

The advent of special-purpose, very-large-scale integration (VLSI) devices has made it possible to manufacture high-resolution monochrome or color graphic display systems (exclusive of the display monitor) for costs below \$1,000 (116). These low-cost systems are capable of generating the types of stimuli needed to implement emerging visual assessment techniques such as those employing sine-wave gratings, low-contrast optotypes, and temporally modulated figures (117). These systems possess the general-purpose processing functions needed to fully automate test administration and scoring. The strategies and benefits of test automation are described further in a subsequent section of this paper.

Display Technology

The factor that limits the cost and quality of state-of-the-art visual graphics is not computational constraints. Currently available CPUs and VLSI graphics processors are more than powerful enough to exceed the spatial-processing limits of the human visual system. Instead, the major constraint on graphics quality is the imaging technology that ultimately translates the computer's electronic signals into visible light energy—for example, the familiar CRT found in video monitors.

Several display characteristics emerge as critical criteria for the selection of an imaging technology for an application such as a multipurpose vision-testing apparatus: spatial resolution, brightness, gray scale, maximum size, contrast, color capability, and cost (118). The minimum spatial resolution, brightness contrast, and cost requirements of a vision tester are self-evident. The need to consider gray scale, maximum size, and color capability, however, is not so obvious. Gray scale refers to the ability of a display to vary

the brightness of each of its picture elements (pixels). The contrast modulation of sine-wave luminance gratings required by CSF assessment paradigms mandates a minimum gray scale of 256 levels (8 bits); a 1,024 gray scale range (10 bits) is optimal (119, 120). General-purpose vision testing would be best served by large, bright displays—especially if assessment of peripheral vision were desired. However, many of the newest technologies can be economically implemented only in small sizes (e.g., electroluminescent and vacuum fluorescent displays). The role of color in driver vision testing is marginal. However, a general-purpose vision tester would need to have the capacity to assess color blindness. Color capacity would enable the display to faithfully depict real-world stimuli in a manner consistent with the requirements of a first-order computer simulation facility.

Given these criteria, the CRT monitor is the unambiguous technological choice for a general-purpose visual screening apparatus. CRTs are capable of the highest resolution, gray scale, contrast, and color capacity at the lowest cost. They can produce brightnesses well above those required by clinical vision assessment ($>100 \text{ cd/m}^2$) and are available in a variety of sizes ranging from 2 to 100 cm (diagonal). No other technology can match the CRT, in a cost/function trade-off analysis, for visual assessment. Liquid crystal displays (LCDs) lack the contrast, brightness, and resolution of CRTs and are available in a limited range of sizes. Electroluminescent panels have limited gray scale and are available only in small-sized configurations. Gas plasma displays suffer from limitations in spatial resolution, gray scale, and color capability. Vacuum fluorescent panels have the same limitations as gas plasma displays and are economically realizable only in relatively small sizes.

Several factors must be considered in the selection of the best CRT configuration for general-purpose vision testing. The principal decisions center on the size-versus-brightness and the color-versus-resolution trade-offs. That is, as the size of a CRT display increases, its maximum usable brightness level decreases. When color is added to a CRT display, its spatial resolution drops to approximately 25 percent of a monochrome equivalent. Finally, increased size and the addition of color affect the cost of a CRT. Fortunately, the computer applications market has created an economy of scale that has reduced the OEM cost of bright, medium-sized, high-resolution ($1,000 \times 768$ pixels) color monitors to under \$500. This price is almost low enough to render such a trade-off analysis moot. The only limitation of the new generation of color displays is that they may be too small (13- to 14-in. diagonal) to be used in visual field testing. Large-scale (19-in. diagonal), high-resolution ($2,000 \times 1,700$ pixels) displays that allow comprehensive assessment of the visual field are currently quite expensive (OEM cost approximately \$1,500). The electronics needed to drive these displays are also more costly and incompatible with standard video disk technology.

Monochrome monitors of comparable size and resolution are available at much lower cost (<\$500). It would appear that, given present economies of scale, a size-versus-color trade-off is unavoidable. Adopting a display that is both large and supports color will be expensive. A large, monochrome display may have the potential for visual field testing but sacrifices color capability. A medium-sized, high-resolution color display can be used to assess color blindness and depict realistic simulations of many targets at the cost of constraining the potential for visual field assessment.

Video Disk Technology

The video disk is an optical storage device specifically developed to record and play back pictorial and graphic information. Full-length feature films can be stored and played back as up to 10,000 or more individual picture fields or frames. The unique advantages of this technology compared with standard film media are that (a) video disks can be easily interfaced and controlled by a computer and (b) video disk frames can be accessed randomly, not just sequentially. Hence, a properly interfaced computer can display, on demand and in real time, any frame or sequence of frames stored on the video disk.

The potential significance of video disk media for driver vision-testing applications is that highly realistic simulations could be supported at a relatively low cost (121, 122). That is, first-order approximations of typical driving scenes could be presented and potentially used in the testing and training of driver's license applicants. For example, because of the realism of the video disk medium, actual video representations of new highway signs could be used in general-knowledge assessment and instruction. Similarly, the technology could be used to show video sequences depicting proper driving procedures or special techniques to compensate for poor weather conditions or diminished sensory capacity, or both. Video disks typically support two audio channels that could be used to provide auditory accompaniment and hearing assessments. Finally, video disks could be used to store and present stimuli needed to implement visual assessments of standard acuity, contrast sensitivity, and low-contrast acuity without incurring the cost of a graphics processor in the host computer controller.

Several manufacturers currently supply video disk players (e.g., Panasonic, Phillips, Pioneer, and Sony). The OEM cost of the units varies from around \$400 to \$1,200, depending on specifications (123). The upper end of this range (\$1,000 to \$1,200) is a good estimate of the cost of a unit with the minimum resolution and picture quality needed to test driver vision (exclusive of the cost of the CRT display and control computer system). The hidden costs of implementing video disk-based stimuli would be incurred in the production of any active materials such as those demonstrating proper driving behavior

and techniques. Such scenes must be thoroughly planned and filmed with the support of a professional video studio. These costs can become quite high if much training footage is to be produced (124).

APPLYING THE NEW TECHNOLOGY

All of the tests currently used to assess driver vision as well as all of the emerging techniques discussed previously could potentially be implemented on a computer-controlled, video-based system. For the purposes of exposition, two prototypical advanced-technology visual assessment systems (ATVAS) are shown in Figure 10. System Configuration A, in the top half of Figure 10, consists of a disk-based (30 meg) control computer (\$1,000), a video graphics controller (\$300), a high-resolution display monitor (\$500), and a four-position response console (\$100). The total estimated cost of this system is \$1,900 based on OEM quantity pricing. System Configuration B, at the bottom of Figure 10, is similar to Configuration A except that the graphics controller is replaced with a high-quality interactive video disk player (\$1,000). The estimated OEM cost of this system is \$2,600. The potential applications and benefits of such video-based vision testing systems are described next.

Automation

The first advantage of computer-controlled video testing systems would be highly automated test administration. Because of the inherent flexibility of the general-purpose computer controller and the programmable video display, the system would be capable of automating standard pencil-and-paper knowledge tests of traffic laws, signs, and procedures that are currently administered and scored by hand. Hence, in addition to providing a gateway for new visual assessment techniques with minimum impact on personnel costs, an automated general-purpose vision tester could off-load current personnel demands by assuming test administration functions.

The potential operational cost savings of automated testing should not be underestimated. Commenting on the personnel demands that would be placed on the Pennsylvania Department of Motor Vehicles if just 1.5 min of test time were needed to assess visual function in each eye, Keeney (125, p. 791) writes:

In Pennsylvania this would require over 8 million examinations. At . . . a minimum test time of 1.5 minutes per eye, this would require 10,000 work weeks or 200 man-years to accomplish. If another 1.5 minutes were required (for preliminary test preparation), Pennsylvania would require 600,000 hours, or 300 man-years to process its drivers once.

Fully automated test stations would not only allow new visual assessment techniques to be implemented in a cost-effective manner but could potentially pay for themselves by taking over the current test administration duties of motor vehicle bureau personnel.

Development of an automated test facility for the mass screening of driver vision would need to carefully incorporate the special needs and characteristics of the older population. Many of these special requirements have been discussed by Schieber (25). Several other age-specific constraints on automated testing were not covered by the DOT studies and are discussed elsewhere (25): general age-related slowing in motor response and information processing (126) and a recent finding that older adults have considerable difficulty recognizing computer-synthesized speech (127). The MARK II (27) Integrated Vision Tester employed prerecorded audio instructions in its successful attempt to apply the principles of automation to visual assessment of drivers. Because of the limited reliability and flexibility of sequential audio tape, more recent attempts at system automation have employed computer-synthesized speech to deliver test instructions and response feedback. Benefits of using computer-generated audio include the more rapid speed at which instructions can be delivered and understood, the ability to implement automation with illiterate populations, and the ease of support for bilingual test administration. However, the "unnatural" quality of low-cost speech synthesizers represents a real obstacle to speech intelligibility in older adults. The reasons for this difficulty with synthesized speech on the part of the aged are not understood but may involve diminished short-term memory processing capacity, lack of previous exposure to and practice with synthesized speech, or changes in the auditory nervous system (128). This problem must be avoided in automated testing of older adults. Fortunately, inexpensive digital-to-audio peripherals that are capable of high-fidelity, random-access replication of the human voice have been introduced recently (e.g., Antex Model VP-600 digital audio interface). The approximate OEM cost of adding digital audio playback capability to the disk-based computer controller shown in Figure 10 is estimated to be less than \$200.

The second age-specific problem with automated test administration is the increased time required by older adults to process and respond to sensory information. As a result, a stimulus delivery rate that would be optimal for young populations would place undue "pacing stress" on older respondents. On the other hand, a more relaxed stimulus presentation rate suitable for older adults would result in diminished efficiency of testing of the young and middle-aged population. Fortunately, the solution to this stimulus pacing problem is straightforward and simple to implement. Despite the simplicity of this solution, however, it is often overlooked by system designers. Pacing stress can be avoided and optimal test time efficiency maintained by programming the automated test system to deliver stimuli at a rate dependent on the

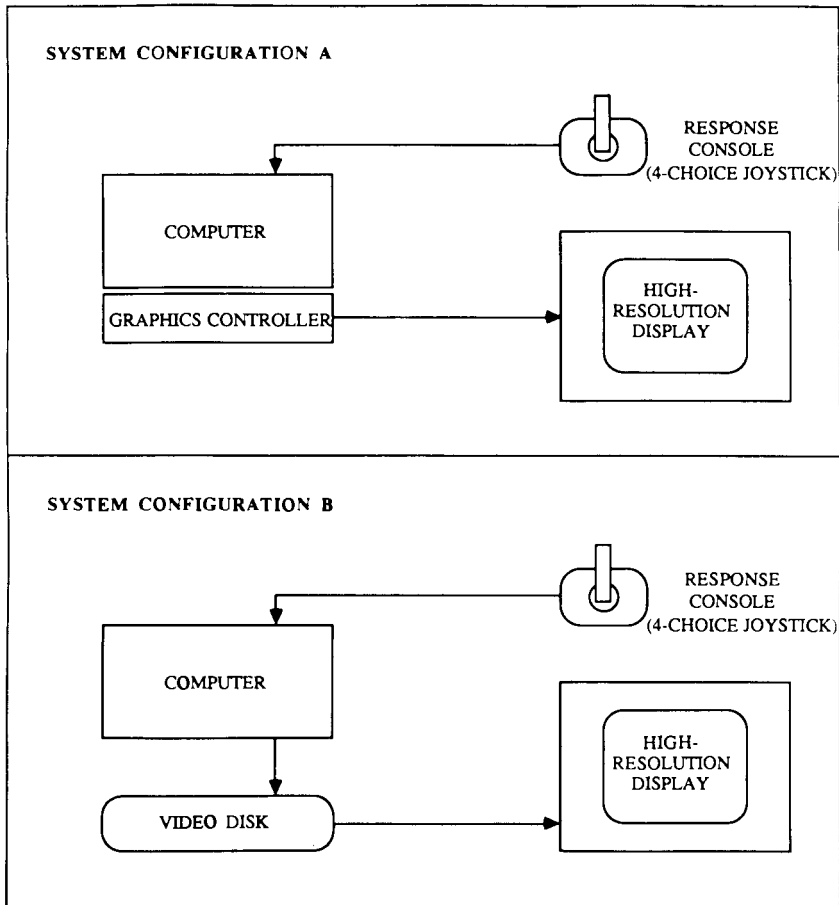


FIGURE 10 Schematic representation of some prototypical electronic visual assessment systems.

observer's response latency. That is, the next stimulus is not presented until the observer signals that he or she is ready to respond. Such self-pacing strategies have been successfully employed for many years by laboratory researchers to reduce response error and variability in older adults.

There is ample precedent for reliable assessment of visual function through the use of automated screening apparatus (129–131). More recently, the efficient use of CRT displays for the administration of basic acuity testing has also been successfully demonstrated (57, 132). Automated visual acuity testing via CRT displays is best performed using Landolt-C optotypes instead of

standard Snellen-like letters. The Landolt-C response can be easily communicated to the control computer (unlike the 26 choices available in the alphabet) and adheres to the recommendations of the National Research Council Committee on Vision (8) standards for acuity assessment.

The use of CRT displays for computer-generated sine-wave gratings and automated collection of the CSF has already been documented. Although many procedures have been used to rapidly assess contrast sensitivity (133), it has been clearly demonstrated that forced-choice methods must be used with older observers (59). Otherwise, their responses tend to be excessively variable and conservatively biased (10). Administration of such forced-choice contrast sensitivity assessment procedures, using pairs of sine-wave grating targets, could be automated quite readily by either of the prototypical systems shown in Figure 10.

A computer-controlled, video-based vision tester could also be used to implement low-contrast acuity testing. As described previously, such assessments would be most easily implemented through the use of Landolt-C optotypes instead of the more familiar Snellen and Sloan letters. Other tests, such as those employing a glare stressor, would require hardware extensions to the prototypical systems shown in Figure 10. The glare test, for example, would require the addition of an external luminaire that could be illuminated and extinguished under computer control. Additional revisions to the basic design might also include a viewing hood to isolate the video display from extraneous light sources and simple optics to allow multiple distance testing (e.g., near versus far acuity).

Finally, the computer control incorporated into the design of the prototypical vision tester could be used to implement state-of-the-art developments in psychophysical procedures that mathematically optimize test efficiency and reliability (134, 135). New "adaptive" techniques based on the maximum likelihood principle and more sophisticated Bayesian estimation approaches are computationally intensive and, hence, are not amenable to manually administered applications. However, the insertion of powerful, high-speed computers into the test administration loop now makes these advanced mathematical procedures practical and readily realizable (136–138).

Research and Development Gateway

A less obvious, yet significant, benefit of implementing an advanced-technology vision testing system is its potential role as a gateway for future research and development. A general-purpose, computer-based video assessment system could be easily reprogrammed to add new visual tests or modify current ones. As a result, researchers could quickly and inexpensively develop and test novel techniques in the field. New techniques and procedures could be

developed and improved within a stable, evolutionary context rather than through "fits and starts" characteristic of approaches that have employed traditional "hard-wired" test instruments. Automation of such experimental procedures would minimize the need to involve field personnel already busy with other duties.

The visual assessment approaches that are more perceptual than sensory in nature could benefit the most from such flexible test hardware. Assessment of visual search abilities and related higher-order "information processing" skills has potential for developing into preliminary screening tools for the determination of "cognitive competency." With sufficient development and testing, it is feasible that computer-based video techniques could be used to identify persons suffering from significant "developmental disability" or age-related dementing illness that could seriously impair driving safety. Such individuals could be subsequently referred to medical personnel for more rigorous physiological and psychological assessment.

Other research issues that could be readily addressed through a flexible, video-based assessment system include the use of nighttime-level luminance and motion in stimulus displays (e.g., the dynamic visual acuity debate). Luminance levels of visual optotypes could be easily reconfigured and tested in the field. The kinetic visual acuity (139, 140) and rotary DVA (141) techniques appear to provide tests of essentially the same functions as traditional DVA but in a manner amenable to implementation on a video display device.

A computerized, video-based test system could be deployed in several phases. First, it could be introduced to automate existing visual and informational testing programs. In a second phase, newly developed visual assessment techniques, such as those based on contrast sensitivity measures or low-contrast optotypes, could be deployed. After these are in place, a third phase that implemented computer-based instruction (CBI) for driving laws, signs, and procedures could be developed. In this manner "continuing education" of the driving population could be assured. Finally, a fourth, much more speculative, phase could be developed in which cognitive competence assessments were performed. In summary, the development and sequential deployment of an advanced-technology visual assessment system hold much potential for cost-effective improvements in the testing and delivery of services to the driving population.

SUMMARY OF RECOMMENDATIONS AND FUTURE RESEARCH REQUIREMENTS

The objective of visual screening for older drivers should be optimization rather than prohibition or restriction. Special tests that are sensitive to the

frequent ocular pathologies of old age are emerging. When detected, most of these age-related visual disorders can be corrected by prompt medical intervention. Hence, successful optimization screening of the elderly would not result in significant increases in the loss of driving privileges; instead, it would yield improved visual functioning with an accompanying increase in driving safety, mobility, and efficiency.

Studies should be conducted to quantify the effectiveness of contrast sensitivity techniques and low-contrast acuity testing for improving the mobility and productivity of the older driver population. Laboratory and clinical evidence clearly demonstrates that contrast sensitivity provides screening sensitivity for age-related visual pathologies that most often elude detection by traditional acuity measures. The modes of contrast sensitivity measurement that yield the most information on age-related ocular pathologies (e.g., cataract, glaucoma, and retinal disorders) are expensive to administer because of the apparatus and testing time required. In addition, standardized procedures for collecting and scoring CSF data remain to be developed. Recent findings have indicated that low-contrast acuity tests may yield a large subset of the information made available by CSF procedures. Unlike the contrast sensitivity techniques, low-contrast acuity tests are simple to administer and interpret. The costs and benefits of these two emerging techniques need to be carefully examined before either is implemented in a mass-screening application such as driver vision testing. The potential for employing a glare stressor for increasing the diagnostic selectivity of these methods needs to be explored. Both the contrast sensitivity paradigm and the low-contrast acuity technique hold promise for improving the level of visual functioning of older drivers.

Advanced technology should be applied to automate driver-screening tasks. The emergence of low-cost computers and high-resolution displays has made it possible to develop a general-purpose vision test station for mass-screening applications. Such a system could be used to implement fully automated administration of existing vision and driving knowledge and information tests. Computerized, video-based vision testers possess the characteristics required to implement emerging visual assessment techniques, such as contrast sensitivity and low-contrast acuity testing, and have the design flexibility to support anticipated future developments in vision testing, such as those incorporating motion and higher-order information-processing skills.

Mandatory periodic retesting of older drivers should be initiated by all driver-licensing agencies. All of the data collected to date clearly indicate that visual function is prone to dramatic changes during the latter part of the human life span. These data need to be carefully analyzed to show changes in the incidence rates of various visual disorders as a function of age. These quantitative data should then serve as the basis for scientifically determining the age at and frequency with which visual retesting is to be conducted. Such a

process would ensure that subsequently determined retest selection criteria would be based on facts rather than arbitrary conventions. The development of advanced automated vision-testing systems would make it possible to administer an ambitious retesting program in a cost-effective manner.

The following three steps need to be taken:

- Establish a photopic acuity illumination standard that is free of potential age bias.
- Transfer automated full-field perimetry technology to one amenable to mass screening.
- Explore the costs and benefits of employing CBI for continuing driver education.

Future attempts to establish causal relationships between measures of visual function and driving performance should employ simulation studies rather than rely entirely on correlational designs.

The feasibility and desirability of cognitive competence screening of driver's license and renewal applicants also need to be studied.

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Headlamp Performance Factors Affecting the Visibility of Older Drivers in Night Driving

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In 1985 in the United States 2,668 drivers over the age of 64 were killed in traffic accidents, representing 10.5 percent of all drivers fatally injured (1). At that time 11.8 percent of the population in the United States was over 64, suggesting that they were not overrepresented.

However, drivers over 64 were only 7.7 percent of those involved in fatal accidents, yet were 10.5 percent of those who were killed, suggesting their lower tolerance to injuries. Only about 7 percent of drivers involved in fatal accidents who were over 64 had a blood alcohol content higher than 0.10, which is about one-third that of younger drivers.

Older drivers are involved in fatal accidents in darkness about half as often as younger drivers. Drivers over 64 appear to have 15 to 30 percent of fatal accidents in darkness (Table 1), whereas drivers as a whole have 50 to 60 percent of their fatal accidents in darkness. The lower percentage of nighttime accidents of older drivers may be due to a number of exposure factors as well as their driving less at night (2).

Further analyses of these data taken together with the 1983 Nationwide Personal Transportation Study (which showed that drivers over 64 drove 14 percent of their mileage at night and younger drivers drove 26 percent at

TABLE 1 DRIVER INVOLVEMENT IN FATAL ACCIDENTS, 1985 (1)

Age (years)	Percent of Involvement by Time of Day			
	8:00 a.m. to 4:00 p.m.	4:00 to 8:00 p.m.	8:00 p.m. to 4:00 a.m.	4:00 to 8:00 a.m.
Over 64	60.3	23.9	10.9	4.9
All	30.2	22.9	37.4	9.5

night) indicate that the night-to-day minimum and maximum fatality rate ratios are 1.3 and 2.0, respectively, for older drivers. For drivers younger than 65 the ratios are 3.4 and 3.5.

The results indicate that the fatality rate at night is perhaps twice the daytime rate for drivers 65 or older, but for younger drivers the night fatality rate is about 3.5 times the daytime rate. Thus, the risk of driving at night increases relatively less for older drivers than younger drivers compared with the risk in the daytime.

Perhaps this could be due to a selection process among older drivers, so that only those who feel reasonably capable of driving at night do so. They may also be the same drivers who are not severely affected by glare and whose abilities to see at night are still relatively good. Such a hypothesis would need to be verified.

Accident analyses have rarely implicated glare as a factor. The Indiana University trilevel study of accidents (3) indicated that glare from headlights was a possible factor as an "environmental cause" in 0.5 percent of the accidents, but none were attributed to "vehicular factors" related to headlamps. Because about 22 percent of the accidents occurred in darkness, it is estimated that in 2.3 percent of those, headlamp glare was a causal factor. A study of 2,130 on-the-spot accident investigations by the Transport and Road Research Laboratory in Great Britain (4) indicated that glare was a factor in 30 of 231 accidents in which "adverse environment" was involved. More recently, a survey (5) in which drivers were asked about the causes of their run-off-the-road events found that glare was mentioned as the major contributing factor in 10 percent of the 30 cases that occurred at night.

Glare was also reported to be "bothersome" in night driving by 65 percent of drivers aged 19 to 39 (6) and in another study (7) 74 percent of drivers reported that they were occasionally dazzled and 33 percent said that glare was a frequent problem. Sixty-eight percent of drivers reported (6) that they became more rapidly fatigued driving at night than in the daytime. These reports show that drivers consider glare a problem in night driving.

CURRENT STATE OF THE ART

U.S. and European Designs

A brief history of the development of headlighting systems in Europe and the United States is provided in a number of recent publications (8–10).

The basic design of the meeting (low) beam of motor vehicle headlamps in Europe and the United States differs primarily in the amount of glare that is permitted. The European philosophy has always been to try to minimize glare for oncoming drivers, and they have achieved this by use of a shield to block light from the filament reflected from the lower part of the reflector. In this way, sharp control of the vertical part of the beam is achieved, and it is aimed so as not to be above the horizontal on the side of the oncoming driver. The beam is characterized by a very sharp cutoff in the lane occupied by opposing traffic and by a rising vertical beam to illuminate the road lane ahead of the driver. Typically, the maximum permissible candle power above the horizontal in the glare zone is about 400 candelas in the European low beam. By comparison, the U.S. low beam provides about twice the intensity of the European beam in the glare zone. This means that drivers meeting each other with low beams will be exposed to more glare from the oncoming vehicle's headlamps.

However, the U.S. beam provides a more gradual transition between pavement illumination and illumination at the sides of the roadway as well as at signs mounted above the roadway. Historically, the U.S. beam has also provided greater illuminating intensities directed on the pavement.

Thus, there is a trade-off between illumination on the pavement, which needs to be maximized to provide visibility of the road and, if possible, objects of importance to a driver at the roadside and even above the roadway, and the need to minimize glare. This is because glare reduces visibility and increases discomfort and may lead to fatigue in long-distance driving.

Glare, however, occurs not only when vehicles are meeting each other in frontal situations but also as a consequence of illumination of the mirrors by a following vehicle. In fact, a number of studies have shown that the reflected glare from mirrors frequently exceeds that from oncoming vehicles (11) and adversely affects visibility, especially that of older drivers (12).

Numerous tests of the visibility provided by the European and the U.S. low beams have been made (13), with the general finding that the U.S. beam provides better visibility on the road lane ahead and to the right side of the road than the European beam, which provides slightly better visibility on the left side. These tests have generally been done under idealized circumstances in which lamps were correctly aimed, the roads were dry, and the atmospheric transmission was high. In those circumstances the differences in the visibility provided by these two beams are generally small (14).

Aim and Alignment

In an evaluation of the performance of headlamps for night driving, many factors other than the beams need to be considered. Primary among these is the ability to aim headlamps correctly as well as to maintain their aim under a variety of circumstances in which vehicles are used (15). Vehicle loading is a major determinant of the resulting alignment of headlamps, as are factors attributable to use and servicing (16). The effect of changing bulbs or lamps on the resultant aim (17) has also been studied. The ability of service technicians to align headlamps properly has been evaluated; there are clear deficiencies in this area (15).

Dirt

The performance of headlamps depends on a variety of factors, some of which are independent of the design of the beam or the type of light source used. For example, dirt on the face of headlamps can greatly reduce the light that they emit and hence the visibility available to the driver, in many cases increasing the effects of glare (18, 19).

Rain and Fog

Although most headlighting tests have been conducted under ideal weather conditions, the weather is by no means always ideal. Night driving in clear conditions with low-beam headlamps provides marginal visibility. When bad weather is encountered at night, such as rain, the visibility provided by headlamps is substantially reduced because of the change in the reflective properties of the pavement; simultaneously, glare effects are increased because of reflections from water droplets on the windshield and the wet pavement. In such circumstances the visibility available to drivers is far less than that required for safety at normal highway speeds.

Nighttime fog is another condition in which visibility is substantially reduced, imposing heavy demands on headlamp technology.

Interaction with Streetlighting

Use of headlamps in areas where streetlighting is provided, and the interaction of the illumination and glare provided by headlamps with that of streetlighting can have complex effects on the ability of drivers to see pedestrians, bicyclists, and other objects. The result of this interaction can lead to an improvement in the ability of drivers to detect pedestrians along one part of a lighted road and a reduction in this ability in an adjacent section (20, 21).

Future Trends

The situation in the United States and Europe concerning future developments in vehicle headlighting is becoming more complex. The recent changes that allow the use of headlamps with separate bulbs in place of sealed beam units, the use of halogen bulbs enclosed in small glass envelopes, the increase in the maximum intensity of the high beam, and a trend toward reducing the height of headlamps above the pavement all generally contribute to a less favorable night-driving environment.

Current trends in motor vehicle headlighting in the United States and elsewhere are to permit headlighting standards to be based entirely on performance criteria and thereby to permit headlamps to be designed in any size or shape. In some respects this may be considered to be a step forward because it could provide an incentive for designing headlamps with the primary aim of improving visibility. There is also the possibility, however, that even if a suitable performance criterion of headlamps could be devised and agreed on, the ultimate objective would be to improve the aerodynamics and styling of vehicles at the expense of improved visibility for drivers of all ages.

VISIBILITY FACTORS IN NIGHT DRIVING

Glare Disability

A definitive study on the effect of glare on the visibility of targets was carried out by Wolf (22). For those in the driving age range, approximately 16 to 85 years old, the maximum differences in the thresholds attributable to age are approximately 1.0 to 1.5 log units.

Shortly after the work of Wolf, Christie and Fisher undertook a study concerned with the effects of glare from street lighting systems on visibility for drivers as a function of their ages (23). The underlying intent of this study was to evaluate the predictive value of the Stiles-Holladay expression of the equivalent veiling luminance: $G = KE/O^N$ and to compare this with an equation proposed by Fry (24): $G = KE/O (1.5 + 0)$.

The factor K in these formulas is a constant determined by the age of the observers; however, relatively little work has been done to establish the value. The conventional value of K is 10 pi.

Christie and Fisher reported three experiments (23) in which values for the age factor K were obtained. The results for the constant K in the three experiments were

1. $K = (0.2A + 0.4)$ pi,
2. $K = (0.19A + 5.8)$ pi,
3. $K = (0.2A + 6.8)$ pi.

These results showed that there was an effect of the background on the effect of the age variable. The general form of the equation is quite consistent in all experiments, however, and shows that age is an important variable in affecting the effective veiling luminance. The value of $K = 10 \text{ pi}$ is fairly representative of the findings of the study by Christie and Fisher. For drivers 60 to 70, K is approximately 16 pi , or a 60 percent increase. Therefore, the glare effect would also be increased by approximately 60 percent.

Computer simulations in which a constant value for the effect of age has been used could incorporate the equations of Christie and Fisher for the effects of age on disability glare.

These findings are consistent with studies made of visibility distances in situations simulating driving at night against the glare of headlamps of oncoming traffic. For example, in one study (25) with one group of subjects age 18 to 30 and another group 65 and over, the older subjects identified the test targets at distances 40 to 60 percent of those reported by the younger subjects for a number of different headlamp beams. In another study (26) subjects over the age of 61 were able to identify the orientation of a letter on a sign at distances 65 to 77 percent of those for persons under 25 years of age in a night-driving test.

Glare Discomfort

Glare not only causes a reduction in the visibility available to drivers, it can also create discomfort and perhaps hasten fatigue in night driving. The effects of disability glare in reducing visibility in night driving are noticeable first; glare levels must be greater to create discomfort (27).

A study of headlamp beam use by Hare and Hemion (28) found that requests by oncoming drivers to dim their beams occurred at a mean distance of 1,700 ft. However, 25 percent of the drivers dimmed their high beams at 2,400 ft or more. At such a distance the angle between the headlamps of the oncoming vehicle and the opposing driver would be quite small and the glare illumination at the eyes of that driver would be about 0.01 footcandle (0.1076 lx). Thus, this level of illumination at the driver's eyes with small glare angles might represent a criterion for discomfort glare tolerance. This was confirmed by Farber and Bhise (29), who evaluated the dimming requests against the discomfort glare scale developed by DeBoer (30) and found that requests occurred at "glare mark" values of 2 to 4, which indicates that the glare was disturbing.

In some experimental evaluations of various headlamp beams (13) drivers made ratings of the maximum discomfort they experienced when approached by each headlamp system. The results are shown in Figure 1. The data show that, even for the conventional U.S. low beam under good visibility and dry

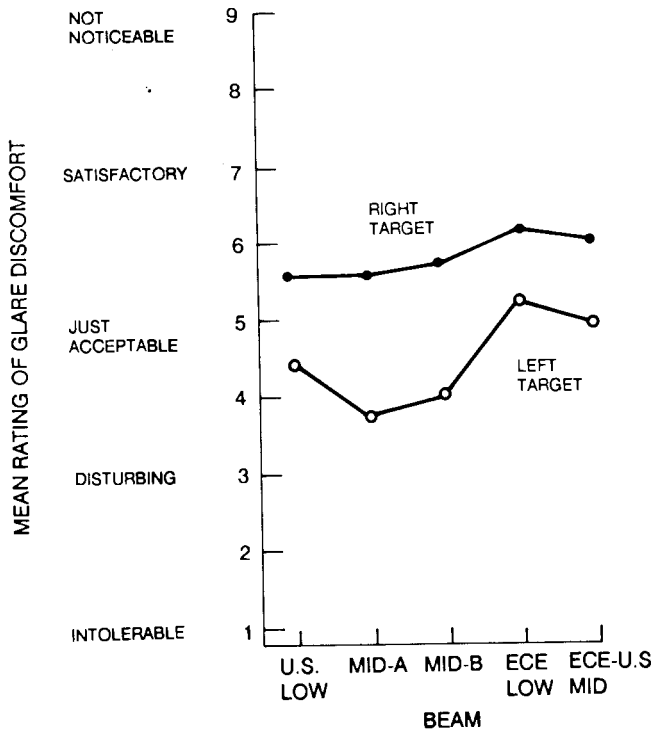


FIGURE 1 Mean ratings of maximum glare discomfort in meetings with five beams when driver is searching for targets on the right and left side of the lane (13).

road conditions, the discomfort glare levels can vary on either side of the "just acceptable" value. It should be remembered that the observers in these experiments were looking for test targets, which directed their gaze either to the right or the left edge of the road. Under normal driving conditions recordings of drivers' eye fixations (31) have shown that they frequently look toward the oncoming vehicle and that the frequencies of those glances increase as the distance between the two vehicles decreases. This means that drivers will be exposed to higher glare levels than may be supposed based on experiments designed to evaluate the visibility of targets. It is understandable that drivers would look toward oncoming traffic, at least on two-lane highways, to make sure that the oncoming vehicle is in its proper lane.

Thus, the extent of discomfort glare experienced by drivers on two-lane roads from the use of the U.S. low-beam headlamp provides an indication of what levels of discomfort glare should not be exceeded. This is particularly striking because the data were obtained under ideal viewing conditions. When

the roadway is wet or when it is raining, the visibility conditions are substantially worse and discomfort glare is greater. Furthermore, the current U.S. low-beam photometrics permit higher glare levels than in 1974, when the study was done. Combined with the growing use of halogen bulbs, this has resulted in a noticeable increase in glare.

None of the glare discomfort models reviewed has taken into account the age of the observers; this is a clear deficiency at this time. Some research shows that age does affect discomfort glare (32); some suggests that it is not a significant factor in discomfort glare evaluations (33). The latter study indicated that the differences between 16 "young" and 24 "old" subjects were negligible at low glare values, only diverging at higher glare levels, which caused more discomfort to the older drivers.

Glare from Rearview Mirrors

The interior mirror of automobiles has a reflectivity of about 0.85, and exterior mirrors have reflectivities of about 0.55. The interior mirror is often fitted with a feature to reduce the reflectivity to about 0.04 so that the glare of headlamps of following vehicles at night can be reduced. At this time, vehicles are not fitted to allow reduction in reflectivity of exterior mirrors other than to move the mirrors out of alignment so that they do not reflect the headlights of following vehicles. Clearly, this is undesirable because it means that much of the information provided by the exterior mirrors is lost.

Studies of the intensities directed at the rearview mirrors of automobiles by the headlamps of following vehicles have shown that they are frequently substantially greater than the intensities at the eyes of a driver from oncoming traffic (11, 34). A small study in which discomfort glare of a rearview mirror was examined found that with headlamps positioned 50 ft behind the mirror drivers rated reflectivities of more than 55 percent as producing excessive discomfort (35).

In addition, the following traffic tends to remain at relatively short distances, say 100 ft behind the vehicle, so that the illumination at the eyes of the driver by light reflected from the mirrors is high and present for relatively long periods compared with the time taken for an oncoming vehicle to pass the driver. Fortunately, the glare effect is mitigated by the relatively large angle between the driver's forward gaze and the mirror, except for those occasions when the driver looks directly at a mirror.

The exterior mirrors also frequently produce more glare for a driver, not only because they have no dimming feature but because when another vehicle is in the passing lane, its low-beam headlamps are directed with their high-intensity portions at the approximate position of the left-side exterior mirror, which results in high glare levels.

In a series of studies concerned with automobile rearview mirrors, Olson and Sivak (12) found that recovery time from glare for older drivers was substantially longer than for younger drivers and that the resulting thresholds were greater for the older drivers than the younger ones, as would be expected. In a driving study, the test subjects also rated the glare levels using the "glare mark" index (W) for 10-sec and 3-min exposures to the headlamps of a vehicle behind the vehicle they were driving. It was found that the longer the exposure of the glare, the more discomfort was experienced and, further, that the level of discomfort was related to the glare illumination at the eyes of the drivers produced from the following car's headlamps. The authors indicate that to avoid glare-mark values of less than 5, the illumination from the rearview mirror should not exceed 6 lx for short durations or 3 lx for longer durations.

A computer simulation of the effect of headlamps in the rearview mirror (36) provided data representative of the illumination due to the headlamps of a vehicle following at a distance of 100 ft, reflected from the rearview mirror into the driver's eyes (Table 2). The illumination criterion of 3 lx mentioned by Olson and Sivak (12) would be found in the case of low-beam headlamps at a mounting height of about 42 in. or for the midbeam headlamps mounted at about 24 in. when correctly aimed. In the case of a 1-degree upward misaim, the glare criterion ($W = 5$) would be exceeded for the low-beam headlamps at the lowest mounting height, indicating the debilitating effects of upward misaim.

Table 2 shows that there is a detrimental effect of glare from headlamps reflected in the rearview mirror of a preceding vehicle as headlamp mounting

TABLE 2 ILLUMINATION IN AUTOMOBILE DRIVER'S EYES FROM MIRROR-REFLECTED HEADLAMPS OF VEHICLE FOLLOWING IN SAME LANE AT 100 FT (36)

Aim (degrees)	Lamp Mounting Height (in.)	Illumination (footcandles) by Beam		
		Low	Mid	High
0;0	24	0.13	0.28	2.79
	30	0.16	0.42	
	36	0.20	0.66	
	42	0.29	0.99	
	48	0.45	1.48	
0;1,up	24	0.38	1.30	
	30	0.61	1.74	
	36	1.01	2.32	
	42	1.42	2.39	
	48	1.91	2.58	

NOTE: Interior mirror reflectivity, 0.85; exterior reflectivity, 0.55. (1 footcandle = 10.76 lx.)

height is increased between 24 and 48 in. (Federal Motor Vehicle Safety Standard 108 allows headlamps to be mounted as high as 54 in.) and due to upward misaim. It can also be noted that high-beam headlamps of a following vehicle at 100 ft clearly cause extremely high glare levels because of reflection in the rearview mirror of a preceding vehicle.

Table 3 shows the results of computer simulations (36) of the effects of a following vehicle on visibility for the driver of a preceding vehicle and the glare discomfort experienced by the driver because of reflections in interior and exterior rearview mirrors. The effects are shown for headlamp mounting heights on the following vehicle of 24 and 48 in. and for conventional low-beam headlamps and experimental midbeam headlamps on the following vehicle and when the driver of the preceding vehicle is viewing targets at the right edge and on the centerline of the road.

When the driver is viewing targets on the right of the road, the decrements in visibility attributable to the disability glare produced by the headlamps of the following vehicle are generally small except for the experimental mid-beam headlamps when they are misaimed 1 degree upward. However, the

TABLE 3 EFFECT ON VISIBILITY DISTANCE OF MIRROR-REFLECTED HEADLAMPS OF FOLLOWING VEHICLE (36)

	Minimum Visibility Distance		Maximum Visibility Distance		W at 500 ft Separa- tion
Beam on Following Vehicle	(ft)	Percent	(ft)	Percent	
Target on Right					
None	247	100.0	277	100.0	5.2
Low, 24 in., nominal aim	246	99.6	273	98.5	3.5
Low, 48 in., nominal aim	241	97.6	265	95.7	2.6
Mid, 24 in., nominal aim	244	98.8	269	97.1	3.0
Mid, 48 in., nominal aim	228	92.3	242	97.9	1.7
Low, 24 in., 1 degree up	242	97.9	266	96.0	2.7
Mid, 24 in., 1 degree up	230	93.1	245	88.4	1.8
Mid, 48 in., 1 degree up	218	88.2	229	82.6	1.3
Target on Left					
None	101	100.0	192	100.0	4.4
Low, 24 in., nominal aim	101	100.0	188	98.0	3.2
Low, 48 in., nominal aim	100	99.0	180	94.0	2.3
Mid, 24 in., nominal aim	101	100.0	184	96.0	2.7
Mid, 48 in., nominal aim	98	97.0	160	83.0	1.3
Low, 24 in., 1 degree up	101	100.0	182	95.0	2.4
Mid, 24 in., 1 degree up	98	97.0	163	85.0	1.4
Mid, 48 in., 1 degree up	95	94.0	147	77.0	0.9

NOTE: Following vehicle is at 100 ft (30.5 m). Interior mirror reflectivity, 0.85; exterior mirror reflectivity, 0.55. Results of computer simulations of meetings on a straight, level, two-lane road between automobiles using low beams.

glare-mark index calculated at a separation to an oncoming vehicle of 500 ft is substantially below the value of 5 ("acceptable") in all cases except the one in which no following vehicle is present. These increases in discomfort glare from the case in which the following vehicle does not exist (shown with a value of $W = 5.2$) are attributable to the effects of the headlamp conditions reflected in the rearview mirrors and are highly significant. The conditions are even worse when the driver is looking at the centerline of the highway, that is, slightly to the left of the vehicle, with all the other conditions the same (Table 3, lower half).

By comparison, the glare-mark index is calculated to have a value of 3.6 when two cars meet each other with high beams and are separated by 500 ft. It can be seen that the effects of a following vehicle are more severe than this in many of the conditions described in Table 3.

Although many vehicles have a day-night interior mirror, which permits the driver to reduce the extent of reflected light from a following vehicle substantially, there is no equivalent means of reducing the light reflected from the exterior mirrors. Following vehicles frequently provide glare for relatively long periods of time compared with oncoming traffic. Because of the effect on discomfort and visibility and the differential effect on the older driver, the problem posed by rearview mirror glare is significant. Clearly, then, it is important to provide a dimming device to reduce mirror glare in the exterior mirrors of motor vehicles as well as in the interior mirror.

Mounting Height of Headlamps

The current standard on the mounting height of headlamps indicates that the centers of headlamps may be mounted at a height of 22 to 54 in. (55.9 to 137.2 cm) above the roadway. Most automobile headlamps are now close to the lowest value in this range, whereas headlamps on pickup trucks and vans are substantially higher and those on large trucks are generally close to the upper value of the range. It is worth noting that European countries [Economic Commission for Europe (ECE) Regulation 48 and European Economic Community (EEC) Regulation 6-756] require mounting heights of 19.7 to 47.2 in. (50 to 120 cm) to the bottom edge of the lamp. However, in practice, vehicles have headlamp mounting heights that conform to a much narrower and lower range.

Within limits, the greater the mounting height the greater the visibility for the driver seated behind them. However, this is counteracted by increased glare for drivers of other vehicles, particularly the glare produced by rearview mirrors. Some of these latter aspects were discussed in the preceding section.

The visibility distances for the truck driver in truck versus car meetings (Figure 2) are greater than those for the car driver (car versus truck). Those

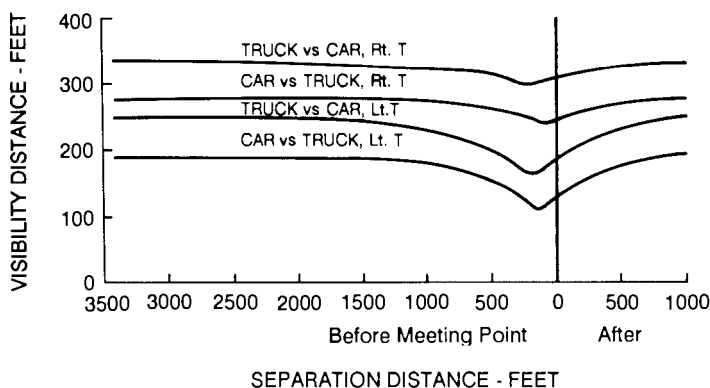


FIGURE 2 Computed visibility distances of 12 percent reflectance targets at right (*Rt. T*) and left (*Lt. T*) of lane for truck and car drivers meeting, both with low beams (36). (Reprinted with permission, Society of Automotive Engineers, Inc.)

differences are due to the greater mounting height of headlamps on the truck (48 in.) than on the car (24 in.) (36).

It appears, therefore, that the major problem of nonuniform mounting heights between cars and trucks is due to the indirect glare from rearview mirrors attributable to a truck, van, or pickup truck following a passenger car. It has already been shown (Table 3) that the higher mounting height of headlamps on trucks causes a reduction in forward visibility due to disability glare for car drivers and also large increases in discomfort glare levels.

For these reasons, the minimum and maximum mounting height regulations for headlamps of all types of vehicles should be reviewed. This is especially true for vans and pickup trucks, whose general performance and use are much like those of automobiles, and which accounted for about 30 percent of the U.S. vehicle market in 1986.

Headlamp Aim

Society of Automotive Engineers (SAE) Standard J599c indicates that headlamp aim should be maintained within tolerances of 0.8 degree from the horizontal and vertical axes of the lamp. Such a recommendation is quite liberal because changes in headlamp aim such as 0.5 degree up or down can cause substantial variations in illumination and glare. A variety of studies have examined the sources of headlamp misaim. One quite detailed examination of this problem (15) found that there were four major sources of headlamp misaim: differences between the beam and the mounting plane, photometric changes in use over time, errors in alignment of the long axis of the

vehicle in aiming, and factors related to the operators of the aiming equipment. Results of the investigation suggested that 43 percent of lamps could be expected to be beyond the SAE tolerances in the vertical or the horizontal direction. For example, it would be expected that the 95th-percentile vertical error would be 1.27 degrees, which is a large error in headlamp vertical aim that would seriously affect visibility and glare. These errors could be reduced by improvement in the practices used by service personnel, by maintaining a constant relationship between the mounting plane of the headlamp and the aiming plane, and by ensuring greater rigidity of the position of the filament over time and correct initial aim.

Improvements in the technology (e.g., the luminoscope) used to aim headlamps at service stations, inspection stations, and at the factory (37) have been demonstrated to be beneficial.

Another serious contributing factor to headlamp misaim has to do with the pitch alignment of the vehicle, which can be significantly affected by vehicle loading. This factor can be controlled by automatic vehicle-leveling devices.

There have also been some suggestions that the horizontal aim position of headlamps can be properly stabilized by suitable design of the headlamp mounting plane so that adjustments of the headlamp in the horizontal would not be required. This would leave the vertical adjustment as the only one with which there need be concern. Automatic headlamp-leveling systems that operate through the vehicle suspension have been constructed and evaluated and appear to work well (38). Such systems compensate not only for vehicle loading, but also for acceleration and deceleration, aerodynamic lift, and settling of the suspension over time. Jones and MacMillan (39) have shown that an automatic headlamp-leveling system that can maintain the standard deviation of aim to 0.25 degree would be satisfactory. They suggest a design goal of 0.3 degree maximum error, which was achieved by a mechanical system they evaluated. Costs of such systems are about \$60 on a mass production basis.

A less expensive approach than the self-leveling system is for the driver to manually adjust the vertical aim of the headlamps, but the driver is only partially capable of solving the aim problem. Clearly, fully automatic headlamp-leveling systems are most desirable because they will account for both the effects of load and transient effects due to the pitching of the vehicle. Nevertheless, many of the advantages of automatic headlamp-leveling systems will not be obtained unless headlamps can be initially aimed with a greater degree of accuracy than they are now and are able to retain their aim over time.

Although automatic headlamp-leveling devices or some kind of driver-actuated headlamp-leveling device is not required in any country at this time, it was reported at a meeting of the SAE Lighting Committee in May 1987 that

the Federal Republic of Germany has proposed regulations that would make headlamp-leveling devices mandatory.

Headlamp Washing and Wiping

Dirt on headlamps will act as a filter and also as a scattering medium, with the consequence that the illumination on the road will be reduced and the original photometric characteristics of the headlamp will be changed, with possible increases in glare levels.

One study (18) estimated that on dry, clean roads the reduction in light output from the headlamps was about 5 to 10 percent; at -15°C it was 15 to 20 percent; with a temperature just below 0°C and moist roads it was 30 to 45 percent; at temperatures of -5 to -10°C on snowy roads with salt it was 60 to 80 percent; and when the temperature was 0 to 5°C on slushy roads that had been salted the degradation was as high as 95 to 99 percent. It was also indicated that drivers are not likely to notice that their headlamps are dirty until the light output is reduced at least 60 percent, which was estimated to reduce the visibility of high beams by about 20 percent and of low beams by about 15 percent. Those data were reported for Sweden, where snow on roads and slush are not uncommon during the winter. Similar results could be expected in other regions having a similar climate.

A Finnish study (7) reported that the mean effect of dirt on a sample of 1,199 cars, 488 trucks, and 132 motorcycles was a 26 to 29 percent reduction in illumination. A lamp-washer system has been required in Finland since January 2, 1981. It was found that 21 percent of the cars and 44 percent of the trucks had such systems, but 5 percent of the cars and 27 percent of the trucks that were inspected lacked washing liquid.

High-pressure washers alone, without wipers, may be quite effective and are estimated to cost about \$15. The estimated cost for a washing and wiping system by lighting experts in the United States was about \$50.

It is obvious that under the worst night-driving conditions, such as in rain or snow or when there is slush and salt on the highway, there is the greatest opportunity for dirt accumulated on headlamps to reduce the illumination and increase the scattering of light from the headlamps. This occurs when the least reduction in visibility can be tolerated and suggests that efforts should be made to maintain cleanliness of the headlamp glass. Because the visibility in night-driving meeting situations is substantially less for older drivers than for others, the additional degradation caused by the loss of light output from headlamps under inclement weather conditions should be avoided. Clearly, this would be one area in which the older driver in particular could be aided.

Other Factors

Factors directly related to the design of motor vehicle headlamps, such as the beam patterns, the location of the lamps on the vehicle, washing and wiping systems, and headlamp aim, can clearly affect the visibility performance of the headlighting system. However, there is little question that the meeting beam of motor vehicles cannot be refined much further to provide improvements in visibility. Improvements under certain driving conditions, such as on straight roads, are attainable as demonstrated by so-called "midbeams," which provide more illumination along the lane being traveled without substantial increases in glare levels.

Overall, factors other than those related to the design of the vehicle are probably of more importance in affecting the visibility of all drivers and particularly older drivers at night.

Reflectorization of important hazards in the roadway is one general approach, as well as the use of paints containing reflective beads for roadway delineation. The types of materials that have been used on road signs have high reflective properties and indicate what can be done to achieve good visibility in night driving. Similar materials need to be used on salient roadside features such as bridge abutments and gore areas.

The roadway itself is frequently difficult to see, especially when wet. This most important of all objects for the nighttime driver must be as well defined as possible under all conditions of night driving; appropriate edgeline and centerline treatments should be used on all roads.

The visibility of the rear and sides of slower-moving vehicles such as trucks, farm equipment (40), and vehicles that make frequent stops on the roadway at night such as garbage vehicles should be improved. Such vehicles need additional lighting to ensure their visibility and to advertise not only their presence on the roadway but also their size and position on the road. These objectives can be partly met by the use of reflective sheeting material that has been available for many years and by improved lighting.

Pedestrians are one class of road user that is particularly difficult to see under many night-driving conditions, especially if low reflective clothing is worn, which is normally the case. Pedestrians should be encouraged to wear very light-colored clothing and in particular to use reflective materials on their outer garments. Other road users such as cyclists and motorcyclists can also benefit substantially from the use of reflective materials on the sidewalls of tires, the vehicle itself, and the clothing of the operator.

Although it is difficult to increase the illuminating intensities of the low-beam headlamps of motor vehicles to attempt to gain an increase in visibility, it is relatively simple to increase the reflectivity of the objects that the driver needs to see and thereby obtain a substantial increase in visibility. It is only by this joint effort between persons responsible for the design and operation of

motor vehicle headlamps and others responsible for the design of the highway environment that a reasonably safe night-driving environment can be attained. At this time, the night-driving environment in the United States and most other countries is far from safe at the speeds that are used on rural highways (41).

CHANGES TO IMPROVE NIGHT-DRIVING VISIBILITY

In the previous sections the current state of the art of motor vehicle headlighting has been described, as well as some of the major problems.

The areas where improvements appear to be warranted and feasible relate to the aim and alignment of headlamps, the mounting height of headlamps, the reflectivity of rearview mirrors, the cleanliness of headlamps, and refinements to the meeting beam. In addition, it has been mentioned that other factors than those directly associated with vehicle systems and headlamps can greatly affect the visibility of objects in the driving environment. The characteristics of the environmental variables, that is, their reflectivity, interact with the headlighting variables to determine the effective visibility. Similarly, the variables that affect headlamp performance, such as aim and mounting height, interact with other factors such as the reflectivity of rearview mirrors in determining the disability and discomfort glare experienced by drivers.

These kinds of interactions indicate the complexity of the task of deciding how to best provide an improved night-driving environment under headlamp illumination. However, some general rules can be stated. For example, the photometric characteristics of headlamps, as defined by the beam they emit and their illumination of the roadway and glare characteristics, are obviously determined by the aim of the lamp, which includes not only the alignment of the headlamp at any instant but also its mounting location and its cleanliness. In simple terms, then, it is essential to maintain aim in the nominal design condition and to keep the lamp clean as well as to take into account the effect of the mounting height of the lamp on the effective beam distribution on the roadway and at oncoming traffic.

The complexity of the interaction among all these variables can probably be simplified by imposing certain restrictions, which are considered in the following sections.

Mounting Height of Headlamps

The mounting height of headlamps is recommended to be restricted to a narrower range than is now permitted (22 to 54 in.). The mounting height of the centers of headlamps on U.S. passenger cars has historically been at about

24 to 25 in., but recently the trend has been to lower it. This has been accompanied by lowering the eye height of drivers. The effect is to produce less visibility of the roadway. Placing the eyes vertically closer to the headlamps has negative effects in rain, snow, and fog because of the increased backscatter from the headlamps to the eyes of the driver. Low headlamp mounting heights also decrease the reach of the headlamps on the road and reduce the angle of incidence of the light reaching the pavement from the vehicle, which in turn will reduce the amount of light returned to the eyes of the driver. For these reasons there needs to be a limit on the lower mounting height of headlamps. The current minimum should not be reduced.

There is much justification for reducing the upper limit on the mounting height of headlamps. The overall benefits in the reduction of glare that would be obtained would be realized rapidly as the vehicle population changes. It is recommended that Federal Motor Vehicle Safety Standard 108 be revised to limit the mounting heights of headlamps to within the range of 22 to 30 in. on all passenger cars, pickups, vans, trucks, and motorcycles.

Rearview Mirrors

The reflection from rearview mirrors is a substantial cause of discomfort glare and in many instances also of disability glare. To counteract this it is necessary to change the reflectivity of the mirrors for nighttime use. The interior rearview mirror of many motor vehicles can be switched to a night position that has a reflectivity of approximately 4 percent. This value is lower than necessary; a higher value would be somewhat more beneficial. Nevertheless, the 4 percent value of the interior rearview mirror is not considered to be a significant impediment to safety.

However, the exterior mirrors, which generally have reflectivities of about 55 percent, should be reduced in reflectivity for nighttime use to reduce glare when there is following traffic. Reflectivities in the range of 10 to 20 percent would probably be reasonable in reducing glare as well as providing adequate visibility of vehicles to the rear. It is important that the reflectivity in the night setting for either the interior or the exterior mirrors be sufficiently different from the daytime setting so that it is clearly apparent to drivers which setting is in use. This is to ensure that in the daytime drivers will use the daytime position and not retain the nighttime one, which could make it difficult to see other vehicles, especially under overcast conditions when vehicles behind may not be using headlamps.

Headlamp Cleanliness

Headlamp-cleaning systems now appear to be of two types. One uses a high-pressure spray and another a spray and wiping action. If both methods are

satisfactory, either one can be used. Such systems could be used in conjunction with the windshield wipers to operate only at night and on an intermittent, automatic basis and have a manual override for additional cleaning action at the option of the driver. In this way, headlamp cleaning would take place on an intermittent but relatively continuous basis even when the driver is not using the windshield-washing system. Headlamp cleaning can provide substantial increases in visibility under the very conditions when visibility is most degraded and when it would be of most advantage, especially to older drivers.

A reduction in visibility of 20 percent when the visibility is, say, 100 ft is much more serious than a 20 percent reduction in visibility when the visibility is 300 ft. Headlamp-washing systems can retain the integrity of the beam pattern in the most marginal visibility conditions. The need for such systems is also highlighted by the fact that drivers are not aware of the reduction in visibility created by dirt on their headlamps and may continue to drive with dirty headlamps even when the weather conditions that produced the dirt are no longer present. Unlike large levels of glare from rearview mirrors, the effect of dirt on headlamps is not readily perceived by drivers and therefore calls for some type of automatic cleaning system.

Headlamp Aim

Aside from the photometric distribution of light designed into the headlamp beam system, the factor that most affects the distribution of light emitted from the headlamps is the alignment of the lamp in practice on the vehicles. The theoretical effectiveness of any headlamp beam system cannot be achieved if aim variance is at all large. The meaning of the term "large" in this context is a very small amount of change from the nominal aim condition. That is, variations in aim of more than about 0.25 degree create relatively large changes in beam effectiveness. This implies a small tolerance in the aim of headlamps because of static and dynamic conditions.

Manual compensation for vehicle loading by providing driver control of the vertical alignment of the headlamps would be a beginning step—the Ford Motor Company believes that vertical adjustment only is necessary if proper mounting of the headlamp is provided so that horizontal adjustment is not required. Suitable design of the headlamp mounting plane, as mentioned earlier, would make reaiming unnecessary when sealed beam lamps are replaced or when bulbs are replaced in units that use separate bulbs. This would require sufficient structural rigidity as well as alignment of the aiming plane of the lamps to that of the vehicle. That would provide a first level of potential improvement that goes hand in hand with the ability to correctly aim the headlamps at the factory and in the field. The type of aiming equipment needed to accomplish this has been demonstrated in Europe (37).

It would be more desirable to incorporate automatic headlamp alignment systems that compensate for both static loading changes as well as the dynamic changes that occur when the vehicle is in motion. Such systems would clearly minimize glare and retain the maximum effectiveness of the headlamp beam. However, glare would not be eliminated because of road geometry such as that on crests of hills or curves, but in other conditions the glare levels should be within design tolerances. If automatic alignment systems were to be incorporated, some small advances in the shaping of the meeting beam could be made and would be worthwhile, but it is questionable if such advances can be made at this time and achieve any significant improvements in overall visibility and comfort in night driving without automatic headlamp aligning and correct initial aiming systems.

Beam Shaping

Both the U.S. and the ECE meeting beam have evolved over many years of development and have become more similar over time and unquestionably are close to an optimal beam pattern. This is probably so within the constraints available on headlamp aim. Unless improvements in headlamp aim are made, it is questionable whether additional changes to the meeting beam can be achieved that would benefit the older driver.

It is quite clear that glare control must be a major consideration for older drivers. Thus, a headlamp beam that achieves this would probably be advantageous to them, even if it results in some overall loss in roadway illumination. In this respect, the ECE beam may well be advantageous for the older driver because of its overall lower glare levels. Therefore, if the vehicles of all drivers were equipped with ECE-type beams, glare levels should be lower under most conditions. However, ECE beams that are misaimed or misaligned can cause substantially greater glare levels than those of U.S. beams. This again emphasizes the importance of achieving better glare control by improved maintenance of aim. Yet it must be remembered that fewer states than in the past now have vehicle inspection requirements, providing little inducement for drivers to have their headlamps checked for aim. Although the quality of aiming by service stations is generally poor, as has already been indicated, that situation could be changed, and the necessary equipment to achieve good quality aim is available.

Recent proposals that would allow a multiplicity of headlamps on motor vehicles would have both positive and negative effects. They may aggravate the aim problem because of the increased number of lamps that may exist on vehicles and would increase the costs of headlamps themselves. However, the increased number of lamps would imply a degree of redundancy so that a

lamp outage need not create a significant loss in illumination and improved beam shaping would become more feasible.

The use of more than two basic beam patterns on motor vehicles has been explored for a number of years with the midbeam. This intermediate between the low beam and the high beam is an approach to improve visibility under many circumstances on both divided highways as well as two-lane roads. It relies, however, on the driver to switch off the midbeam under conditions when it would provide excessive glare to oncoming traffic, primarily on curves. If the dimming function from the midbeam to the low beam, or any change in beam pattern commensurate with oncoming or preceding traffic, could be accomplished automatically and reliably, such beams would become more feasible. Up to now, headlighting engineers have believed that the driver cannot be relied on to adequately use a three-beam system. That is a debatable issue that has not been properly evaluated; with the probability of multibeam headlamp systems being permitted it is a matter that requires further consideration. Nevertheless, automatic beam selection appears to be a way in which improved illumination and visibility could be provided, and is therefore worth much more investigation.

Polarized Headlighting

The subject of polarized headlighting has been omitted from this review because it has been adequately dealt with elsewhere. The advantages and disadvantages of the concept have been evaluated, and it appears to be more and more feasible from a technical standpoint. The implementation problems are still quite large, but further consideration should be given to this concept.

Factors Unrelated to Vehicle Design

Factors other than those related to vehicle design considerations that determine the visibility of objects in the driving environment offer the greatest scope for improving night-driving visibility and permitting glare levels from headlamps to be reduced. The advantages of increasing the reflectivity of objects and the feasibility of doing so are far greater than providing increased illumination from headlamp beams. For example, an increase in reflectivity of an object by a factor of 2 may increase its visibility by 20 to 40 percent and would in many instances be entirely feasible. The same effect could be obtained by increasing the illumination from headlamps by a factor of 2, but this approach appears not to be feasible at this time. For this reason changes in the night-driving environment offer the most immediate hope for improving visibility and comfort.

RESEARCH NEEDS

Gaps in Knowledge

There is little question that sufficient information is not available on the types of accidents in which older drivers are involved as well as the risk of night driving among older drivers compared with others. The severity of accidents in which older drivers are involved should also be estimated.

In addition, more information is needed on the role of discomfort glare for older drivers and the extent to which it discourages them from driving at night. The percentage of older drivers for whom discomfort glare is a significant problem is not known, nor is it known if these are the same persons who reduce their night driving for that reason.

Improvements in the modeling of discomfort glare as a function of driver age would allow improved estimates to be made of the effects of changes to vehicle and environmental variables for older drivers by the use of existing computer simulation models.

The effects of age on disability glare and visibility in night driving should probably be further evaluated so that improved computer simulation models can be devised or changes to current models can be made if necessary. In addition, although both laboratory and analytical studies should be conducted to evaluate the effects of a host of variables upon night-driving visibility of older drivers, these should also be confirmed by studies conducted in the field. Dynamic field studies should be undertaken to assess the effect of visibility under a variety of weather conditions, not just under ideal conditions, as has been done in the past.

Cost-benefit analyses and effectiveness studies on factors such as automatic headlamp-aiming systems, headlamp-cleaning systems, and day-night exterior rearview mirrors should be made. It would be important to try to ascertain more clearly the role of vehicle lighting and associated factors that have an effect on the visibility available to drivers and their risk in night driving.

Research Programs

Perceptions of Older Drivers about Night Driving

The exposure of older drivers at night is low. Is it because of factors related to driving at night or to others unrelated to driving? Would mobility be increased among older drivers if night driving could be made safer and more comfortable for them? Do older persons who drive at night have better visual abilities than those who do not? What do older drivers perceive to be the major problems in night driving and do they think these problems could be reduced? Would they be willing to pay for improvements that would improve visibility and reduce glare? Questions of this type and others should be elicited in

surveys of older drivers to learn more about their perceptions about night driving in general.

Effectiveness of Headlamp-Cleaning Systems

The effectiveness of headlamp-cleaning systems should be evaluated under actual or simulated rainy, wet road, slush, snow, and slush and salt conditions in terms of changes in the photometric distribution of the headlamps and for a number of beams (e.g., U.S. low, ECE low, U.S. high). Costs of installation at the factory and after sale of the vehicle, maintenance, frequency of operation for adequate performance in various environmental conditions, the manner of control by the driver, and whether the operation should be semiautomatic or fully automatic need to be determined.

Effect of Age on Discomfort Glare

The effect of age on discomfort glare from vehicle headlamps needs to be established so that age can be used as a factor in discomfort glare models. It will be important to ensure that the studies use background luminances within the range of those found in night driving, including those that are found in inclement weather and good weather conditions. Laboratory studies should be complemented by field tests, conducted dynamically in representative weather conditions.

Effect of Age on Disability Glare and Visibility in Night Driving

A study should be undertaken to confirm the relationship between the age of drivers and disability glare, preferably using a dynamic paradigm. The results of such a study would provide a confirmation of disability glare equations, including the age factor, or suggest revisions to them. The study should also attempt to model the "readaptation" and "recovery" process (42) from glare. Computer simulation models [e.g., that discussed by Bhise et al. (27) and by Mortimer and Becker (14)] should then be revised, if necessary, to better account for the age factor and the transition from glare to no-glare as the vehicles approach and pass each other in simulated meetings, and the effects of age on visibility should be determined for a variety of vehicle, headlamp, and road conditions.

The laboratory and analytical studies should be further confirmed by dynamic field tests of visibility in a variety of weather conditions.

Involvement of Older Drivers in Nighttime Crashes

There is now inadequate information on the involvement of older drivers in nighttime crashes. Analyses need to be conducted to take into account their exposure and their accidents to confirm the risk of older drivers compared with those of other ages in night driving. The character of the accidents in which older drivers, compared with younger drivers, are involved should also be investigated to discern whether visibility problems are greater or different among older drivers. Such analyses should also attempt to discover the potential role of variables that could be used to improve night-driving visibility for older drivers in particular.

Day-Night Exterior Mirrors

Exterior mirror glare is a severe problem in many night-driving conditions. Means to reduce the glare should be developed and an appropriate reflectivity of exterior mirrors for nighttime conditions should be ascertained, taking into account the age distribution of drivers.

Automatic Headlamp Beam Switching

In order to allow the use of multiple beams (e.g., three or more or infinitely variable beam systems) that enhance visibility on divided highways and on two-lane roads, automatic control of the beam is needed. Automatic beam selection must satisfy the need to reduce glare to oncoming traffic at crests of hills, on curves, and when following other vehicles.

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