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Visibility Problems in Nighttime Driving

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ABSTRACT

Many traffic accident cases involve questions of driver visual perception. It is common for one or both sides to employ experts in such matters. These individuals often make use of reconstructions in an effort to arrive at an opinion concerning driver perception. While such reconstructions can be helpful, they can also be very misleading. The purpose of this report is to review basic information concerning visual perception, to lay a foundation for understanding how the visual system works under nighttime driving conditions. Applied research on night driving will be covered as well, with a particular focus on detecting conditions in the forward field. The report concludes with a section on problems that can degrade visual performance at night.

THE PROBLEM - Many traffic accident cases argued before juries in this country involve questions of driver visual perception, e.g., what a driver could or should have seen, when or at what distance he/she should have seen it. While preparing their case it is not unusual for one or both sides to hire experts to address this issue. The experts will sometimes prepare reconstructions of the event in an effort to estimate the values in question. On the surface, this sounds like an ideal approach. Indeed, it can sometimes be very useful. However, it has distinct limitations. For example, estimating something like nighttime detection distance for an object by measuring the distance at which one or even several persons can see it in a reconstruction is like trying to estimate the stopping distance of a large truck by using a sports car. No judge would allow the latter type of evidence to be introduced. No judge should allow the former evidence to be introduced either.

But, if one cannot estimate values such as these from a reconstruction, where are they to come from? There are two possibilities. First

there are data that can be helpful, if knowledgeably employed. Second, if all else fails, reconstructions can be used. However, the investigator must understand the limitations of such an approach, so that appropriate corrections can be made to the resulting data.

This paper is intended to summarize information on the question of driver visual perception under nighttime operating conditions. The hope is that it will aid individuals involved in accident analysis and reconstruction to better understand visual perception and how its operation and limitations may affect a given situation.

ESSENTIAL STEPS IN DRIVER INFORMATION PROCESSING - Before a driver can be expected to make an appropriate response to any roadway situation four things have to happen. According to Alexander and Lunenfeld (1) these are:

1. Detection. Detection results in a conscious awareness that something is present. *COG*

2. Identification. In this step enough information is acquired about the "something" to allow the driver to make an appropriate decision as to what, if anything, to do about it. The information would typically include what the something is, and, if it is capable of movement, what it is doing. The identification need not be complete in detail. For example, a driver doesn't have to know if the object ahead is a cow, truck, or boulder; it is enough to know the lane is blocked.

3. Decision. The driver decides on a response to the condition.

4. Response. Orders are issued by the motor center of the brain to the appropriate muscle groups to initiate the response decided on.

The first two steps, detection and identification, involve perception and information processing, and will be the focus of much of

this report. The key point to be made here is that detection and identification are different processes. Correct identification does not automatically follow detection, and a failure in either one can result in disaster.

Some accidents that have been attributed to a failure on the part of the driver to maintain a proper lookout were quite possibly due to misidentification. Sometimes drivers find themselves in situations that can be deceiving. For example, vehicles with unusually closely spaced headlamps may look further away than they actually are. Other situations tax the limits of the perceptual system. Examples of these will be offered later. It may not be possible to determine with certainty what happened in a specific instance, but a more complete understanding of the operation and limits of visual perception can at least aid in determining whether the statements offered by a witness are reasonable for a given set of circumstances.

DRIVER RESPONSE TIME - The steps in information process just described require time to accomplish. How much time is a question that is not only frequently raised in litigation, but is of considerable importance in roadway design as well.

The time that it takes a person to respond to a stimulus has been a subject of investigation for a long time. In the simplest of situations, i.e., fully attentive young subject, a clear stimulus, and a simple response such as

pressing a button, response times of about 0.15 second will normally be obtained. As the amount of information the subject is required to process is increased, response time increases as well.

A number of studies have been concerned with the time it takes a driver to apply the brakes when confronted with some kind of stimulus. This was sometimes measured by simple tasks such as pressing the brake when a hood-mounted light came on. An early review of such data (2) concluded that brake reaction time for the majority of drivers is between 0.5 and 0.7 second.

The real question is how long does it take drivers to respond to unexpected stimuli of various types under realistic driving conditions? Such studies are very difficult to carry out because of the need for catching the subject unaware in a driving situation without causing undue risk. However, in recent years there have been some very interesting studies reported. For example, Triggs and Harris (3) observed the response times of passing motorists to a variety of conditions they had set up. Table 1 is a listing of the 85th percentile reaction times they found for the different situations. Not all the conditions have the same urgency value. For example, the Roadworks sign, in the absence of evidence of construction, would not be expected to elicit a strong response. The authors also point out that the response of drivers to

Table 1

85th Percentile Reaction Time Values

C.R.B. "Roadworks Ahead" Sign	3.0s
Protruding vehicle with tyre change	1.5s
Lit vehicle under repair at night	1.5s
Parked Police Vehicle	2.8s
Amphometer* : Beaconsfield	3.4s
Amphometer : Dandenong North	3.6s
Amphometer : Gisborne	3.6s
Amphometer : Tynong	2.54s
Railway crossing : Night (General Population)	1.50s
Railway crossing : Night (Rally drivers)	1.50s
Railway crossing : Day	2.53s
Car following	1.26s

From: Triggs and Harris, 1982.

*An amphometer is a speed-measuring device consisting of two pneumatic tubes spaced some distance apart. It is commonly used in Australia.

stimuli such as a parked police vehicle or the amphotometer (a speed measuring device) depends to some degree on how fast they are going relative to the speed limit at the time of detection.

Summala (4) also measured the response time of passing motorists. In one case he parked a car by the side of the road, and briefly opened the driver's door as a car approached. Measures were made of the time from the door opening until the approaching car began to move left. It was found that this displacement began an average of 1.5 seconds after the door opening.

In another study (5) subjects drove a test vehicle for "familiarization" purposes for some time, finally encountering an obstacle in their lane over a hillcrest. Response times to this stimulus ranged from 0.9 to 1.8 seconds.

The results of these investigations indicate that response times for drivers under normal states of alertness should be taken to be not less than 1.5 seconds. If allowance is made for less compelling stimuli, driver fatigue, drug and alcohol use, longer response times should be assumed.

THE HUMAN VISUAL SYSTEM UNDER NIGHTTIME DRIVING CONDITIONS

THE EYE - The eye has often been compared to a camera. Indeed, there are substantial similarities on a structural level. Figure 1 is a diagram of the eye, with some of the principal parts labeled. These can be described as follows:

The cornea is the transparent front surface of the eye through which light enters.

The lens is one of two media that bring light to a focus on the retina (the other is the cornea). The lens is flexible. It is suspended in a network of muscles that can change its focal length by causing it to become fatter or thinner. By so doing the lens can bring both near and distant objects to a sharp focus, a process known as accommodation.

The lens is an unusual structure in that it continues to add layers of cells throughout life. Since it cannot grow larger it becomes more dense and less flexible instead. The result of this is that the eye gradually loses its ability to focus up close. This is called presbyopia, and the result for many people is an eventual need for reading glasses or bifocals. The lens also becomes somewhat yellow with age, reducing the level of illumination reaching the retina, particularly from the blue end of the spectrum.

The iris is the colored portion of the eye. It functions to control the size of the opening in front of the lens (the pupil), regulating the amount of light that can enter. It is one of two mechanisms (the other other is the retina) that allow the eye to function through a very broad range of lighting conditions.

The maximum opening of the pupil becomes less with age, varying in diameter from about 7.5mm at age 20 to about 4.8mm at age 85 (6). In area, this is a change from about 44 to 18

ILLUM.
square millimeters, meaning that nearly 2 1/2 times more light is getting by the iris in a 20 year old eye, compared to an 85 year old eye, under dark-adapted conditions.

The retina is the light-sensitive layer of the eye, the central portion of which is called the fovea. The retina covers about two-thirds of the interior of the eye and contains the light-sensitive cells. There are two types of cells, the rods and cones, which differ functionally as well as in their distribution throughout the retina.

The cones function at higher light levels (providing what is called photopic vision), and are wavelength sensitive, producing the sensation of color. Rods function at lower light levels (providing what is called scotopic vision), and are not wavelength sensitive. Hence, pure rod vision is in shades of gray. There is a middle range of light levels in which both rods and cones function. This is called mesopic vision. Typically, night driving is done under mesopic conditions (7).

Compared to rods, cones have far fewer neural interconnections, hence are capable of finer discriminations. Cones are found exclusively in the fovea, and in rapidly diminishing numbers as one moves away from the fovea. Rods are found throughout the retina, with the exception of the fovea.

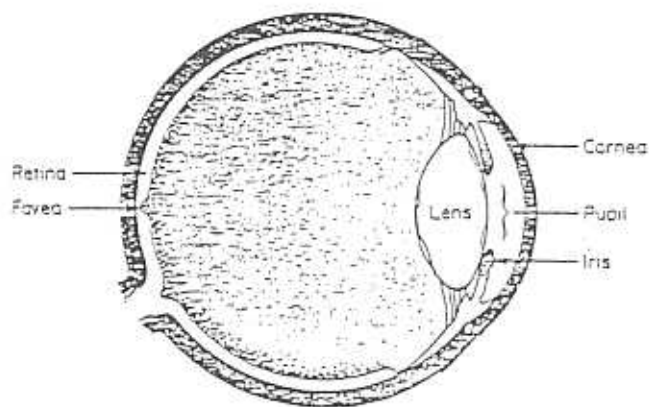


Figure 1. Diagram of the human eye.

VISUAL PERFORMANCE - Measurement of Visual Performance - The measure of visual performance with which most people are familiar is static acuity. Static acuity is a measure of the ability to distinguish fine detail in a stationary target. It is typically represented as a comparative figure, e.g., 20/20. The first number represents the performance of the person being assessed, and it does not change. The second number represents the performance of a "standard observer." A score of 20/20 means that the person being tested can resolve fine detail as well at 20 feet as can the standard observer. It does not mean "perfect vision," as people sometimes claim. A score of 20/40, which is sometimes set as the lower limit of acuity

for a driver's license, means the person being tested can resolve fine detail as well at 20 feet as can the standard observer at 40 feet. A person with an acuity of 20/40 can read a highway sign at only half the distance of someone with an acuity of 20/20.

There are a number of other measures of visual performance, many of which do not correlate highly with static acuity, but may be meaningful in the driving context. Some of those that are appropriate for night driving are: (1) low-luminance acuity, (2) low-contrast acuity, (3), glare susceptibility, (4) glare recovery, and (5) low-contrast target detection threshold. Measures such as those listed are rarely taken, except for experimental purposes, and it is not known whether they relate to accident experience.

Performance Implications From the Structure of the Eye - The response characteristics of the rods and cones, and their distribution in the retina, have implications for visual performance. Under photopic and mesopic conditions we can see most clearly things that are imaged on the fovea. The quality of vision falls off very rapidly as one moves away from the fovea. For example, in daylight, if a person's acuity for objects seen foveally is 20/20, acuity for objects imaged at five degrees from the fovea will be about 20/60 (8).

Because the fovea is so small relative to the entire visual field, detection typically occurs in the periphery. The eyes may then be shifted to bring the detected object into sharp focus in the fovea as part of the identification process. However, in order to be detected, an object in the periphery must be much more conspicuous than if its image had fallen on the fovea. One common error accident investigators make is attempting to estimate nighttime detection distances based on foveal inspection of the scene. More about that later.

The Processing of Visual Information - At any given point in time there may be a great deal of information imaged on the retina. However, in the higher centers of the brain information is handled serially. This means that people can typically concentrate on only one thing at a time. Humans have the ability to rapidly switch from one item of information to another if they wish to do so, and can process a great deal of information in a fairly short period of time if necessary. However, the serial nature of human information processing presents difficulties if there is other information of which an individual should be aware. Not only is the new information likely to appear in the periphery, where it is less well seen, but it must somehow capture the attention of an observer who is quite possibly otherwise occupied. In motor vehicle operation, the time available for all this to happen is typically fairly short.

Fortunately, there is a mechanism, sometimes called the "peripheral filter," the function of which is to determine what will come to the attention of an observer. While the way in

which the filter works is not understood, the types of stimuli that are likely to pass it and result in a foveal fixation are known. In general, the eye is attracted toward areas that contain a great deal of information, such as concentrations of signs, lights, people, etc. (9, 10, 11); objects that differ greatly from their backgrounds in terms of brightness, color, texture, etc. (12); flickering or flashing stimuli (12, 13); objects of large size (12); and objects that are moving (12). Most people would probably agree that the characteristics listed are those that make something "conspicuous."

"Conspicuity" can be defined as the characteristics of an object that determine the likelihood that it will come to the attention of an observer. The fact that something may be present in the visual field does not necessarily mean that it will be detected, because it may have less conspicuity than other visible features. This is especially true in areas where there is a great deal of information available. In an urban center, particularly at night, not only is there much to be concerned with (e.g., vehicles and pedestrians, advertising, and various signs and signals), but it would not be unusual for the most conspicuous features of the environment to be something like advertising signs, which at best are irrelevant to the driving task.

Adaptation to Different Levels of Illumination - The human eye is capable of responding to illumination through a range of ten to eleven log units. As noted earlier, only the cones function at high levels of illumination. As light levels decrease the cones become more sensitive. According to Grether and Baker (14), about four log units below the upper level of visual tolerance, at a level of illumination approximating two foot-candelas on a sheet of white paper, the rods begin to function together with the cones. Rods and cones continue to function together as illumination is decreased about another 3.5 log units. Finally, at a level about that of average earth viewed in a full moon, the cones cease to function.

The process of dark adaptation takes time. How much time depends on the level to which the eye is originally adapted and the new level to which it must adapt. For example, if an individual walks from bright sunlight into a photographic darkroom, a half hour or more may be required to reach maximum sensitivity. In typical driving situations the changes are much less drastic. As a consequence, adaptation times are much shorter. Adaptation problems are sometimes experienced in driving from bright sunlight into a tunnel or from a brightly lighted commercial area into an adjacent unlighted area. However, the most common stimulus that can alter driver dark adaptation is the headlights of oncoming cars. From the driver's point of view it can be difficult to separate the unpleasantness and loss of visibility associated with the glare experience from its after effects. Sometimes a driver can see so

much better after the glaring vehicle has passed that the lesser effect of adaptation change goes unnoticed. Ottander (15) measured the readaptation time after moderate levels of headlamp glare and found it to be a maximum of two seconds. This represents a normal exposure. Adaptation time would be increased by more severe conditions, e.g., higher levels of glare, longer exposure.

VEHICLE LIGHTING SYSTEMS

INTRODUCTION - Humans are not creatures of the night by design. In order to be able to function adequately at night illumination is required. In the context of motor vehicle operation, this illumination may be provided by fixed lighting installations, by the vehicle's headlamps, or by a combination of the two.

There are street-lighting installations that are of such high quality that they make headlamps unnecessary, except possibly as vehicle markers. These are the exception, however. Many installations are of lesser quality, characterized by lower levels of illumination overall and considerable variation in pavement luminance from one area to another. Such systems can be deceptive, with the capacity to hide significant problems in the dark areas.

While there is no question that wide use of high-quality fixed illumination systems is desirable, they are costly to install and

operate. As a result most people drive most of their nighttime miles on roads that are unlighted, or lighted at levels that make the illumination provided by the vehicle's headlamps necessary.

This section of the report will deal with motor vehicle headlamps. It will discuss the different types of equipment in use today, general problems in design, the performance that can be expected, and factors limiting performance.

LIGHTING EQUIPMENT - Virtually all vehicle headlamps offer two beams. The upper beam is designed for use when there are no other vehicles nearby in the forward field. Its design presents no serious problems. Of much greater concern is the low beam, which must provide adequate visibility while simultaneously protecting other drivers from excessive glare.

An inspection of Figure 2 will help in realizing how difficult this job is. The figure is a view of a straight, flat road. The numbers on the V axis show the distance, in feet, in front of the car. The dashed line in the upper left-hand quadrant shows the trajectory of the eyes of an oncoming driver. The numbers on that line also represent distance, in feet, from the car in the right lane.

The trick in low-beam design is to get as much illumination below the H-axis as possible to help the driver see, while controlling illumination above the H-axis to reasonable levels, because it causes glare for other

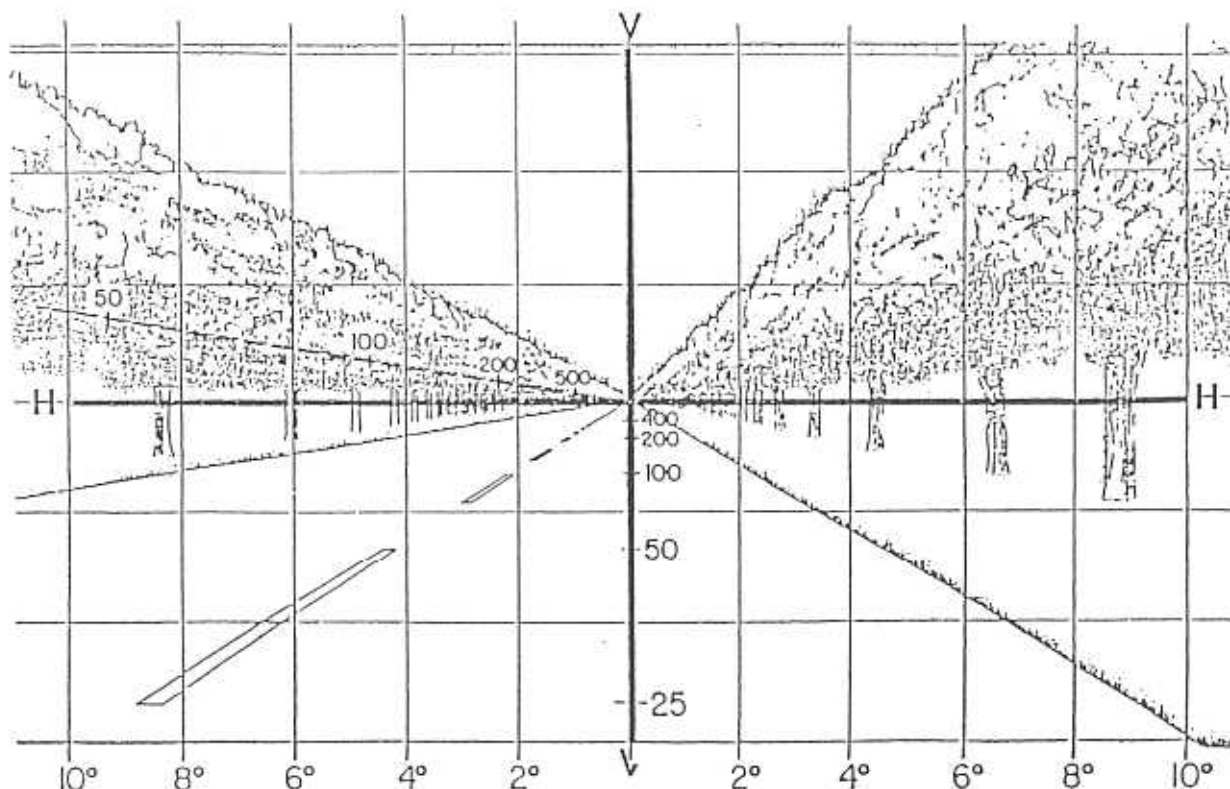


Figure 2. A headlamp's view of a road.

drivers. However, the angular separation between areas where illumination is helpful and where it is harmful is very small. Furthermore, roads tend not to be flat and straight like the one shown in Figure 2. Allowance must be made for the effects of road curvature, as well as for problems such as vehicle loading, and aim variance. Finally, some illumination must be projected above horizontal, to aid in seeing such things as signs.

Because of these and other considerations, what has emerged as the low beam pattern is the result of much compromise. A great deal of research (e.g., 16) suggests that it is probably close to optimum, at least for present-day technology.

There are two different low-beam patterns in use for automobiles in the world today. Lamps legal for use in the United States rely on lens prisms and some filament shielding to control illumination. They produce a pattern like the example shown in Figure 3. The introduction of halogen sources, stylized headlamps, and replaceable bulb units in recent years has had no significant effect on the beam pattern.

In lamps legal for use in much of Europe, and some other parts of the world, the primary control element is a small shield between the low-beam filament and the lower half of the reflector. This produces a beam pattern that looks very different from the US pattern. An example is shown in Figure 4. European headlamps are characterized by uniform illumination below horizontal, a sharp horizontal cut off, and generally lower levels of illumination above horizontal than US units. Despite the fact that the beam patterns from the two systems look very different, a great deal of research has shown that they perform about the same (17).

Motorcycle headlamps are covered by regulations that are different than those for automobiles and trucks. These regulations allow a much broader range of beam patterns, including the European system. As a result, motorcycle headlamps are available in a variety of patterns, sizes, wattages, and types of construction (18). The best of these units are about equal to automotive headlamps. Therefore, since most motorcycles have but one headlamp, they produce at best about half the illumination of an automobile. However, since motorcycle headlamps are generally mounted higher than those on cars, visibility distances provided the operators of the two types of vehicle are roughly equal (19).

FACTORS LIMITING LIGHTING SYSTEM PERFORMANCE - The Intensity-Visibility Distance Relationship - The illumination on an object varies inversely as the square of the distance from the source of illumination. For example, if an object has an illumination level X at distance Y from a light source, it will have an illumination level of $1/4 X$ at distance $2 Y$. Based on this relationship, doubling the output of a headlamp, as recently became possible with high beams when the maximum output increased from 75,000 cd to 150,000 cd, should increase

visibility distance by about 40%. Unfortunately, this is not the case. Figure 5, taken from Roper and Howard (20) suggests that an increase of about 20% is all that can be expected.

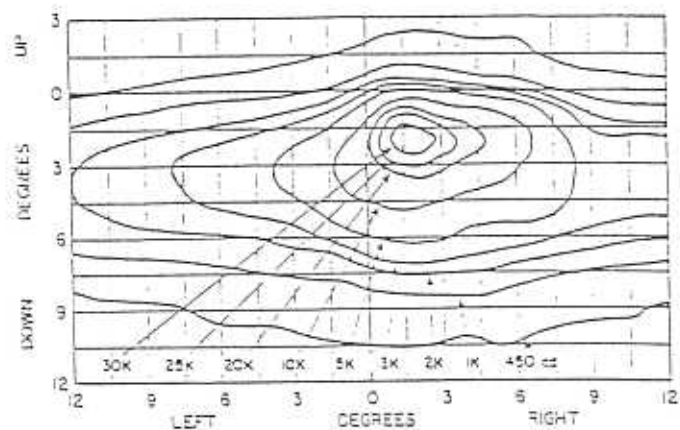


Figure 3. Isocandela diagram of U.S. low beam. Units are candelas (cd).

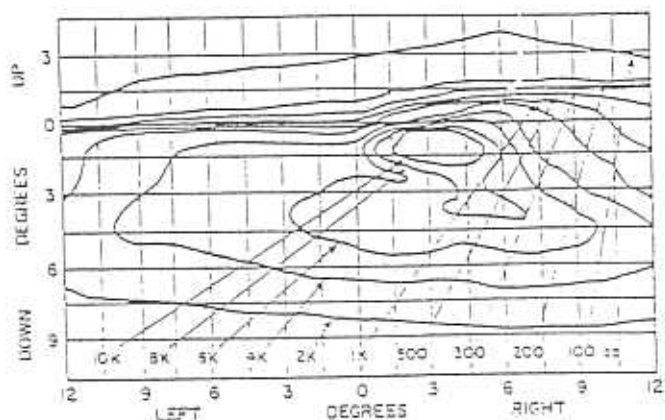


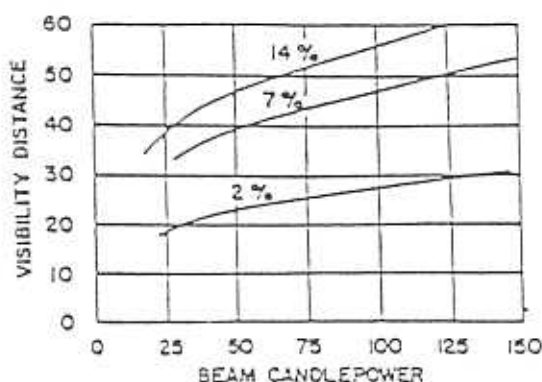
Figure 4. Isocandela diagram of E.C.E. low beam. Units are candelas (cd).

The reason that headlamp visibility distance does not increase as indicated by the distance squared law is partially due to factors such as atmospheric attenuation. But the main reason, as will be discussed later, is that contrast is far more important in determining whether something will be visible than is overall level of illumination. Increasing visibility distance is not a simple matter of increasing lamp output, even if the problems such an increase would cause could be ignored.

Glare - Glare is the result of brightness within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause adverse effects on driver visibility and/or comfort. These effects are

GLARE

generally referred to as disability and discomfort glare respectively, although sometimes the latter is called psychological glare.



(From: Roper and Howard, 1938)

Figure 5. Visibility distance as a function of beam candlepower and target reflectivity (50). (Candlepower values are X 1,000.) (Visibility distances are X 10 feet.)

The term "disability glare" should not be construed to mean that the observer is completely blinded by the exposure, although that sometimes happens. Rather, it refers to a diminished visual capability. Disability glare arises from the fact that light entering the eye is scattered somewhat by the optic media, so that some of it ends up on other portions of the retina. This stray radiation reduces the contrast of objects imaged on the retina, and makes them more difficult to detect (21). The effect becomes more pronounced with age (22), compounding the problems older drivers face.

Sudden exposure to very bright light can cause obvious discomfort. Why this happens is not clear, but work by Fry and King (23) suggests that it may be due to minute fluctuations in pupil size. Discomfort glare may be no more than an annoyance, although there is the possibility of increased fatigue if the levels are high enough and persist long enough.

Since discomfort is a subjective phenomenon, there are difficulties in measuring it and establishing a reasonable upper limit. The most extensive and significant research on the subject in the context of automotive lighting has been reported by Schmidt-Clausen and Bindels (24). Some other work, conducted under field conditions (25), suggests that their recommendations may be somewhat conservative. It is an area where more work is needed.

Lamp Aim - To a very significant degree, headlamp performance depends on the units being properly aimed. Work reported by Hull, et al. (26) provides an indication of how much difference relatively small aim changes can make. For example, if headlamps are misaimed up by one degree, as might happen if a heavy load was placed in the trunk of a vehicle, visibility

distance can increase by 60 to 75%. Unfortunately, glare for other drivers increases greatly as well. Misaim down by a degree poses no glare problems, but can reduce visibility distance by 24 to 45%.

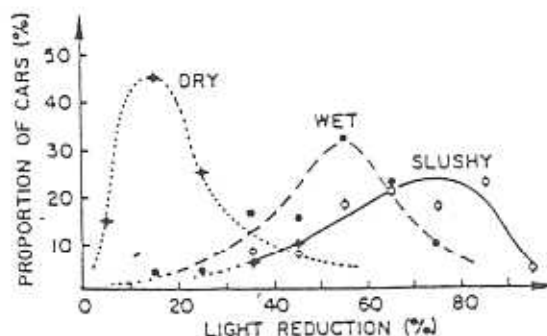
Maintaining proper aim is difficult, for two reasons. First, as noted earlier, the angular separation between areas of the forward field where illumination is desirable and harmful is small. As a result small amounts of misaim can be very significant. Second, there are many sources of aim error, some of which are difficult to control.

Misaim can arise from the lamp itself (e.g., improper filament position), by the lamp being incorrectly oriented in its mounting, and from the vehicle. Limited research also suggests that obtaining accurate aim through service outlets is a chancy business (27). Poor service can itself be a source of aim variance.

A recent survey on the condition of vehicle lighting equipment (28) found that headlamps were commonly aimed outside limits suggested by the SAE (plus or minus 4 inches at 25 feet). On cars four or more years old, only 25 to 30% of vehicles had both low-beam units aimed within SAE limits. Nearly 60% of vehicles less than one year old had both low-beam units within SAE specifications.

Recognizing that aim is a major limitation to the effectiveness of headlamps, considerable thought has gone into means for improving it (29). However, no radical changes are likely, and aim will likely continue as a significant problem in headlighting for the foreseeable future.

Effects of Dirt - Headlamps can become very dirty, particularly in wet weather. Dirt on the headlamps causes light to be absorbed and scattered, reducing useful illumination and often-times increasing glare to oncoming drivers. Figure 6, from Rumar (30) shows the results of measurements made on samples of vehicles under various driving conditions. Under wet and slushy conditions most cars had useful illumination reduced by more than half.



(From: Rumar, 1970)

Figure 6. Proportion of cars at gas stations having various degrees of light reduction in the central part of the high beam caused by dirt under three road conditions.

In, an effort to reduce the detrimental effects of dirt on headlamps, cleaning systems have been developed. The most common are wiper-washer systems like those used on windshields. High-pressure spray devices have also been developed. Such systems are common in some parts of the world, but have not yet come into use in this country.

VISIBILITY AT NIGHT WHEN DRIVING

INTRODUCTION - A pedestrian wearing dark clothing walks along the right edge of an unlighted road, with his back to traffic. A car, using low-beam headlamps, and travelling about 35 mph, strikes the pedestrian, inflicting serious injuries. At trial the driver of the car claims that he saw the pedestrian just before impact and did not have enough time to stop or swerve out of the way. However, the plaintiff produces an expert who, quoting from a manual for drivers, says that visibility distance with low beams is 350 feet. On that basis the driver should have had plenty of time to detect the pedestrian and avoid the impact. Who is the jury to believe, the driver, who has an obvious reason for wanting the visibility distance to be as short as possible, or the (presumably unbiased) expert? This section is intended to provide an answer to this question, together with the reasons for it.

THE IMPORTANCE OF CONTRAST - Contrast refers to characteristics that cause something to appear different or separate from something else. The eye responds to contrast. Under daylight levels of illumination there are a variety of forms of contrast available (e.g., color, texture, brightness). In addition, the visual system is operating at the highest level

of sensitivity and has the greatest capability of distinguishing differences. However, under night driving conditions brightness contrast is generally the only form of contrast of any consequence, and the visual system has a reduced capability for distinguishing differences. Thus, in order to be seen at night, objects must be sufficiently brighter or darker than their backgrounds. Sometimes objects can be seen at great distances silhouetted against a bright background (e.g., the headlights of an oncoming car, a road surface illuminated by streetlights, the lights of a shopping center). More typically the object must be illuminated by the headlights of the approaching car until it is enough brighter than the background to be seen.

Assuming the target object is seen against something other than the sky, the job of the headlamps in providing the necessary brightness contrast is complicated by the fact that they illuminate both the target and its background. Table 2 (from Bhise et al. [16]) shows the reflectivity levels associated with common highway backgrounds. Clearly, someone wearing dark clothing may be seen against a background having similar reflective characteristics and under conditions where contrast would increase very slowly as the car approached.

VISIBILITY DISTANCE - To return to the hypothetical mishap described at the start of this section, at what distance should a reasonably alert and prudent driver have been able to detect the pedestrian? To provide an answer, we will rely on data developed in a field test of different headlighting systems (25).

In the study in question subjects drove or rode in a car that was operated on a private road. There were four possible targets. Three

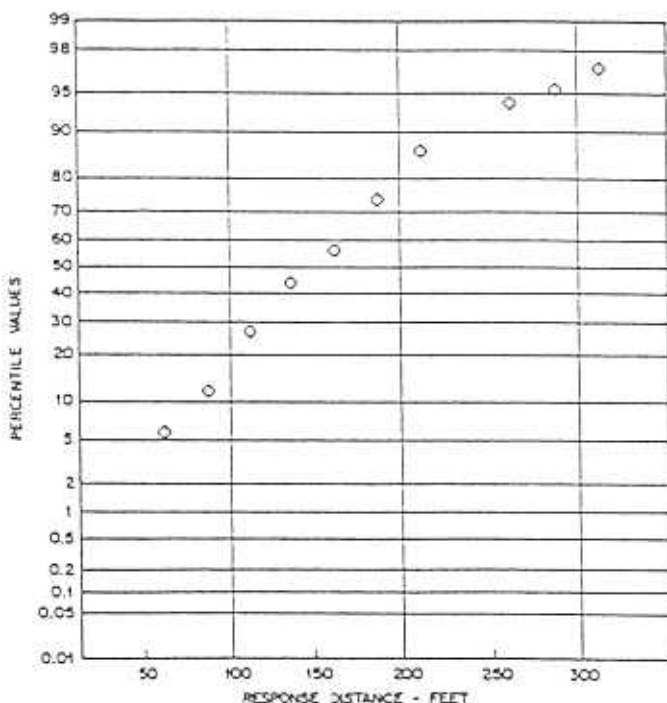
Table 2
Reflectivity Levels of Common Objects

Target	Reflectance	
Pine Trees	.02-.08	
Grass	.08-.16	Long, dormant, pale green
Grass	.10-.18	Lush green, closely mowed
Forest	.02-.26	Mixed green
Dirt	.23-.43	Packed, yellowish
Asphalt	.06-.13	Oily with dust film
Concrete	.25-.37	White aged
Pedestrians	.055	Median of 54 winter coats
Pedestrians	.03	5th percentile winter coats

(From: Bhise et al., 1977)

of these were clad in blue denim, were of about equal width, and differed in height. One was an experimental assistant (pedestrian). The other two were, respectively, 2.5 feet (76mm) and 6 inches (15mm) high. The fourth target was the pedestrian, wearing a white vest. One or more of these targets could appear on each run though the course, at any point in the course, and on either the right or left of the test vehicle. The subjects had to detect the target, identify it by size, and press an appropriate button on a box in their lap. The distance from the target at which they pressed the correct button was recorded.

Figure 7 gives the results of this study for the pedestrian target, standing one to two meters to the right of the vehicle, using US low beams, and with no glare. It is based on about 60 trials from 23 young subjects. Under these conditions, the 5th and 95th percentile response distances were about 50 and 250 feet (15 and 76m), respectively. (This means that on 5% of the trials the subjects responded at 50 feet or less, and on 95% of the trials they responded at 250 feet or less.) If the same target was located to the left of the test vehicle, the 5th to 95th percentile range was from about 25 to 125 feet (8 to 38m). The 5th to 95th percentile response distances to the pedestrian wearing the white vest were about 150 to 450 feet (46 to 137m) on the right side and about 100 to 350 feet (30 to 107m) on the left side. The older



(From: Olson and Sivak, 1983)

Figure 7. Normal probability plot of response distances measured to a dark-clad pedestrian standing on the right edge of the road using standard, low-beam headlamps. No glare, young subjects.

subjects did less well, their response distances averaging about 60% of those recorded for the younger subjects.

To illustrate what these data mean in practical terms, estimates were made of the percent of trials in which the subjects would not have been able to stop short of the pedestrian from speeds of 35, 55, and 70 mph (56, 88 and 113 km/h). The original data were taken at 25 mph (40 km/h). It was assumed that the subject hit the brake, instead of pressing a button, and brought the car to a stop at a deceleration of 0.75 g. It was further assumed that the brake application was made at the same distance from the target as the button press regardless of speed.

Under these assumptions, with the pedestrian on the right, the percent of trials in which young subjects would not have been able to stop short of the pedestrian were as follows:

35 mph (56 km/h)	1
55 mph (88 km/h)	45
70 mph (113 km/h)	89

Because most of the energy from a low beam is directed to the right side of the road, positioning the pedestrian on the left made the results somewhat worse:

35 mph (56 km/h)	22
55 mph (88 km/h)	95
70 mph (113 km/h)	>99

As already noted, the older subjects did not do as well. There were fewer of them in the study, so the following analyses are based on averages across several lighting systems that were tested. Since some of these systems were more powerful than the US low beams, the results may be somewhat conservative. The first analysis is for the pedestrian on the right:

35 mph (56 km/h)	22
55 mph (88 km/h)	83
70 mph (113 km/h)	98

And, with the pedestrian on the left:

35 mph (56 km/h)	49
55 mph (88 km/h)	94
70 mph (113 km/h)	98

An analysis was also made of the condition in which the pedestrian was wearing the white vest. For the young subjects, with the pedestrian on the right, the results were as follows:

35 mph (56 km/h)	<1
55 mph (88 km/h)	3
70 mph (113 km/h)	24

With the pedestrian on the left:

35 mph (56 km/h)	<1
55 mph (88 km/h)	9
70 mph (113 km/h)	48

The analyses just presented suggest that when confronted with a low-contrast object, such as a pedestrian wearing dark clothing, low-beam headlamps may not provide adequate detection-identification distance at speeds in excess of about 35 mph. If the pedestrian is approaching from the left side of the vehicle, or if the driver is elderly, the situation can be appreciably worse. However, pedestrians who must venture forth at night can make themselves much more likely to be seen by wearing light-colored garments.

While these data indicate a potentially serious problem in night visibility while operating a motor vehicle at medium and higher speeds, it should be recalled that they are based on a structured test in which the subjects were alert, free from drugs and alcohol, aware of the purpose of the test and the nature of the targets, and had no concerns with other traffic. Because of these conditions, the response distances described earlier are probably greater than could reasonably be expected in the real world.

An interesting study reported by Roper and Howard (20) provides some indication of the difference in visibility distance between structured studies and the real world. The subjects in Roper and Howard's study were taken out to conduct "subjective evaluations of headlamps." After a time they were told the test was complete and they should drive back to the starting point. Without the knowledge of the subject, a dark-clad mannequin had been set up in the return lane. Measures were made of the distance from the mannequin at which the subject released the accelerator. With this "surprise" phase completed, the subjects were briefed on the true purpose of the study and then asked to back up and approach the target again, releasing the accelerator as soon as they could see it. Under the second, "alerted," condition response distances averaged twice those obtained in the surprise trial. *See summary of test 100. Summary*

Roper and Howard's results may seem extreme. However, they appear reasonable when some of the differences between the surprise and alerted conditions are considered:

1. In the alerted condition the subjects knew where the target would appear and could fixate that spot foveally. It is likely that detection in the surprise condition was accomplished peripherally.

2. Knowing the nature of the target makes it possible to "detect" it using subtle cues that may not be adequate in the absence of such special knowledge.

3. With full knowledge of the nature of the test, the subjects' expectancies are much different than they would be in normal driving. Under test conditions they typically focus their attention on the target detection task and are less likely to be distracted by other things that might be going on.

In accident reconstruction, an investigator is sometimes interested in estimating the distance at which a driver should have been able to detect the target of interest. Such tests are often set up much like the alerted portion of the Roper and Howard study. It is possible to obtain useful information by such an exercise. However, for the reasons given above, it is essential that the investigator understand that the likelihood of something being detected at all, as well as the distance at which it should have been detected, will probably be substantially overestimated.

To return to the question posed to the jury by the hypothetical case described at the start of this section, the data presented here suggest that the version told by the defendant driver is more believable than that told by the "expert." The fact is that individuals who walk in traffic at night, relying on the drivers of oncoming cars to see them, are placing themselves in grave danger. Unfortunately, this situation is unlikely to be resolved by improvements in vehicle lighting anytime in the near future. Because of this, it is important that efforts be made to: (1) improve the understanding of roadway users concerning limitations in nighttime visibility, and (2) increase the contrast characteristics of objects in the road, particularly people, by encouraging the wearing of light-colored garments at night and by wider use of retroreflective materials.

NIGHTTIME DRIVING HABITS - Having discussed at some length the visibility problems associated with night driving, it is reasonable to point out that people do not drive much slower at night, and ask why.

There is evidence that people overestimate the visibility provided by vehicle lighting systems. For example, Allen et al. (31) had subjects stand along the side of a road and estimate the distance at which an approaching driver could see them. At the same time the driver indicated the distance at which he/she could see each pedestrian. On average, the pedestrians' estimates were about twice the distance at which they actually could be seen. This work was extended and confirmed by Shinar (32). There are no comparable data for drivers, but the behavior of many of them while operating a vehicle at night suggests that they think they can see a good deal better than they really can. If this is true, we have an unfortunate combination of errors, with both drivers and pedestrians thinking visibility is better than it is.

Leibowitz et al. (33) have advanced a theory that may account for the fact that people often drive well in excess of speeds that would allow them to stop if confronted with an unexpected, low-contrast object. The theory assumes two independent modes of processing visual information. One of these is called the "focal" mode. It is concerned with object discrimination and identification. Focal functions are optimal in the foveal area, and are affected by level of illumination and refractive error. The

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other mode is called "ambient." It is concerned with spatial orientation. Spatial orientation can be accomplished in the foveal area, but, unlike the focal functions, it is adequate in the peripheral areas as well. In addition, ambient functions are much less sensitive to illumination levels and refractive error than focal functions. Under night driving conditions there is a selective degradation of these two modes, with focal vision being much more affected. This means that we suffer relatively little loss of ambient vision, which is useful for maintaining lateral position on the road. The fact that focal vision is greatly reduced is less appreciated because the demands on it are intermittent. Thus, since the driver can carry out the routine control function about as well at night as during the day, overconfidence concerning the whole driving task may be generated.

FACTORS THAT DEGRADE VISUAL PERFORMANCE

INTRODUCTION - The information on driver visibility offered in the preceding section is based on tests run under ideal circumstances. Conditions in the real world are not always ideal. In fact, there are a great number of conditions that can affect a driver's visibility. Some of these have already been mentioned, i.e., glare, aim and dirty lamps. In this section a number of other conditions will be discussed. These fall under three general headings, based on whether they arise from the environment, the vehicle, or the driver.

PROBLEMS ARISING FROM THE ENVIRONMENT - In general, "environmental" problems refer to anything in the atmosphere that interferes with vision. Most often these would be in the form of precipitation or fog. However, they also include conditions such as smoke, haze and dust. At night all of these conditions have in common the characteristic that they absorb and scatter light to some degree. This absorption and scattering has two effects. First, less light from the vehicle's headlamps reaches a target object, and less of the light reflected by the object is returned to the driver's eyes. Second, some of the scattered illumination is reflected back into the driver's eyes, causing the atmosphere to appear to light up. This reduces the target object's contrast, making it more difficult to detect.

"Wet" conditions such as rain, and sometimes snow and fog, create other problems as well. The most immediately noticeable is the fact that the windshield becomes wet, and requires wiping in order to maintain reasonable visibility. Even under the best of conditions visibility is reduced when the windshield is wet. If the wipers are worn, if the windshield is badly pitted or scratched, if the car is moving at high speed, or if the rainfall is very heavy visibility may be reduced a great deal (34, 35, 36, 37).

A film of water on the road can greatly increase the driver's problems in determining his/her lateral position as well as where the road

is going. There are two problems. Normally the road surface, being rough, acts as a diffuse reflector. It reflects some of the illumination from the vehicle's headlamps back into the eyes of the driver, causing the pavement to appear relatively bright. The first problem is that water fills in the small voids in the pavement surface, and creates a smooth film that acts as a mirror. As a result headlamp illumination is reflected forward, causing the road to appear very dark and increasing glare for oncoming motorists. Under such conditions delineation becomes very important.

All of which brings us to the second problem. Many forms of delineation also suffer when wet. The most common form of delineation, painted lane lines, are reflectorized by sprinkling them with glass beads before the paint dries. Water forms a film over these beads, changing their refractive index so they no longer function as retroreflectors. As a result, painted lane lines seem to disappear when the pavement is wet.

However, not everything is lost when the pavement is wet. The headlamp illumination reflected off wet pavements can significantly increase the brightness of objects such as signs in the forward field, compensating to some degree for the loss in visibility due to other causes (38).

The effect of water on pavement visibility has been a matter of concern for some time. Raised pavement markers have been the best solution so far, and are used extensively in the south and far west. However, they present difficulties in snow-belt states because plows tend to destroy them. A great deal of research has been carried out (e.g., 39) to find a satisfactory and economical solution to this problem. Work is still continuing.

PROBLEMS ARISING FROM THE VEHICLE - One of the most critical components in the vehicle from a standpoint of driver visibility is the windshield. Windshields must meet a number of criteria, some of which are specialized (e.g., protection in crash situations). But, what a windshield does most is allow the driver to view the road. Hence, good optical quality is very important.

Unfortunately, windshields lead a hard life. Subject to continuous bombardment by airborne particles, occasional encounters with larger objects, abrasive action from the wipers and careless efforts at cleaning, plus films that build up on both sides of the glass, many windshields have optical characteristics that significantly degrade driver vision, particularly at night. Contaminants, surface pitting and scratches scatter light passing through the glass, reducing visibility in general and increasing the effects of glare. Rompe and Engel (40) showed that the probability of detecting targets of varying contrast decreased from 91% with a clear windshield to 73% with a windshield having a haze level of 4.9%. Performance was greatly degraded when glare sources were introduced.

Heat-absorbing (tinted) windshields have been an object of some controversy for a number of years. The purpose of the tinting is to reduce the sun load on the vehicle's occupants and interior, thus improving comfort on hot days. While it does this effectively, the tinting also reduces visible light transmitted through the glass. Because of this, some persons (e.g., 41) have argued that tinting the entire windshield is a bad idea, due to loss of visibility at night.

The loss in transmitted light due to windshield tinting is significant. A clear windshield, installed at an angle of 60 degrees from vertical, will transmit about 80% of light passing through parallel to the ground. A tinted windshield will transmit about 68% under identical conditions. This translates to an effective loss of illumination on objects in the forward field, and a consequent loss in visibility. Given the already inadequate visibility provided drivers, as discussed in Section 4, further reductions may seem difficult to justify.

The argument concerning heat-absorbing windshields comes down to balancing advantages and disadvantages. There have been a number of studies of visibility distance at night comparing clear and tinted glass (42, 43, 44). Generally, these have shown losses in visibility distance associated with tinted glass ranging up to about 6%, depending on the target and test conditions. Whether this loss in visibility under night driving conditions is worth the gain in comfort under warm, sunlit conditions is something that will apparently continue to be debated.

PROBLEMS ARISING FROM THE OPERATOR - Problems with the operator that may affect visibility can be temporary or permanent. Temporary problems include fatigue, psychological states such as stress that may reduce attention to the driving task, and the effects of drugs and alcohol. Alcohol has been shown to be a contributing factor in about half of fatal and serious-injury accidents. Other temporary degraded states are probably also very significant. However, this section will deal with certain problems that are permanent in nature. The reason is that many of the temporary degraded states have received much attention in recent years. The areas that will be discussed here are also important, but have received far less attention.

Aging - One of the most easily observed effects of aging on vision comes about when one can no longer read comfortably and reading glasses or bifocals must be used. This condition is due to the increasing inflexibility of the lens, and is called presbyopia. Although it may make it more difficult to read information presented on the dash panel, presbyopia is not typically a problem in motor vehicle operation.

However, other effects of aging on vision may be a significant problem. For example, visual acuity, since it involves the ability to resolve fine detail, affects the ability to read

signs along the road, as well as the ease with which various conditions can be detected and identified. Studies have shown a relationship between acuity and age. On average, acuity peaks at about age 15, and declines steadily thereafter, reaching about one-third peak value at age 80 (45).

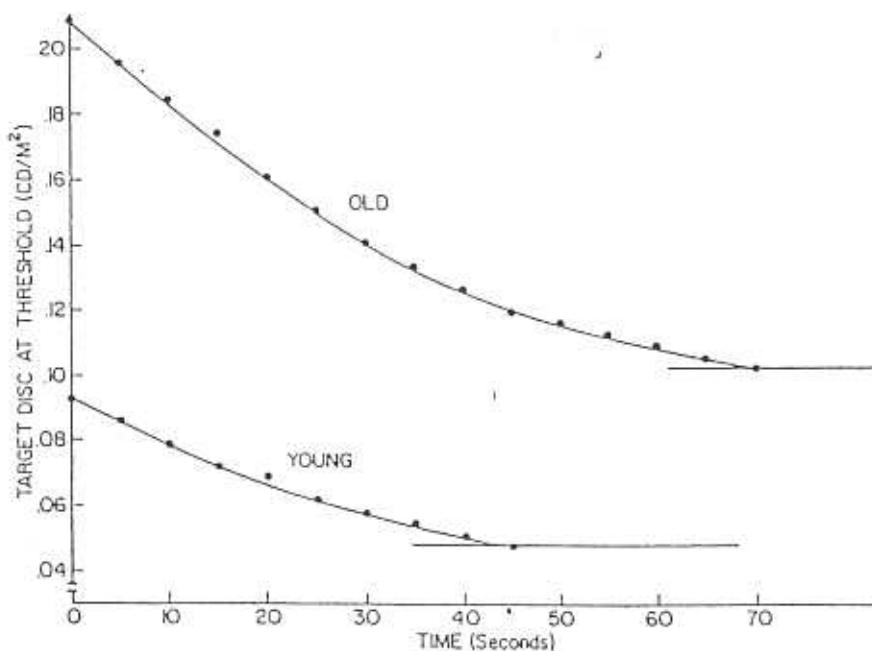
The most critical condition is at night. In general, acuity and other visual functions decline as the level of illumination decreases. However, the effects are more marked in the elderly. It is not completely clear why these losses in visual capability come about. It has been known for some time that the minimum level of illumination to which the eye can adapt, as well as the time to adapt from one level to another, increases with age (46). Three possibilities (22) are: (1) a reduction in the oxygen supply to the retina; (2) a reduction of the maximum opening of the iris; and (3) yellowing of the lens. All of these factors may play a part. Whatever the reason, as illustrated by the safe stopping calculations presented in the preceding section, older persons tend to do less well than younger persons on visual tasks at low levels of illumination. Indeed, even when matched in daytime acuity, Sivak et al. (47) found that older subjects were able to read highway signs at only about two-thirds the distance of the young subjects at night.

The disabling effects of glare are also more pronounced in older persons. Not only are older subjects more affected by glare, it takes them longer to recover when the glare source is removed. Figure 8 (48) shows the results of measures made on threshold detection of a disc target starting when a glare source is extinguished. The older subjects were much more affected by the glare when it was on, and it took them about 50% longer to adapt to the ambient level. Note too that the target disc had to be about twice as bright to be visible to the older subjects at the ambient level.

Night Myopia - Myopia is commonly referred to as near-sightedness. It results when the lens-to-retina distance in the eye is too great. With this condition close objects can be brought into sharp focus on the retina, while more distant objects are brought into focus in front of the retina, resulting in a blurred image.

In total darkness the eye accommodates to an intermediate state (dark focus) that varies from person to person. Owens and Leibowitz (49) have shown that the eye tends to accommodate to distances between infinity and that represented by dark focus as illumination levels are reduced. The result is "night myopia." Because most events of consequence to a vehicle operator occur at visual infinity (i.e., beyond about 20 feet), an eye that is accommodated to an intermediate distance will see them less well.

Available data indicate that a great number of people may have night myopia to some degree. However, there are large individual differences. In extreme cases, individuals may have a focus



(From: Olson and Sivak, 1981)

Figure 8. Luminance required on target disc to provide threshold visibility as a function of time after onset of glare.

point only a few feet in front of them, with objects in the far field seriously blurred. Fortunately, most people are much less affected.

An obvious solution to the problem of night myopia is to measure individual accommodative changes and prescribe corrective lenses to be worn while driving at night for the more serious cases. There are two problems in doing this. First, a person may have serious night myopia and not be aware of the fact. Thus, affected individuals are not likely to seek assistance voluntarily. Second, it is difficult to carry out conventional refractive measures at low levels of illumination, and night myopia cannot be predicted from measures taken at high levels of illumination. So, even if an individual felt the need, an Ophthalmologist or Optometrist could not conduct the necessary tests and write a prescription. The development of a laser optometer (50) has made such measures practical. There may be merit in screening for night myopia, with corrective lenses required for night driving where appropriate, just as we require corrective lenses for daytime operation.

Expectancy - A safety agency once offered a new slogan that was given wide publicity. On billboards and in other media they touted the theme "good drivers expect the unexpected." It's a catchy phrase, and the idea probably sounds reasonable to many people. Certainly, no one will argue the point that drivers should be alert and attentive to the driving task. However, taking the slogan in a literal sense, the variety of things that could happen is so vast that it is unreasonable to expect drivers

to be prepared for all of them all of the time. In fact, the soundest approach to safe traffic management is to minimize the unexpected. One of the major efforts of traffic engineering in the last several decades has been in just this direction. Through publications such as the Manual of Uniform Traffic Control Devices (MUTCD), and concepts such as Positive Route Guidance (1), considerable progress has been made in producing a nationwide traffic control system that provides necessary information in a timely manner and minimizes nasty surprises.

Based on their driving experience, people develop expectations about matters such as traffic control devices, roadway design, and driver behavior. This is true both night and day, however it becomes more important at night because so much of the information available during the day is lost when it becomes dark.

Two general types of expectations have been identified, a priori and ad hoc (51). A priori expectancies come from general experience. Examples are the assumption that freeway exits will be on the right, that curves can be taken at the speed limit or will be otherwise posted, and that no-passing zones will be marked with a solid yellow line and signs. A priori expectancies are the basis for assumptions about traffic operations that people bring with them whenever they take to the road. Ad hoc expectations are based on very recent experience. For example, a driver encountering a road with numerous sharp curves that require a speed reduction will adapt his/her expectations to that situation.

The important points to be made here are that all drivers have expectations, that these expectations are based on exposure to (generally) sound traffic engineering practice, and that conforming to driver expectations facilitates traffic flow and minimizes accidents. When these expectations must be violated (construction work that requires lane closures and left-hand exits from freeways are good examples) great care must be taken to alert approaching drivers to the condition in time so that they can make the necessary adjustments. What traffic agencies, police and accident investigators should not do is adopt an attitude excusing the existence of conditions that violate driver expectations, as reflected in statements that start out "If only he/she would have been paying attention. . ."

Judgments of Closing Speed - Missing his exit from a freeway, a truck driver slows and looks behind him. It's two AM and there is no traffic in sight. The driver decides to stop and back up the quarter mile to the exit rather than go several miles out of his way by proceeding to the next exit and turning around. Staying in the right-hand lane, he backs up for ten seconds or so, then sees a car approaching in the distance. The driver stops and waits for the car to pass. He does not activate the emergency flashers. The car continues to approach in the right lane, and swerves left too late, striking the left-rear corner of the truck. At trial the defendant produces an "expert" who claims that there was no excuse for the driver of the approaching vehicle not seeing the truck, because it was well and properly lighted. The expert is perfectly correct in maintaining that the driver should have seen the truck. He is wrong in inferring that nothing more than detection was required.

Successful driving requires frequent interaction with other vehicles. It seems clear that vehicle operators have to be able to judge speed and spacing relationships to a reasonable degree in order for the system to function adequately. However, research indicates that there are two issues involved. Drivers are reasonably accurate in determining whether the spacing between their own and a lead car is opening or closing (52), but appear to be poor in estimating the rate of change (53). Due to the reduced number of cues available, this situation is probably worse at night.

In a situation such as that described, what these data suggest is that an overtaking driver could discern from a considerable distance that he/she was closing on the truck ahead, but could not determine that there was a large speed discrepancy until much closer. Here expectancy may come into play. Since stationary vehicles are extremely rare events in freeway traffic lanes, the approaching driver is likely to initially assume that the truck is moving, and the speed discrepancy is relatively small. By the time the gap has closed to the point where the speed discrepancy is obvious, it may be too late to avoid a collision.

Because of this limitation in human visual perception, the causative factor in accidents like the one described at the start of this section is often failure to identify the dynamic state existing between the vehicles, not failure to detect the lead vehicle. For this reason it is important that vehicles that are stopped or moving much slower than other traffic be distinctively marked. Emergency flashers are effective for this purpose because flashing lights have great attention-getting power, and the system has come to be identified with stopped or slow-moving vehicles.

CONCLUSIONS

This paper has been concerned with problems in driver visual perception under nighttime conditions. Three general points will be noted as a summary.

First, the visual system is constructed in a way that allows information to enter from a very wide field forward of the observer. However, the structure of the system is such that only the small portion of the field that falls on the fovea of the eye can be observed with maximum clarity. Because most of the visual field is peripheral, most unexpected objects or conditions must be detected while in the periphery. Since information is processed serially (i.e., one item at a time), and the information being processed at a given time is probably located on the fovea, the peripheral information not only must be more conspicuous than if it were seen foveally, but it must compete with other information for the driver's attention. If these considerations are ignored, reconstructions of a situation that are used to estimate "visibility distance" or some such parameter can yield very misleading results.

Second, especially on low beam, vehicle lighting systems do not provide enough illumination to ensure that low-contrast objects will be detected in time at anything other than very low speeds. It is target contrast, not amount of illumination, that has the major effect on target visibility. Pedestrians can greatly increase the probability of their being seen by drivers by wearing light colored clothing at night, or, better yet, retroreflective materials. Due to limitations on beam design, the visibility distance provided by automotive lighting systems will probably not improve significantly in the foreseeable future.

Third, there are a number of variables that can affect driver visibility under nighttime operating conditions. These may arise from the environment, the vehicle or the driver. The accident investigator must be aware of the effects of variables such as these and, when relevant, include them in his/her evaluation, to the extent that they can be assessed.

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