

Driver Eye Fixation and Reading Patterns while Using Highway Signs under Dynamic Nighttime Driving Conditions: Effects of Age, Sign Luminance and Environmental Demand

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Abstract

The purpose of this study was to quantify real-world highway sign reading behavior while driving at night. Sign reading behavior was assessed using traditional self-report augmented by an in-vehicle eye tracking system. Good agreement was found between eye movement data (last-look distance) and verbal report measures of sign legibility distance ($r = 0.9$). Significant reductions in legibility distance were observed as sign reflectivity was reduced from “newly installed” levels down to a level representing proposed FHWA minimum retroreflectivity values. The magnitude of this effect varied as a function of the driving environment. Decreasing sign reflectivity was accompanied by a 17% reduction in legibility distance while driving on a high speed (65 MPH) rural road; while a reduction of 24% was observed for a low speed (35 MPH) road located in a visually cluttered suburban business district. No age differences in sign legibility were observed. Mean duration of the last fixation made while reading exceeded 3 seconds. Total eyes-on-the-sign time exceeded 6 seconds given unrestricted sight distance. Dynamically determined measures of average sign reading distances yielded legibility indices that ranged from 32-36 ft/in on a rural highway at 65 MPH to 30-37 ft/in for a suburban street at 35 MPH, significantly shorter than the 40 ft/in in the MUTCD design recommendation. Taken together, the eye fixation data suggests that reading a mission-critical highway sign requires more attentional resources than expected. Long-range conspicuity afforded by highway signs could not be adequately quantified since measurement reliability of the eye movement data was poor beyond distances of 300 m.

INTRODUCTION

The major objective of this study was to quantify real-world driver highway sign reading behavior at night. Several factors previously demonstrated to systematically influence sign legibility distance were experimentally manipulated. These factors included: sign luminance, driver age and the visual complexity of the driving environment.

Prior to 2000, the recommended design standard for highway signs was a legibility index of 50 ft/in [1]. Even under ideal static viewing conditions, a legibility index of 50 ft/in presupposes a driver visual acuity just slightly worse than 20/20 (1 minarc) – a level that fails to accommodate the visual capacity of approximately half of the drivers over the age of 65 [2]. In response to mounting evidence that the 50 ft/in legibility standard failed to meet the needs of the majority of older drivers [1], the 2000 edition of the *Manual of Uniform Traffic Control Devices* (MUTCD) recommends a legibility index of 40 ft/in. Under static nighttime viewing conditions (i.e., 10 cd/m², 5:1 internal contrast), the 40 ft/in specification should accommodate the 85th percentile older driver [3].

However, a series of recent investigations that have assessed highway sign legibility (usually) under more naturalistic driving conditions suggests that achieving an 85th percentile nighttime legibility of 40 ft/in may be more difficult to achieve than previously assumed. For example, Chrysler, Danielson and Kirby [4] reported that experimental signs (8-in Landolt ring) *barely* achieved an average legibility of 40 ft/in with a select group of healthy older adults (mean age = 65.6 years). This was despite the fact that the test subjects were passengers in the front seat without the attentional load of driving) and the test vehicle proceeded at a relatively slow speed (25-30 MPH). Young drivers in the study performed at a level that yielded a legibility index of 58 ft/in. In a similar experiment (closed course; passenger rather than driver; 20 MPH), Hawkins, et al. [5] obtained mean nighttime legibility indices of approximately 52, 44, and 38 ft/in for samples of young (<40), middle-aged (55-64) and older (65+ years-old), respectively. When older persons were required to read signs while actually driving on real roads at moderate rates of speed sign legibility performance has been shown to lag 5-20 ft/in behind their younger counterparts [6]. Little is known about how the information-processing demands of driving a vehicle influences sign reading performance – especially at highway driving speeds (e.g., 65 MPH).

Zwahlen and his colleagues [7, 8] have demonstrated that eye fixation data can be used to gain important insights into driver sign reading behavior. However, little is known about how eye gaze behavior varies as a function of driver age and/or highway sign luminance.

METHOD

Participants. Twenty young (ages 18-29) and 20 older (ages 65-79) residents of Vermillion, SD were recruited to participate in this field study. All participants held a valid South Dakota driving license and identified themselves as “frequent drivers”. All participants demonstrated normal color vision (AO Pseudo-Isochromatic plates) and cognitive status. Average results for the visual screening tests are presented in Table 1. Acuity was assessed using a Landolt-ring chart at a viewing distance of 18 feet. Contrast sensitivity was assessed using the Oakland Low Contrast Letter Chart at a viewing distance of 10 feet. Stimulus materials for both vision tests had a background luminance of 85 cd/m². Four of the younger (20%) and 8 of the older (40%) volunteers were excluded from participation because of difficulties encountered during the calibration of the eye-tracking system. Reasons for such difficulties included: bifocal eyeglasses that distorted the image of the pupil; anti-reflective coatings on eyeglasses that interfered with the transmission of infrared light; ptosis; and, working distances that were shorter than the minimum distance (26 inches) which could be accommodated by the eye-tracker optics.

Table 1. Visual characteristics of participants: Average (Standard deviation, σ).

Age Group	N	Age	Acuity	Contrast Threshold
Young	16	21.6 years (1.6)	0.64 minarc (0.11)	0.022 % (0.006)
Old	12	74.4 years (5.6)	1.10 minarc (0.46)	0.042 % (0.019)

Experimental Design.

The objective of the study was to quantify the sign reading behavior of drivers under real-world nighttime driving conditions. To achieve this objective required the test subject to be the driver of the vehicle, the vehicle had to be operated on the open road, the signs had to approximate the performance of real materials, and the experimental task had to be representative of how signs are actually used in practice. The function of road signs is to transmit information to the motorist. Unlike earlier studies, we chose to look at the behavior of the motivated driver who would be actively looking for the information a sign provides. Common real world examples of such a task are looking for a specific street name and searching for the Speed Limit as one makes the transition into and out of a speed zone.

Four experimental factors were systematically manipulated in this field study: retroreflective material type, sign luminance, driver age and driving environment.

Two types of *retroreflective material optics* were used: ASTM Type IX and ASTM Type VII microprismatic sheeting (Table 2, supplied by 3M Company). Over most observation

conditions, the Type VII sheeting material is designed to provide high luminance to the driver at “far” viewing distances (typically > 180 m) while Type IX sheeting is designed to provide high sign luminance at near viewing distances. Hence, a comparison of reading performance and eye gaze behavior across signs made from Type IX versus Type VII materials provided a means for exploring the performance tradeoffs of “near” versus “far” biases in the luminance supply to the driver.

Three levels of *sign luminance* to the driver were examined for the Type IX material. The effective nighttime luminance of the Type IX stimulus signs was manipulated through the application of a neutral density film overlay that reduced sign reflectance to approximately 15% and 39% of new sheeting values, respectively. As such, Type IX signs were presented at nominally 100%, 39% and 15% of their “newly installed” reflectance values. By manipulating nighttime sign luminance in this manner we were able to look directly at the effects of sign luminance without the confounding influence of diverse light return patterns associated with using different sheeting optics types (e.g. beaded Type I, Type III, etc.) to manipulate sign luminance. Preliminary analytic studies revealed that reducing the reflectance of white Type IX sheeting material to 15% of “new” values would provide the driver with a sign luminance of 8-10 cd/m² within the critical reading distance region – values comparable to the luminance value that formed the basis for the originally proposed federal sign reflectivity minimums [9]. Type VII signs were presented only at the 100% level.

Table 2. Coefficient of Reteroreflexion (R_A – cd/lux/m²) of Test Signs as a function of Observation Angle (ASTM E810 [10] at -4° Entrance Angle/0° Presentation/0° Orientation): Average of All Test Signs (σ)

	Observation Angle (deg)				
	0.2	0.33	0.5	1.0	1.5
Type IX-15%	76 (5)	62 (4)	54 (3)	26 (2)	11 (0.8)
Type IX-39%	220 (7)	173 (6)	148 (4)	66 (1)	24 (0.8)
Type IX-100%	540 (17)	412 (13)	337 (8)	133 (2)	43 (2)
Type VII-100%	887 (20)	867 (10)	600 (37)	27 (1)	6.7 (0.2)

Two levels of *driver age* were examined: young (18-29 years) versus older (65-79 years). The sample was stratified on the basis of age given the fact that visual acuity and contrast sensitivity are known to decline appreciably in persons over the age of 65 – especially under nighttime viewing conditions.

Two levels of *driving environment* were examined: rural versus suburban. These environments were selected because they were representative of many of the conditions likely to be experienced by drivers while at the same time providing very different

constraints upon both the driver and the traffic engineer. The differences between these environments in the current field study are summarized in Table 3.

Table 3. Characteristics of Experimental Road Environments: Rural versus Suburban

Rural Environment	Suburban Environment
20-mile divided highway; rural countryside low traffic density	3-mi 4-lane highway; commercial district moderate traffic density
8 stimulus signs; 2 replications for TYPE VII, TYPE IX 100%, 39% and 15% (0.5-2.0 mile between signs)	4 stimulus signs; TYPE VII, TYPE IX 100%, 39% and 15% (approximately 0.75 miles between signs)
flat, straight, dark with unconstrained sight- distance	overhead illumination; constrained sight distance
65 MPH speed limit	35 MPH speed limit

Stimulus Signs. The stimulus signs were 24 in wide by 30 in tall with non-reflective black text on a white retroreflective background. The size and basic design was chosen to be similar to the Speed Limit sign used on a Conventional Road (MUTCD 2000, Sec. 2A-01). As shown in Figure 1, each black-on-white stimulus sign contained the word “TEST” followed by a letter-numeral target pair (e.g., “E8”) centered beneath. Letters/numerals were 8 inch Highway Series D font. Stimulus signs were installed (according to MUTCD specifications) by the South Dakota Department of Transportation – Yankton Region.

The position of the test signs at each location matched that of the other standard traffic signs along that stretch of roadway. Table 4 describes the sign mounting heights and lateral offsets at the experimental locations. A total of 8 experimental signs were posted along a segment of SD HWY 50 that served as the *rural* driving environment. Four signs (Type VII-100%, Type IX-100%, Type IX -39% and Type IX -15%) were posted on a segment of highway without a shoulder bordering the right driving lane (Rural 1-4). Another replication of these same four types of signs was posted on another segment of the same rural highway that had a shoulder bordering the right driving lane (Rural 5-8). Two randomized sequences of stimulus sign placement were used to counterbalance order effects across subjects.

Another set of four signs were posted along the segment of U.S. HWY 81 that served as the *suburban* highway environment. Again, two randomized sequences of sign placement were used to counterbalance order effects across subjects. The suburban test signs were mounted higher and nearer to the driving lane than the rural signs. Note that the first 4 signs in the rural driving environment (Rural 1-4) were approximately 10 ft closer to the road than the second set of signs (Rural 5-8). While the magnitude of the lateral offsets of the rural signs may at first glance seem rather large, they are not unusual for many of the traffic signs located along rural highways.



Figure 1. Sample stimulus sign.

Table 4. Stimulus sign mounting heights and lateral offsets measured to the center of the sign . Standard deviations in parentheses.

	Driving Environment		
	Suburban	Rural 1-4	Rural 5-8
Offset from right lane edge (ft)	4.7 (1.2)	21.4 (0.7)	31.9 (0.8)
Height from road surface (ft)	8.9 (0.3)	6.9 (0.7)	6.5 (0.2)

Instrumented Research Vehicle. A specially instrumented 1998 Toyota Avalon served as the test vehicle driven by all of the research participants in this study. The headlamps were carefully aimed and electrically regulated. The research vehicle was equipped with an ASL ETS-PC eye tracking system that provided real-time estimates of driver eye gaze location within the forward driving scene. This eye-tracking system is distinctive in that it is mounted in the dashboard of the vehicle and provides an unobtrusive method for tracking the driver's eye and head movements. Distances were determined using a Starlink Model 212G differential GPS system that provided real-time position information with sub-meter accuracy. Eye gaze position, vehicle distance from the sign, vehicle speed and related parameters were collected and logged by a real-time computing system. Complete photometric characterization of both headlamps was conducted by Gilbar, Inc (Michigan) after the completion of the data collection phase of the study. This headlamp data along with the vehicle dimensions and sign positions were subsequently

used for analytical determination of sign luminance available to the driver while reading the experimental stimulus signs. The luminance to the driver for the sign backgrounds was calculated over the range from 250 to 15 meters from the sign from the headlamp illuminance and sheeting R_A measured at the angles corresponding to each sign scenario on a photometric range [11]. The contribution of each headlamp was taken into account and the total corrected for windshield transmission.

Dependent Measures. The dependent variables were the distances at which signs were recognized according to verbal report, the pattern of eye glances associated with sign reading behavior, and the luminance available from each experimental highway sign under dynamic, real-world viewing conditions.

Experimental Procedure. The participants were escorted to the instrumented test vehicle (1998 Toyota Avalon) and adjusted their seat and rearview mirror positions prior to driving to the calibration track located approximately 2 miles from the University of South Dakota. Upon arriving at the calibration track they pulled the vehicle into a parking booth that placed them 16 ft from a wall containing the stimulus targets needed to calibrate the ETS-PC eye tracker. Following a brief procedure in which the eye tracker was trained to recognize the driver's eye and then calibrated, the 30 minute test drive began.

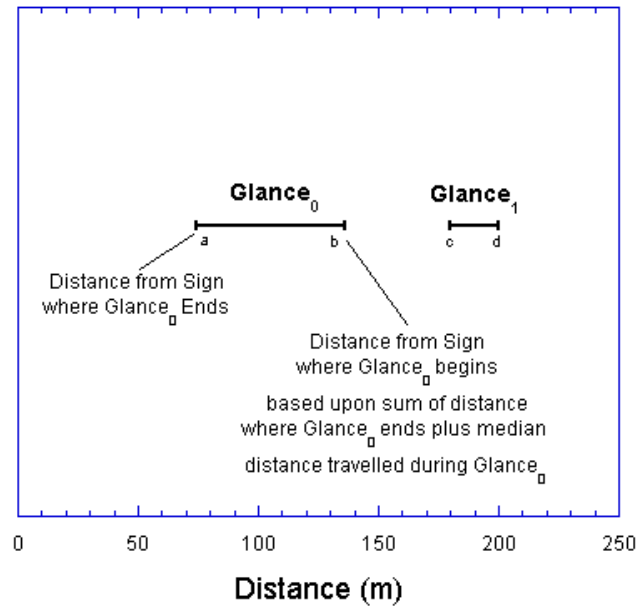
The subjects were shown a sample "target" sign and informed that several signs of this design were located along SD HWY 50 West on the drive to Yankton as well as along US HWY 81 North through the Yankton business district. Their task was to locate these signs among the other standard signs along the roadway and to read them "aloud" as each was encountered. They were instructed to drive at the speed limit at all times. The experimenter, seated in the rear of the vehicle, monitored driving speed on his status display and informed the driver to reduce his/her speed on any occasions where the speed limit was exceeded.

RESULTS

Eye Gaze Patterns during Highway Sign Reading

The eye fixation data collected while driving was both voluminous and complex. An initial attempt to simplify this data and visualize overall patterns and trends was accomplished by constructing a *Two-glance Model* for each of the experimental factors manipulated in the current investigation [8]. The model depicts the last ($Glance_0$) and next-to-last glances ($Glance_1$) made while reading a sign in terms of the distance from the sign being read. A prototypical 2-glance model is depicted in Figure 2. *Two-glance models* were constructed for each experimental condition as follows: First, the median distance from the sign at which the last glance ended (point-a) was calculated. Next, the distance at which the last-glance began (point-b) was computed by adding the median total distance covered by the last-glance to point-a. Hence, points-a and -b define $Glance_0$. Points-c and -d were defined analogously and were used to define the next-to-last glance to the target stimulus (i.e., $Glance_1$).

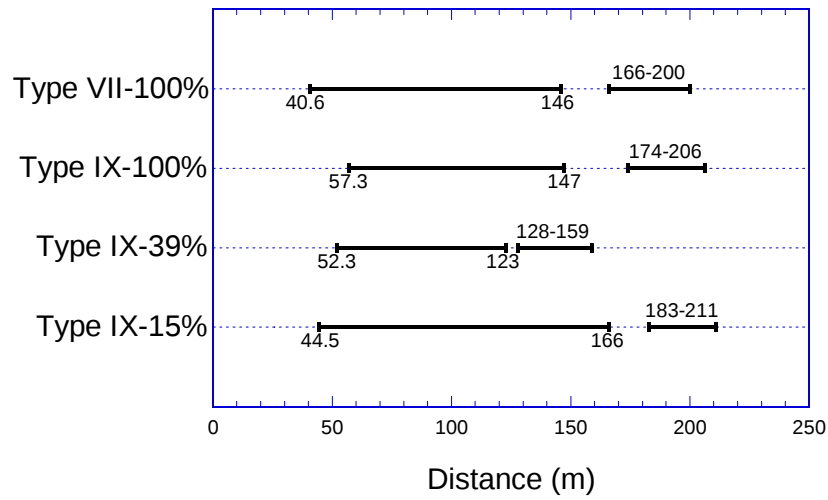
Figure 2. *Two-glance Model* depicting the last (Glance_0) and next-to-last (Glance_1) glances made while reading a sign in terms of the distance from the sign being read



Rural Driving Environment. Figure 3 depicts the glance models for each of the four levels of retroreflective sign treatments in the rural setting for the young and older drivers. The most obvious trends in these patterns of eye glances include the following:

- (1) Last look distance (point-a in Figure 2) decreases with sign luminance as Type IX reflectivity drops from 100% to 15%,
- (2) Shortest last-look distance occurs for the Type VII signs
- (3) Younger drivers tend to finish looking at signs, and by inference complete their visual processing of the information, at *slightly* greater distances than their older counterparts.

a) Young drivers in the rural driving environment



b) Older drivers in the rural driving environment

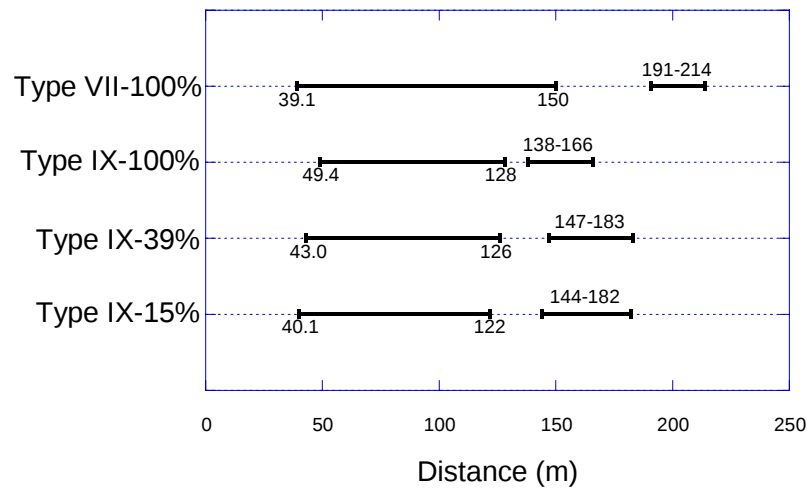


Figure 3. Two-glance models for each level of retroreflectivity observed in the rural driving environment.

In addition to specifying the driving distance covered during the last-look at a target highway sign, the temporal *duration* of this last-look was also calculated. A (2) Age by (3) Levels of Reflectivity ANOVA was conducted upon the last-look duration data observed while reading the Type IX stimulus signs. None of the main effects nor their interaction approached statistical significance. Hence, last-look duration was independent of driver age and manipulations of luminance for the Type IX subset of stimulus signs. The mean last-look duration collapsed across conditions was 3.50 sec.

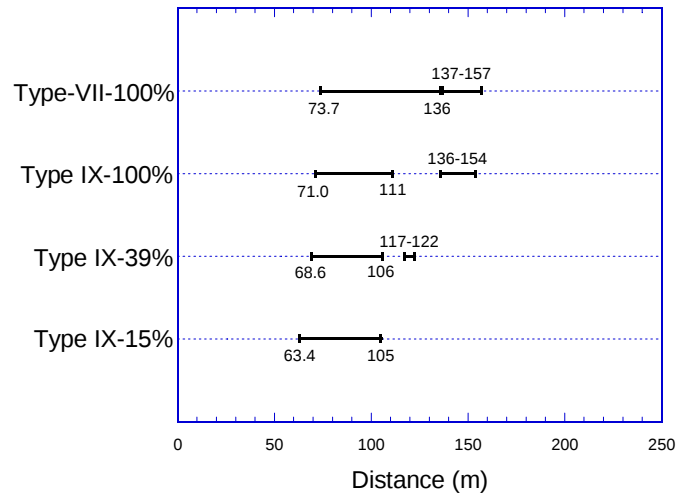
A (2) Age by (2) Material Type ANOVA was used to test for systematic differences in last-look duration across the Type IX-100% versus Type VII stimuli. The Material Type main effect was statistically significant ($p < 0.05$), indicating that the mean last-look duration of 4.2 sec for the fully-reflective Type VII material was systematically greater than the mean of 3.5 sec observed for the Type IX-100% stimulus. Neither of the effects involving the age factor were significant.

The *total glance time* was also computed by summing the duration of each glance to the target sign made prior to reading its legend aloud. A (2) Age by (3) Type IX Reflectivity ANOVA revealed that neither driver age nor the manipulation of Type IX reflectivity systematically influenced total glance time to the sign being read. Mean total glance time was 6.2 sec collapsed across all experimental factors in the Rural driving environment.

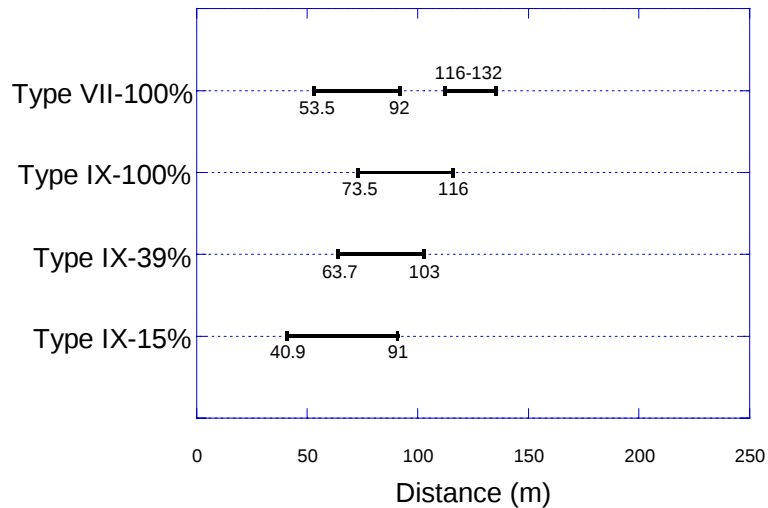
Suburban Driving Environment. Figure 4 depicts the *2-glance models* for each of the four levels of retroreflective sign treatments in the suburban setting. Some of the more obvious trends apparent in a visual inspection of these figures include:

- (1) Driver's last visual contact with the signs appears to occur at a greater distance relative to the rural setting,
- (2) The decline in last-look distance accompanying the reduction in sign reflectivity appears much more robust for older drivers,
- (3) The next-to-last glance ($Glance_1$) appears to be truncated or missing, especially for older drivers and
- (4) The reduced last-look distance for the Type VII material has disappeared for the younger drivers but remains for the older drivers under suburban viewing conditions.

a) Young drivers in the suburban driving environment



b) Older drivers in the suburban driving



environment.

Figure 4. Two-glance models for each level of retroreflectivity in the suburban driving environment.

A (2) Age by (3) Levels of Reflectivity ANOVA was conducted upon the *last-look duration* data obtained for the Type IX signs in the suburban driving condition. Results revealed that none of the tests of main effect nor interaction were significant. A statistical comparison of Type IX-100% versus Type VII failed to reveal a statistical difference in last-look duration unlike that found in the rural condition. Mean last-look duration was 3.1 sec collapsed across experimental factors in the suburban driving

condition. A follow-up (2) Age by (3) Type IX Reflectivity by (2) Driving Environment ANOVA revealed no significant differences across driving environments.

A (2) Age by (3) Levels of Reflectivity ANOVA was conducted on the *Total glance time* values observed for the Type IX signs in the suburban driving environment. No significant influences upon total glance time were revealed. A (2) Age by (2) Material Type ANOVA was conducted to contrast total glance times for reading Type VII versus Type IX-100% signs. Again, no statistically significant differences were obtained. Finally, a (2) Age by (3) Levels of Reflectivity by (2) Driving Environment ANOVA revealed that the mean total glance time of 4.6 sec in the suburban setting was significantly less than the 6.2 sec value observed for the rural driving environment ($p < 0.002$).

Legibility Distance

The legibility distance afforded by each of the experimental highway signs was assessed using two distinctly different approaches. The first approach, termed *reading distance*, was determined by measuring the distance to the target sign at the instant the driver completed his/her verbal report of the sign's message contents. The second approach, termed *last-look distance*, was determined by measuring the distance to the target sign at the instance the driver terminated his/her last eye fixation of the target.

In general, these two dynamic measures of highway sign legibility distance were highly correlated ($r = 0.9$). Drivers tended to terminate eye contact with the target sign shortly following the completion of their verbal report of the sign's contents. The only situation in which there was a sizable mismatch between the two measures of legibility distance occurred when young drivers were reading the Type VII sign in the rural environment (where last-look distance was much shorter than the verbally reported reading distance). It is significant that the drivers consistently continued to look at the stimulus signs for a brief period after their verbal report. This may indicate the driver needs to confirm the sign message before moving on.

Rural Driving Environment. The relationships between the reflectivity (relative luminance) of the experimental Type IX signs and the two indices of legibility distance are depicted in Figure 7. Both approaches to assessing legibility distance reveal highly similar descriptions of the effects of sign brightness on the ability to read textual information while driving at highway speeds.

A (2) Age by (3) Levels of Reflectivity ANOVA conducted upon the *last-look distance* data for the Type IX test signs revealed that legibility distance declined significantly with reductions in sign reflectivity ($p < 0.004$). Neither the age factor nor its interaction yielded a statistically significant effect. Follow-up analysis of the effects of sign reflectivity revealed a significant difference between the Type IX 100% stimulus and both the 39% ($p < 0.019$) and 15% ($p < 0.006$) levels of reflectivity. The difference between the last-look distances for the 39% and 15% reflectivity signs was not statistically significant.

The *reading distance* data, which was analyzed in the same manner, yielded results virtually identical to the statistical analysis of last-look distance. Analyses of the effects of sign reflectivity revealed significant differences in the reading distances between the 100% reflective sign and both the 39% ($p < 0.006$) and the 15% ($p < 0.009$) Type IX test signs. No significant difference in reading distance was observed between the 39% and 15% reflectivity levels.

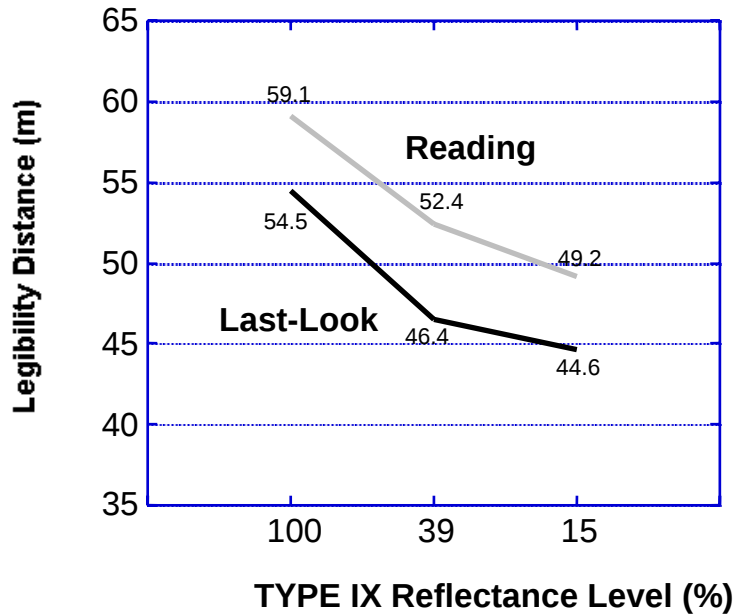


Figure 7. Mean Nighttime highway sign legibility distances as a function of Type IX reflectivity levels for high-speed driving in a rural environment.

Finally, the visual performance distances reported in Figure 7 were translated into legibility indices to foster convenient comparisons with other studies (see Table 5). These legibility index values appear to be systematically lower than those reported previously [4,5,6]. For example, the 24.2 ft/in legibility index derived from the reading distance obtained for the Type IX-100% signs falls far below the 38-58 ft/in range of legibility index values reported by Chrysler, et al.[4] and Hawkins, et al. [5].

Table 5. Legibility index (ft/in) equivalents for reading distance and last-look distance as a function of Type IX sign reflectivity (luminance) level.

	Type IX-100%	Type IX-39%	Type IX-15%
Reading distance	24.2	21.5	20.2
Last-look distance	22.4	19.0	18.3

Much of this difference between the current and past legibility findings can be attributed to differences in the procedures used to measure legibility distance. Previous studies, including those cited above, used stationary or slowly moving (20 MPH) vehicles when measuring sign reading behavior. As a result, little or no difference existed between the distance where the sign first became “readable” and the distance at which sign legibility was successfully reported. However, when the research participants are driving at 65 MPH – as was the case in the current study – a distance of 95.33 ft (29 m) separates the point at which its contents are reported and the “traditional” static legibility distance (assuming a perception-response time (PRT) of 1.0 sec). Thus, the legibility indices reported in Table 5 are lower than the average values typically reported in the research literature because they represent the driver’s distance from the target sign at the completion of the perception-response chain (rather than at the beginning of the perception-response interval as is typically the case for *static* estimates of driver visual performance).

Assuming a representative perception-response time of 1.0 sec (see Reference 12), adjusted legibility indices can be calculated to estimate the distance at which the signs first became “readable” under the dynamic assessment scenario used in the current study. These adjusted legibility indices are presented in Table 6. Note that these adjusted values are more consistent with previously reported findings obtained for signs constructed with microprismatic materials.

Table 6. Adjusted legibility index (ft/in) equivalents for reading distance and last-look distance as a function of Type IX sign reflectivity level (see text for description of adjustment).

	Type IX-100%	Type IX-39%	Type IX-15%
Reading distance	36.2	33.4	32.1
Last-look distance	34.3	30.9	30.2

Type VII versus Type IX sheeting – Rural environment. A (2) Age by (2) Retroreflective Sheeting Type ANOVA of the *last-look distance* data was performed to compare the Type VII versus Type IX-100% signs in the rural driving environment. The results of this analysis revealed that the last-look distance (54.7 m) observed for Type IX-100% signs was significantly greater ($p < 0.001$) than that demonstrated for Type VII signs (44.6 m). Neither the age factor nor its interaction with sheeting type approached statistical significance. Figure 8 maps these legibility distances to the concomitant luminance levels available to driver. These luminance availability curves show that Type VII signs were much brighter than the Type IX signs in the “conspicuity zone” ($> 100\text{m}$) preceding the “legibility zone”. However, in the “legibility zone” ($< 80\text{ m}$) this relationship was reversed; i.e., the Type IX signs were brighter than the Type VII signs at this range.

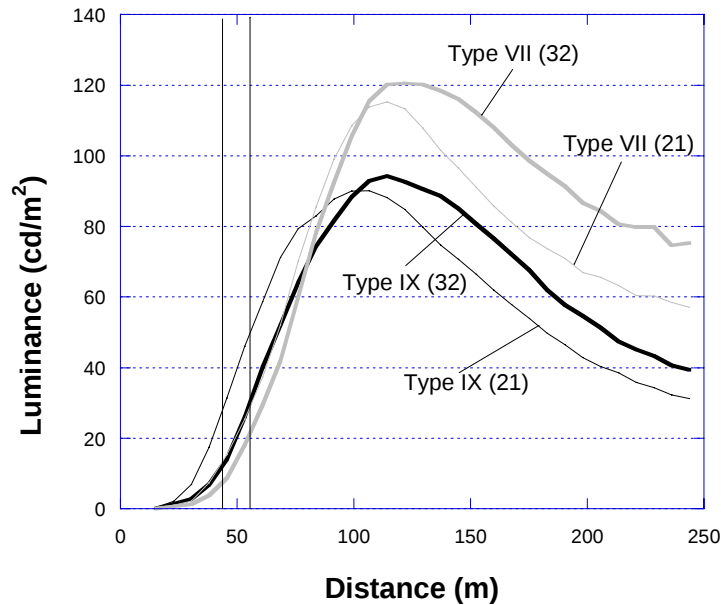


Figure 8. Available luminance as a function of driver observation distance for Type VII and Type IX-100% test signs in the rural environment. Two functions appear for each type since each sign was presented at two levels of horizontal offset from the road (21 and 32 ft, respectively). Vertical lines mark average legibility distances observed for each sign type (see text).

A (2) Age by (2) Retroreflective Sheeting ANOVA was also performed upon the *reading distance* data. No reliable difference in reading distance was observed across the Type IX-100% (58.8 m) versus Type VII (55.3 m) retroreflective sheeting categories. Neither the age effect nor its interaction approached statistical significance.

Suburban Driving Environment. The relationships between the reflectivity of the Type IX stimulus signs and the two indices of legibility distance are depicted in Figure 9. Again, as was the case for the rural driving environment, both approaches to assessing legibility distance reveal highly similar descriptions of the effects of brightness on the ability to extract information from a sign while driving in a real-world environment.

A (2) Age by (3) Levels of Reflectivity ANOVA conducted upon the *last-look distance* data for the Type IX test signs revealed that legibility distance declined significantly with reductions in sign reflectivity ($p < 0.025$). Neither the age factor nor its interaction approached statistical significance. Follow-up analyses of the sign reflectivity effect revealed a significant decrease in last-look distance for the Type IX-15% sign relative to both the Type IX-39% ($p < 0.039$) and Type IX-100% ($p < 0.005$) stimuli. No significant difference in performance was observed between the 39% and 100% reflectivity levels.

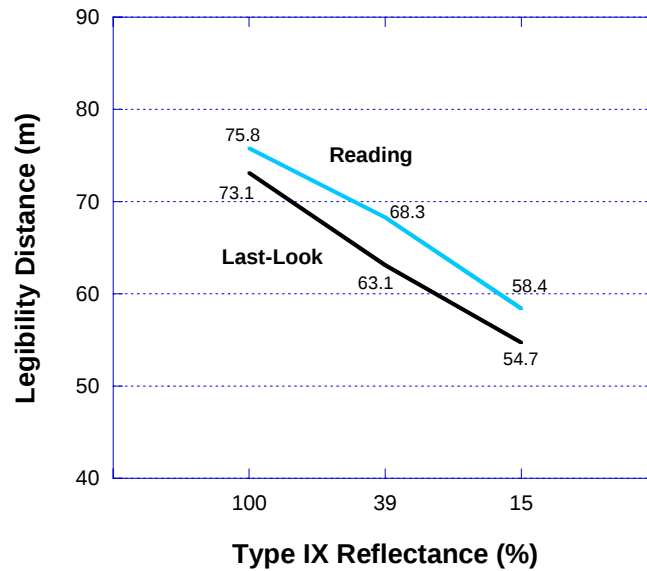


Figure 9. Mean Nighttime highway sign legibility distances as a function of Type IX reflectivity levels for low-speed driving in a suburban environment.

A (2) Age by (3) Levels of Reflectivity ANOVA conducted upon the *reading distance* data for the Type IX test signs revealed that legibility distance declined significantly with reductions in sign reflectivity. Neither the age factor nor its interaction approached statistical significance. Follow-up analyses of the sign reflectivity effect revealed a significant difference between the Type IX-100% and Type IX-15% stimuli ($p < 0.004$). However, last-look distance for the Type IX-39% stimulus did not statistically differ from either the 100% or 15% reflectivity conditions.

Reading distance declined by approximately 18 m in the Suburban driving condition as Type IX sign reflectivity (luminance) was decreased from 100% to 15%. The magnitude of this effect, relative to the Rural driving condition, is graphically represented in Figure 10. Statistical analysis revealed that the size of the luminance reduction effect upon sign legibility was significantly greater in the Suburban than the Rural driving condition ($F_{(1,17)} = 11.9, p < 0.003$).

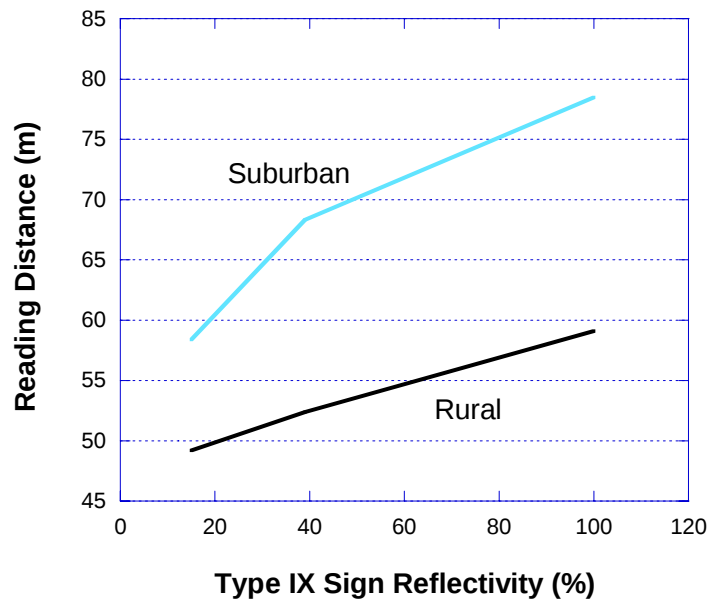


Figure 10. Reading distance (m) as a function of sign reflectivity for Rural versus Suburban driving environments.

However, when the reading distances and last-look distances are converted into *adjusted legibility indices* (adjusted for the 51.33 ft traveled during the presumed 1.0 sec perception-response interval when driving at 35 MPH) the performance differences across driving conditions appears much less pronounced (see Table 7).

Table 7. Legibility index (ft/in) equivalents for reading distance and last-look distance in the Suburban environment as a function of Type IX sign reflectivity level.

	Legibility Index (ft/in)		
	Type IX-100%	Type IX-39%	Type IX-15%
Reading distance	31.1	28.0	23.9
Last-look distance	30.0	19.0	18.3

	Adjusted Legibility Index (ft/in)		
	Type IX-100%	Type IX-39%	Type IX-15%
Reading distance	37.5	34.4	30.4
Last-look distance	36.4	32.3	28.8

DISCUSSION

Eye gaze. Perhaps the most interesting finding revealed by the eye movement data was the very protracted duration of the fixations at the target signs while reading. Average last-look durations in excess of 3 sec were consistently observed across all levels of sign luminance, driver age and driving condition (Rural versus Suburban).

Few studies have carefully quantified eye fixation behavior of drivers while viewing signs at night. Those that have collected such data report average glance durations ranging from 0.5 to 0.75 sec [7, 8, 13]. It is important to note, however, that these previous studies examined sign viewing under very different task conditions. Drivers in these studies were not made explicitly aware of the fact that the researchers were interested in their sign reading behavior. No verbal or nonverbal responses were monitored to ascertain whether or not the drivers processed the information contained on the signs. Instead, these studies focused upon incidental sign “viewing” behavior and are important insofar as they provide a very “naturalistic” data base for modeling driver response to familiar but unexpected warning signs. The current study, however, focused upon a “mission critical” sign reading task. Rather than monitor incidental interaction with unexpected warning sign stimuli, the current investigation required drivers to read a text sign from as far away as possible without compromising the safety of the driving task. Although this paradigm is not “naturalistic” since the drivers knew that their sign reading and eye movement data were being recorded, the task itself remains realistic insofar as the need to read signs from far away is commonly required when navigating a vehicle in unfamiliar environments. All of us, for example, have missed a turn or a freeway exit because we were unable to extract roadway information far enough in advance to safely maneuver our vehicle.

Average total glance time to a target sign was 6.24 sec in the Rural driving condition. Typically, the last-look was the longest in duration and was preceded by two or more shorter glances to the sign (see Figure 3). Drivers often appeared to make their first glance to a sign at a distance exceeding 300 m. However, only gaze data obtained within 300 m of a sign were analyzed in order to maintain acceptable levels of data reliability (see below). This very long total glance time suggests that diverting gaze to a distant sign was not perceived as very “demanding” by drivers. It may be that drivers can divert their gaze a few degrees to the right while trying to read a distant sign without interfering with the main task of operating the vehicle; and, hence, feel comfortable doing so. It is likely, however, that this behavior may still reduce the probability of detecting hazardous situations in the roadway ahead. Additional research is needed to better understand such trade-offs in the allocation of driver attentional resources.

Despite the fact that last-look durations did not differ across the Rural and Suburban driving settings, average total glance time fell to 4.6 sec in the Suburban condition. The most likely explanation for this reduction in total glance time was the fact that the visual environment was much more “cluttered” in the Suburban condition. That is, numerous visual stimuli competed for the driver’s attention; and, one can’t look at a sign when one is looking at something else. The pattern of eye glances depicted in Figure 4 is consistent

with this explanation. The magnitude of the next-to-last-glance (Glance_i) was reduced in the Suburban driving condition – especially among the older drivers. Consistent with previous research finding [14], our older drivers appear to be more distracted by background visual clutter.

More basic measures of highway sign *conspicuity* based upon eye movement data (e.g., first-look distance) did not produce reliable results. Qualitative analyses of the data strongly suggested that drivers tended to make their first-glances to Type VII signs at greater distances than observed for 100% Type IX signs. However, the reliability of this pattern of results was compromised by the fact that inter-rater reliability was judged by the experimenters to be very weak for any fixation events occurring more than 300 m from the target of interest. Since most of these apparent “early” fixations to the Type VII stimulus sign occurred beyond this 300 m “confidence limit” any claims regarding the improved conspicuity of the Type VII material remained of questionable reliability. Great caution is suggested in the interpretation of any driving visibility claims based upon eye tracking data that extend beyond the 300 m limit.

Last-look distance correlated very highly with verbally-reported reading distance ($r = 0.9$). It is interesting to note, however, that the termination of the last eye glance *always* occurred after the driver made the verbal report. This lag may be indicative of a need for drivers to “confirm” their initial verbal estimates – potentially reflecting the magnitude of driver decision-making uncertainty.

Legibility distance. Both self-report and eye fixation data revealed that reductions in sign reflectivity resulted in statistically significant decreases in legibility distance. Rural reading comprehension distances dropped from 59.1 to 49.2 m as sign reflectivity fell from 100 to 15% for the Type IX signs – a reduction of nearly 17%. The consequences of reduced sign luminance were even greater in the Suburban driving condition with reading distances dropping from 75.8 to 58.4 m (23%) across the same reductions in sign reflectivity. Possible reasons for this difference across driving conditions are discussed below.

Qualitative analysis of the luminance distribution curves generated for the 100% reflective Type IX signs in the Rural versus Suburban driving environments (see Figure 11) suggest that little of the Suburban advantage in legibility can be attributed to differences in *static* luminance levels across driving conditions. Reference to Figure 11 reveals that at a distance of 76 m (i.e., the mean legibility distance achieved in the Suburban viewing condition) the luminance available to the Suburban driver was approximately 67 cd/m^2 while the luminance available to the Rural driver at this same distance ranged from $64\text{--}79 \text{ cd/m}^2$ (for 32 and 21-ft sign mounting offsets, respectively). That is, the average luminance available to the Suburban driver at the critical legibility distance of 76 m was actually *less* than the luminance available to Rural drivers at the same distance from the Type IX-100% signs.

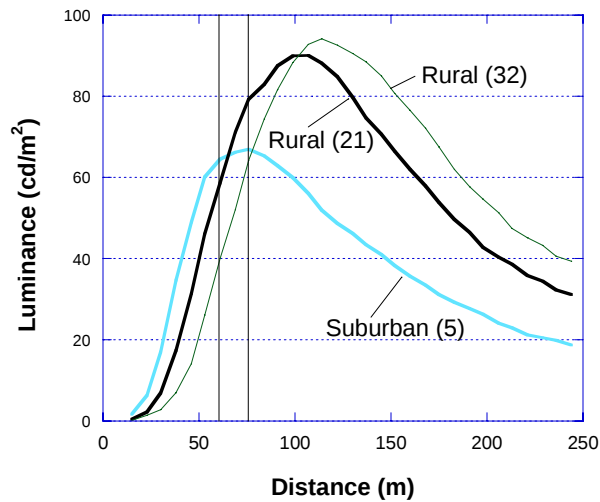


Figure 11. Sign luminance as a function of driver viewing distance for TYPE IX 100% reflective stimuli presented in the Rural and Suburban viewing conditions. Numbers in parentheses denote horizontal sign offset from the road. Vertical lines denote the 60 and 76 m mean reading distances observed for the Rural/Suburban environments, respectively.

It is interesting to note that the *peak level* of the luminance distribution (Figure 11) is considerably reduced in the case of the Suburban environment (mostly due to increased sign mounting height). However, this apparent disadvantage seems to have been offset by the fact that the peak of the luminance distribution occurred at an optimal *distance* from the target stimulus signs. Unlike the case of the Suburban environment, the peaks of the luminance distributions for the Type IX signs in the Rural environment were located at nearly twice the distance at which the signs were actually being recognized. This suggests that the shape of the Type IX luminance distribution was nearly optimal for the Suburban condition but highly suboptimal with respect to the high-speed Rural driving condition. It must be strongly emphasized, however, that this conclusion holds only for the 8-in tall text fonts used in the current investigation. That is, had larger (e.g., 12-in) letters been used on the test signs legibility distances would have most certainly shifted toward the peak of the luminance distribution in the case of the Rural environment but away from the peak in the case of the Suburban driving environment.

Sign reading behavior was assessed in two very different driving environments in order to maximize the generalizability of the experimental findings. Besides the differences in lateral offset and mounting heights of the signs discussed above, the Rural and Suburban settings also differed along other important dimensions such as driving speed, ambient illumination and the amount of background visual clutter (see Table 3). Hence, factors that could have contributed to the small but significant increase in the size of the sign luminance effect observed in the Suburban condition may have involved: (1) differences in the attentional demands of the driving task across conditions, (2) differences in the angular velocity of the target signs at the critical legibility distances, (3) differences in

ambient illumination (adaptation) level, and (4) differences in competition for attentional resources due to visual clutter. Since the resources available to conduct this project did not allow us to independently assess the influence of each of these factors we can not directly assess their relative impacts upon performance across the Rural and Suburban driving conditions. Nonetheless, we can attempt to address each of these factors to the extent possible given the data in hand.

The difference in the workload demands imposed by the driving task across conditions is complex. On the one hand, the high driving speed of the Rural setting probably contributed to increased attentional demands. However, the increased complexity of the driving environment (intersections, vehicular traffic, etc.) in the Suburban setting also contributed to increasing the workload of the driver. Hence, we cannot readily attribute performance differences across conditions to a systematic increase in driver workload.

The instantaneous angular velocity of the signs at the critical reading distance systematically differed across driving conditions. Due to the large lateral offset of the sign mounting positions and the high driving speed, the target signs had an average angular velocity of 5.12 deg/sec in the Rural condition compared to 0.36 deg/sec in the Suburban driving condition (with its lower driving speed and small sign lateral offsets). Visual acuity and/or reading legibility is known to decline as angular velocity is increased [15]. Sign visibility could have been generally “depressed” in the Rural condition due to limitations imposed by *dynamic visual acuity* - resulting in a less robust effect of the sign luminance manipulation (relative to the Suburban condition). The effects of increasing angular velocity upon highway sign reading may merit additional study.

The increased ambient illumination (due to the presence street lighting) in the Suburban condition may have contributed to the increased size of the sign luminance effect. Increased luminance adaptation in the drivers could have decreased the legibility of the dim test sign relative to the brightest signs. Inspection of Figure 10 suggests such a disproportionate decrease in the legibility of the 15% reflectance sign in the Suburban setting (relative to its Rural counterpart). This raises the important issue of the effects of ambient illumination level upon sign minimum luminance requirements for adequate legibility.

Previous research [16] suggests that the visibility of dim signs is disproportionately reduced in the presence of complex background visual clutter. Hence, the pattern of results potentially attributed to differences in the luminance adaptation state of the driver in the preceding paragraph could also be explained by the deleterious effects of the background stimulus clutter that prevailed in the Suburban setting. Given the data currently available, there is no direct means to choose between these complementary mechanisms of luminance adaptation and visual clutter effects.

Sign reading is a dynamic process that unfolds across time. Previous studies have estimated that the perception-response time (PRT) required to read and accurately recognize a highway sign falls somewhere between 0.75 and 1.25 sec [12]. Traditional

studies of highway sign legibility have typically relied upon static protocols to assess the maximum distance at which a sign can be read. That is, research participants were either stationary or positioned in very slowly moving vehicles (e.g., 20 MPH). As a consequence, one typically observed little or no difference in the distance at which the sign first became readable and the distance at which the recognition response was measured. However, in the current study we assessed reading distance under highly dynamic (real-world) driving conditions. In the Rural driving condition, our research participants were driving at a speed of 65 MPH. If their perception response-times averaged 1.0 sec, then a distance of 95.33 ft would be traveled between the point at which the traditional static legibility distance had been reached and the distance at which their actual recognition response (or termination of gaze fixation response) was recorded. Similarly, driving at 35 MPH in our Suburban condition would result in a 51.33 “gap” between equivalent static legibility distance and our more dynamic estimate of reading distance. In summary, the reading distances obtained in the current investigation already include the “costs” of the perception-response time interval. As a consequence, our legibility distance estimates (see Tables 5 and 7) are consistently shorter than those reported by previous studies using more convention (i.e., static) assessment techniques.

In order to present our legibility distance findings in a manner that allows a more direct comparison to previous (static) legibility studies, we converted our data to adjusted legibility index values. Assuming an average PRT of 1.0 sec, we added the distance traveled during the PRT interval to our dynamic legibility distance estimates then divided this sum by the 8 inch letter height (see Results sections for additional details). The reading distance data from Figure 10 are plotted below in terms of this adjusted legibility index (see Figure 12). These adjusted values are still somewhat smaller than the legibility indices reported by recent studies [4, 5]. It is interesting to note that the experimental participants in these previous studies were *passengers* in the research vehicles rather than *drivers*. Perhaps the added attentional demands of actually operating a vehicle at highway speeds – as was the case in the current study – extracts an additional “cost” in terms of the efficiency of the highway sign reading process. Additional research that directly compares static to dynamic reading distances is needed to address this possibility. Another complementary explanation for our shortened adjusted legibility indices could be that the assumed PRT value of 1.0 sec was too short. This alternative explanation is speculative but consistent with the protracted last-look durations observed in virtually all of our research participants. We plan to conduct a follow-up study in which we directly compare reading distances under static and high-speed dynamic conditions. Given the driving speed and the difference in reading distance obtained across static and dynamic conditions we hope to obtain a direct estimate of PRT in a variety of dynamic sign reading scenarios.

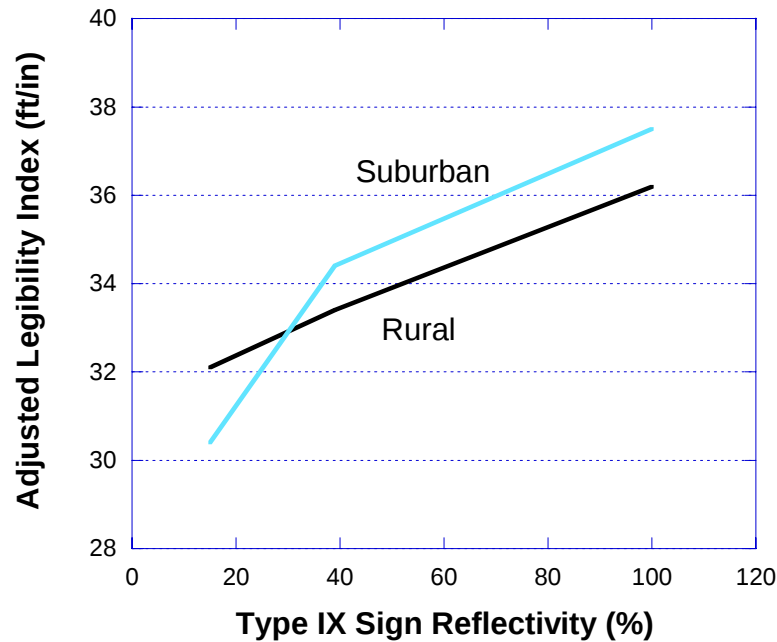


Figure 12. Adjusted legibility index (ft/in) as a function of sign reflectivity for Rural versus Suburban driving environments.

The adjusted legibility index data presented in Figure 12 provide a metric for comparing the results of the current study with previous research findings (as discussed above). In addition, this data also permits a bit of speculation regarding the appropriateness of the proposed FHWA minimum brightness levels for retroreflective highway signs observed under headlamp illumination at night. None of the signs evaluated using our dynamic assessment technique afforded a legibility index of 40 ft/in or more as specified in the MUTCD 2000 guidelines. For the sake of argument, one can assume that the luminance of the Type IX-100% signs was adequate (but that the letter heights used in the current study were too small to achieve the criterion legibility target of 40 ft/in). Given this assumption, the small performance decrements observed under the 15% reflectance condition (relative to 100% reflectance) appear to suggest that the proposed FHWA minimum sign luminance levels adequately accommodate the legibility needs of the *average* driver.

One somewhat surprising result observed in the present investigation was the complete lack of any statistically significant differences based upon driver age (or its interaction

with other experimental factors). Indeed, the average legibility distances demonstrated by the older observers in this study were typically “worse” than those of their young counterparts (as depicted in Figure 13). However, the “overlap” of the performance distributions of the two age groups was so great as to preclude the finding of reliable differences between the group means. This failure to observe age differences in performance was unexpected but not without precedent in driving-related research [17]. It is difficult to interpret this finding given our great difficulty in recruiting older participants who were willing to drive at night. This great reluctance to volunteer for the study (relative to previous laboratory and daytime field studies) suggests that we may have employed a “cream of the crop” sample that may not be representative of the typical older driver.

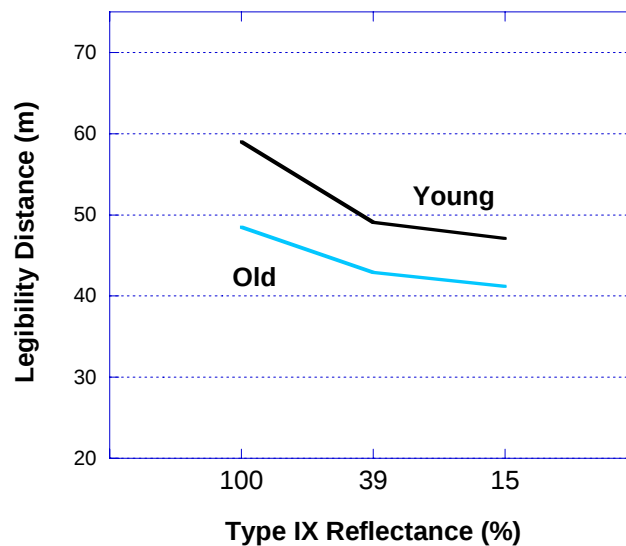


Figure 13. Legibility distance as a function of sign reflectivity and driver age. Although not statistically significant, the size of the age difference is approximately the same size as the reflectivity effect.

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Acknowledgments

Support for this project was provided by the Traffic Control Materials Division of The 3M Company, St. Paul, MN, the National Science Foundation (Grants # 0116030 and EPS-0091948) and the State of South Dakota. Special thanks to Dave Huft and Ronald Peterson of the South Dakota Department of Transportation for their enthusiastic support and assistance.