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16. Abstract
Traffic sign visibility at night is largely determined by sign luminance. Sign luminance, in turn, is determined by viewing geometry, retroreflective characteristics of the sign material, and headlamp illumination. Computer modeling of sign luminance has advanced to allow sign luminance to be predicted based on data sets of retroreflective material performance and headlamp luminous intensity matrices. This research project sought to assess the amount and variability of illumination provided to sign positions by a sample of Texas vehicles. The Texas Transportation Institute measured vehicle dimensions and headlamp illuminance at prespecified points representing typical sign locations. Data collection included 25 passenger cars and 21 light trucks and vans. Vehicles were measured without aiming, but after cleaning the headlamps. Each lamp was measured independently and total illuminance at sign locations was calculated. The project found that the vehicle dimensions specified in computer models encompassed the vehicles measured. The illumination values obtained were also in the range of those provided by the composite lamps in the existing computer models. Theoretical sign luminance values for different types of retroreflective sheeting were calculated using the median illumination values from the vehicles measured. The project confirms the validity of using computer models to predict sign luminance. It also confirmed current TxDOT retroreflective sheeting policy. It is recommended that TxDOT consistently aim the headlamps of vehicles used to perform nighttime sign inspections to assure consistency of sign appearance.

17. Key Words
Traffic Control Devices, Signing, Visibility, Retroreflectivity, Vehicle Forward Lighting, Headlamps

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HEADLAMP ILLUMINATION PROVIDED TO SIGN POSITIONS BY PASSENGER VEHICLES

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CHAPTER 1. INTRODUCTION

Signs must be visible for them to function effectively. Sign luminance is one of the primary factors that determine the visibility of a sign. In daytime conditions, sign luminance is a function of the ambient lighting. In nighttime conditions however, sign luminance is a function of the retroreflectivity of the sign material, the illumination provided by the vehicle headlamps, and the relative locations of the vehicle, sign, and driver. Figure 1 illustrates the relationship between the three key elements that determine the luminance of a sign at night – source, target, receptor, and the relative location of these elements. For a sign to be visible at night, it must receive adequate illumination from a vehicle's headlamps.

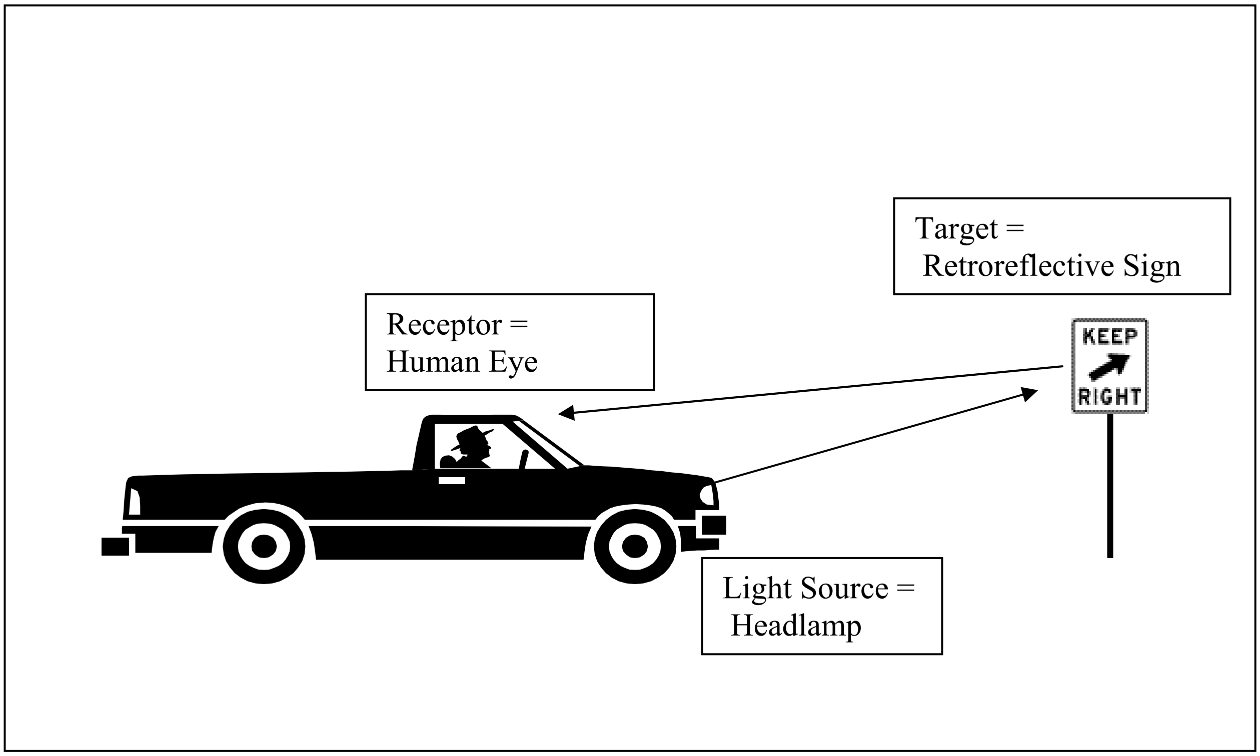


Figure 1. Source – Target – Receptor Model of Luminance.

Over the years, transportation agencies have devoted significant resources to research and analysis of the signing and driver elements that affect nighttime sign visibility. The impact of different vehicle headlamps was rarely a concern because, until the 1990s, most of the vehicle fleet used sealed beam headlamps. The limited number of headlamp types provided a relatively consistent illumination across different vehicles makes. During the 1990s, vehicle manufacturers moved away from using sealed beam headlamps, introducing greater variability in the amount of illumination reaching signs. In addition, over this period most states discontinued inspecting headlamp aim as part of an annual vehicle inspection or discontinued inspections altogether. As a result, the variability of vehicle headlamp illumination has received greater attention from researchers and agencies. Several researchers have shown that there is considerable variation across vehicles in the amount of light reaching sign positions (*1*,*2*,*3*,*4*). These findings indicate that any assessment of nighttime sign visibility must include consideration of the impacts of headlamp illumination.

PRIOR RESEARCH EFFORT

In 1997, the Texas Department of Transportation (TxDOT) initiated a research project to evaluate various aspects related to sign retroreflectivity. One element of that research project was a series of workshops for TxDOT sign crews that included an evaluation of sign inspection procedures. The evaluation was conducted to determine if nighttime visual inspections could be an effective alternative to implementing minimum retroreflectivity values (*5*). In the evaluation, TxDOT personnel conducted a nighttime visual inspection of signs on a closed-course using TxDOT vehicles. Because sign luminance is dependent upon the illumination provided by a vehicle's headlamps, the researchers measured the illumination of the vehicles used in the evaluations as one element of the overall evaluation process. The variability in headlamp illuminance identified during these field measurements prompted a modification of the research project to include a more controlled assessment of the variability in headlamp illumination on Texas highways.

Previous research in the area of sign retroreflectivity and visibility has shown the range in the amount of light reaching sign positions (*1*,*2*,*3*,*4*). The variation in illumination observed during the sign crew workshops is consistent with that reported by other researchers. These prior studies of headlamp illumination were drawn from older vehicles and primarily from passenger sedans.

CURRENT RESEARCH EFFORT

In the effort described in this report, researchers measured headlamp illumination provided at four sign positions and three viewing distances for 46 typical vehicles. The purpose of the measurements was to:

- determine the variability in headlamp illumination present in a sample of typical vehicles in Texas,
- determine the amount of illumination present at several typical sign positions for a sample of typical vehicles in Texas, and
- determine if changes are needed in retroreflective sign sheeting selection to accommodate any changes in the amount of illumination provided by vehicles.

PROJECT ACTIVITIES AND REPORT ORGANIZATION

This report describes the activities and findings associated with one task of a larger TxDOT research project on sign retroreflectivity. The activities that are associated with this task are described below. The following also indicates the chapters of this report that address each of the activities.

- *Literature Review* – The research team reviewed previous research concerning the visibility of signs and pavement markings, vehicle lighting trends, minimum retroreflectivity requirements, vehicle headlamp and driver eye positions, and geometrical viewing conditions of signs and pavement markings. Chapter 2 summarizes the research reviewed.
- *Field Headlamp Measurements* – The initial need to conduct controlled evaluations of headlamp illuminance was identified through field headlamp measurements associated with the sign inspection evaluations. Chapter 3 summarizes the results of these field headlamp measurements.
- *Indoor Headlamp Measurements* – The results from these field measurements prompted the research team to seek more precise measurements of headlamp

illumination across a broader range of viewing conditions and distances. The controlled measurements of headlamp illuminance were performed in a vacant airplane hangar. The measurement procedure, results, and applications of the results in computer modeling are described in Chapter 4.

- *Conclusions and Recommendations* – Based on the results from the research conducted, the research team developed recommendations for sign sheeting and nighttime inspection procedures. Chapter 5 describes the overall findings and the resulting recommendations.

CHAPTER 2. LITERATURE REVIEW

The scientific principles regarding illumination and sign visibility are described in this section. Computer modeling is used extensively in this area of research. These computer models are explained, as well as how they are used to determine minimum levels of retroreflectivity for sign sheeting materials. In addition, trends in vehicle and headlamp design are detailed which may affect sign visibility in the future.

ILLUMINATION AND RETROREFLECTIVITY

The luminance of a traffic sign at night is controlled by the retroreflectivity characteristics of the sign face material, the relative position of the sign and the vehicle, and the amount of illumination provided to the sign by the vehicle. Four terms are commonly used in describing the nighttime performance of retroreflective sign materials. The luminance is the amount of light produced by the sign or pavement marking and represents what the driver sees. Luminance is a function of the illuminance and the retroreflective properties of the material.

- *Luminous intensity* – measured in candelas (cd) refers to the amount of light produced by the headlamps in a particular direction. The English unit is candles.
- *Illuminance* – measured in lux (lx) refers to the amount of light falling on a sign face, measured at the sign face. It is equal to cd * $1/d^2$ where d is the distance between the light source and the sign. The English unit is footcandles.
- *Luminance* – measured in cd/m^2 refers to the amount of light produced per unit area of the object. Human visual systems interpret luminance as brightness. The English unit is footlambert.
- *Coefficient of retroreflection* – measured in $cd/lx/m^2$ refers to the light returning efficiency of a material at specified angles relative to the light source and the observer. The English unit is $cd/fc/ft^2$. The term Specific Intensity per unit Area (S.I.A.) was used in the past to refer to the coefficient of retroreflection. The lay term “candlepower” is often used as a substitute when referring to the coefficient of retroreflection of a sign sheeting material.

Computer models of traffic control device photometry, such as ERGO or TarVIP (6, 7) typically contain a data file of retroreflectivity values for sheeting across a wide range of photometric angles. These data are measured in a photometric range using a calibrated light source and a goniometer to rotate the sample through all the necessary angles. These data files characterize how well the material reflects light back to its source. It is important to remember that these data are calculated to a single light source, not a pair of lights as found on a vehicle. On the road, the angles between the left headlamp and the sign will differ from the angles between the right headlamp and the sign. The total luminance of a sign is the sum of the two products. Figure 2 illustrates the differences in entrance and observation angles between each headlamp.

$$\text{Sign Luminance} = (R_{A\ \text{Left}} * \text{Illumination}_{\text{Left}}) + (R_{A\ \text{Right}} * \text{Illumination}_{\text{Right}})$$

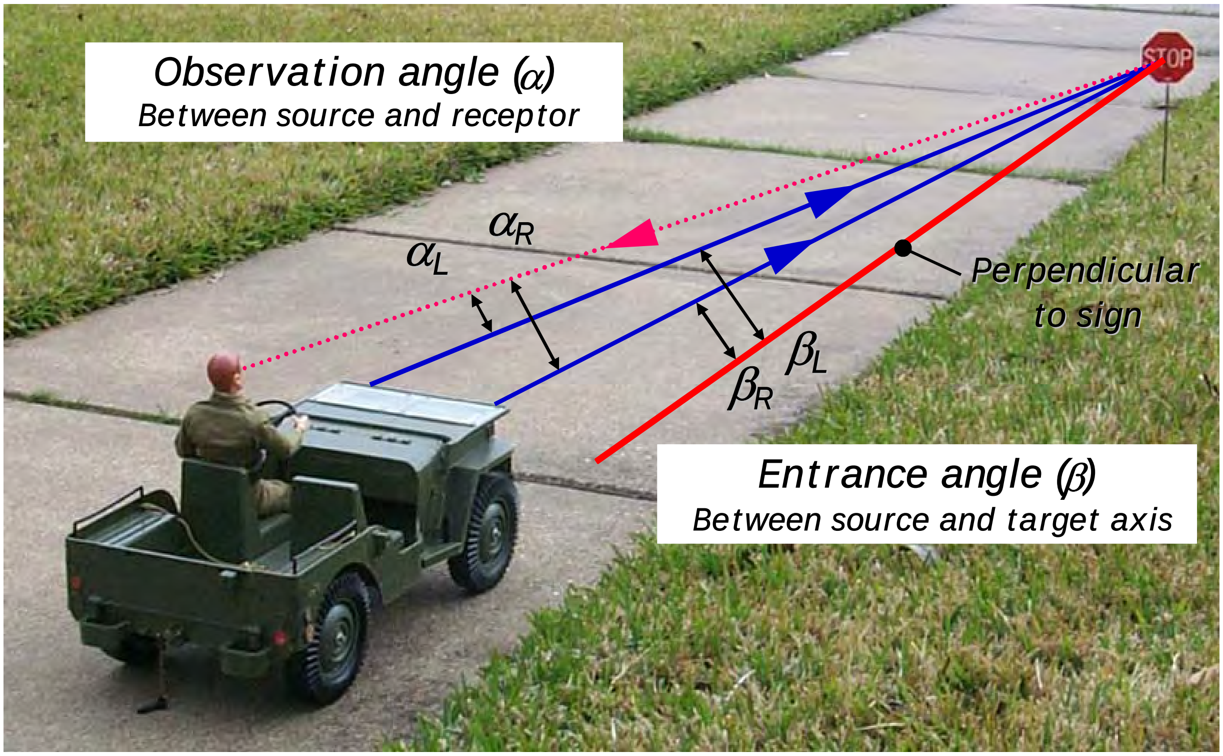


Figure 2. Illustration of Photometric Angles.

Retroreflectivity of a sign material is only one factor in determining the overall luminance (visibility) of a sign at night. A retroreflective material can only return a portion of the light that is directed at the sign. A sign with high retroreflectivity can have low luminance if only a small amount of light (illuminance) falls upon the sign. Conversely, a sign with low retroreflectivity can appear bright (high luminance) if the illuminance is high. Figure 3 illustrates the impact of illuminance on the nighttime visibility of a sign. In this figure, all four photos are of the same sign. Each photo used the same camera and setup. The only difference between the photos is the amount of light that was directed toward the sign face. A similar analogy can be made for vehicles that direct low or high illuminance on a sign face.

Note: Sign position and photographic conditions are identical, only the illumination intensity has changed.

Figure 3. Effects of Illumination on Sign Appearance.

MINIMUM RETROREFLECTIVITY

Traffic control devices provide one of the primary means of communicating vital information to users of the street and highway transportation network in the United States. Traffic signs are one of the three basic types of traffic control devices and they provide important regulatory, warning, and guidance information about the roadway environment. The *Manual on Uniform Traffic Control Devices* (MUTCD) establishes the requirements for signs and other types of traffic control devices (*8*). One of these requirements is that "*Regulatory and warning signs ... shall be retroreflectorized or illuminated to show the same shape and color both by day and night*." Guide signs have the same requirement unless exempted for a particular sign in the appropriate section. However, the current MUTCD does not contain end-of-service life retroreflectivity values for traffic signs. Such values would indicate a minimum level of retroreflectivity at which a sign should no longer be used.

One of the first actions by the Federal Highway Administration (FHWA) to establish minimum levels of retroreflectivity was a 1985 request for comments and a notice of proposed amendment to the MUTCD in the *Federal Register* (9). This notice summarized the issues associated with minimum retroreflectivity levels and asked 10 questions regarding retroreflectivity of signs and markings. The FHWA also initiated a research program to develop minimum levels of retroreflectivity. In 1993, the FHWA published a report that presented the initial research recommendations for minimum levels of retroreflectivity for traffic signs (*10*). These recommendations were revised in a later report after the FHWA conducted validation evaluations and received input from public agency personnel (*11*). More recently, the Texas Transportation Institute (TTI) researchers have updated the minimum retroreflectivity research recommendations (*12*). The TTI research includes consideration of the recent changes in headlamp illumination, among other factors.

Congress has also addressed the issue of minimum levels of retroreflectivity by including the following statement in the 1993 Department of Transportation Appropriations Act:

> *"The Secretary of Transportation shall revise the MUTCD to include a standard for a minimum level of retroreflectivity that must be maintained for traffic signs and pavement markings which apply to all roads open to public travel."*

The FHWA research recommendations for minimum levels of retroreflectivity define the minimum as a function of sign color and other factors. The other factors that may be used to determine the applicable minimum value include roadway speed, sign size, type of retroreflective sheeting, and type of legend. As such, there is not one minimum retroreflectivity number that applies to all signs in all situations. In general, the minimum retroreflectivity increases as the roadway speed increases or the size of the sign decreases.

As the FHWA has moved closer to issuing a proposed rule on minimum levels of retroreflectivity for signs, public transportation agencies have become increasingly concerned about the impacts of minimum retroreflectivity requirements. Several previous efforts have used the research-recommended values as a basis to determine the extent to which existing signs in the field meet the minimum values (*13, 14, 15, 16, 17, 18, 19*). At best, however, there have been limited evaluations in which the research recommendations for minimum retroreflectivity have been compared to actual field visual observations of retroreflectivity by transportation agency personnel responsible for making sign replacement decisions (*5, 11, 13*).

COMPUTER MODELING

The minimum in-service retroreflectivity values were developed largely through computer modeling. These models rely on two data sets. The first is a data file containing the coefficient of retroreflection values for a material as measured in the laboratory across a wide range of the four photometric angles. The second data file contains light output data from laboratory measurements of a headlamp at a range of horizontal and vertical deflection points. The computer program takes input from the user about the location in space of the vehicle, the sign, the driver's eye within the vehicle and the lamps' positions on the vehicle. The program then calculates, for a specified viewing distance, the values of the four photometric angles at which the sign appears for the given roadway geometry. In addition, the sign's position relative to the headlamp beam pattern is determined. This position is referred to as a sign's H/V point; its horizontal and vertical position relative to some point, typically the front center of the vehicle or the center of an individual lamp. This sign position and the corresponding photometric angles are different for each headlamp on the vehicle. All these calculations are geared toward defining the geometry of the light entering the sign so that the amount of light that can be retroreflected can be looked up in the data file. Once the coefficient of retroreflection is determined, the program then looks up the amount of light falling on the sign (illuminance) in the headlamp data file. By multiplying these two values, a luminance value expressed in candelas per square meter is obtained for each headlamp separately. The two luminance values are summed to produce the total sign luminance at that distance. The calculations of computer modeling can be performed as a set of vector equations in a spreadsheet, but several computer programs have been developed that allow luminance modeling to be conducted easily provided the user has access to headlamp and reflectivity data (*6, 7, 20, 21, 22, 23*). All computer modeling done as part of this research project used the ERGO 2001 software program.

The laboratory measurements of retroreflection use a calibrated, standard light source that has a known amount of illumination that is very even across its beam spread. This light source is the correlate to a headlamp on the road, while a photo detector cell mounted near the light source is the counterpart to the human eye. A sample of retroreflective material is placed on a goniometer and rotated to the proper angle relative to the light source. The amount of light illuminating the sample is a known quantity because of the calibrated light source, and the amount of light returned is measured by the photocell. The ratio of these two per unit area of sample material (cd/lx/m^2) is the coefficient of retroreflection. A data file is created that lists the coefficient of retroreflection for every combination of observation, entrance, presentation, and orientation angles. The most widely used data set in the research field comes from the ERGO program (). These measurements were made in the Avery-Denison (Stimsonite at the time) laboratory and are based on 10 samples of each type of material pulled from different lots. The exact sampling of the material has never been published. The data resolution is at 0.05° for observation angles, 4° for entrance angles, 30° for rotation angles, and 10° for orientation angles. Interpolation is done to derive retroreflectivity values at intermediate angles. The data used by the Computer Analysis of Retroreflectance of Traffic Signs (CARTS) model used by FHWA to determine the minimum retroreflectivity values were more limited and included only one type of microprismatic material (Type VII).

The headlamp data files used by these programs are the other major factor to be considered. The CARTS model used a 50th percentile low-beam headlamp derived from measurements of 26 U.S. headlamps from vehicle model years 1985 - 1990. More recent revisions to the recommended values (*23*) have used a 50th percentile market-weighted low-beam headlamp derived from measurements of 20 headlamps from the 20 best-selling U.S. vehicles for model year 2000 (*1*). The headlamp data used in these models consists of a two-dimensional matrix with luminous intensity (cd) values at each *x*,*y* intersection, typically in 0.5° increments.

Laboratory measurements of vehicle headlamps are done using a goniometer. The lamp is removed from the vehicle and mounted in a bracket that allows it to be rotated precisely. The photometer is typically fixed, and the lamp rotates to present the proper steradian to the detector. This is the equivalent of having the lamp stationary and sweeping a light meter in 0.5° steps horizontally and vertically to create a matrix in front of the lamp. Luckily, many engineering firms routinely test lamps in this way and then make the resulting data files available for purchase. In addition, for an extra fee, a specific make and model of vehicle can be measured. The data in these files are arranged so that the candela value is listed for each H/V point measured. Based on the user input concerning sign, vehicle, and observer position, the H/V point of the sign is calculated. This point is then looked up in the lamp output data file. If the specific H/V point was not measured in the lab, a candela value is interpolated using nearby measurement points.

The University of Michigan Transportation Research Institute (UMTRI) has purchased the headlamp output data files for the top 10 best-selling passenger vehicles, light trucks, sport-utility vehicles (SUVs), minivans, and full-sized vans for the model years 1992, 1996, and 2000 (*1, 2, 3*). They created a composite lamp file that is weighted according to sales volume for each particular vehicle. In most computer modeling, the median lamp is used. They created this file by taking the median illumination value *at each measurement point*. This data handling creates a composite whose overall shape doesn't look like any actual vehicle on the road. Alternative methods for creating composite lamps have been proposed (*24, 25*), but they relied on older data sets not representative of today's vehicle fleet. The UMTRI data represent the best "snapshot" of the vehicle fleet available. The composite files for 1996 and 2000 model year data are available to researchers in electronic files and can be formatted to be used in most modeling software. The headlamps used to create these data files were all brand-new, aimed properly, and clean; this is not the case with vehicles on the road. In addition, these lamps are typically attached to a power source of 12.8 volts. While this is the standard measurement voltage in the U.S., typical operating voltages are usually higher and have been reported to be 13.2 to 14.2 volts with a mean of 13.7 volts (*26*). Higher voltage means more luminous intensity, but the relationship is not linear. For instance, an increase in voltage from 12.8 to 13.7 volts, which equates to an increase of 7 percent, translates into a 26 percent increase in luminous intensity.

Figure 4 and Figure 5 illustrate the difference in the headlamp patterns between the 2000 UMTRI and the CARTS data. These plots are of the luminous intensity (candela) of a single lamp with isocontour lines illustrating areas of equal intensity within the range illustrated by the colored key.

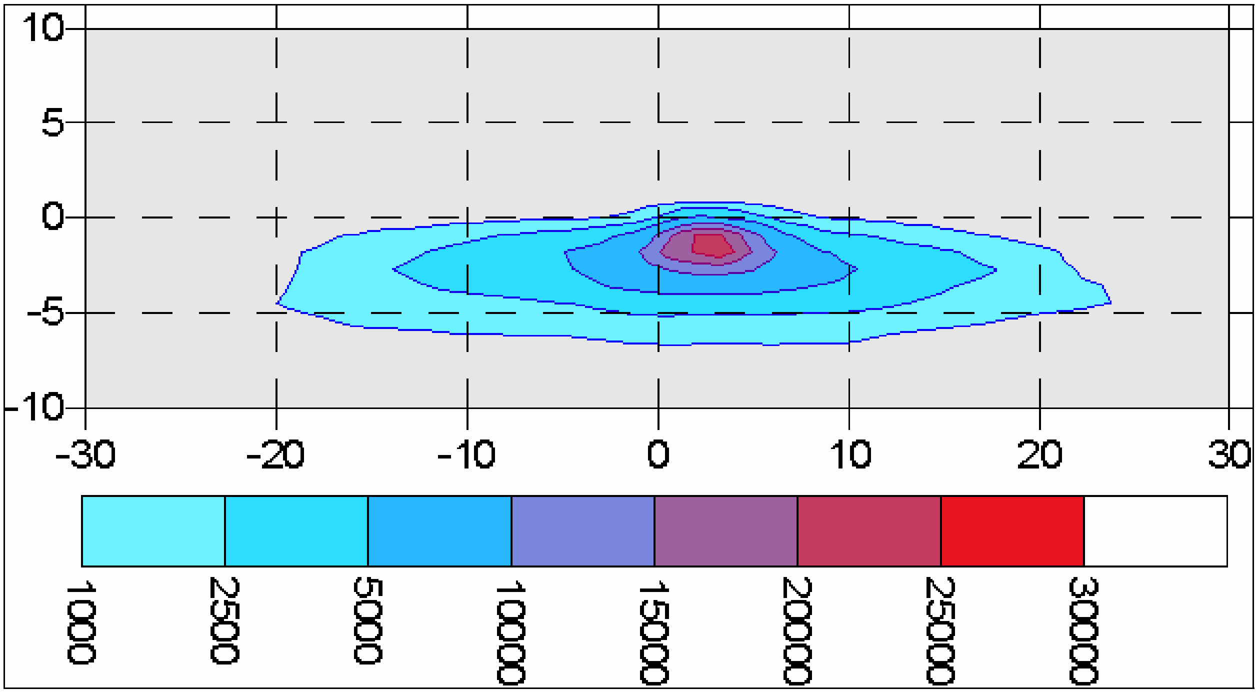


Figure 4. Headlamp Isocandela Plot for UMTRI 2000 Median Passenger Car.

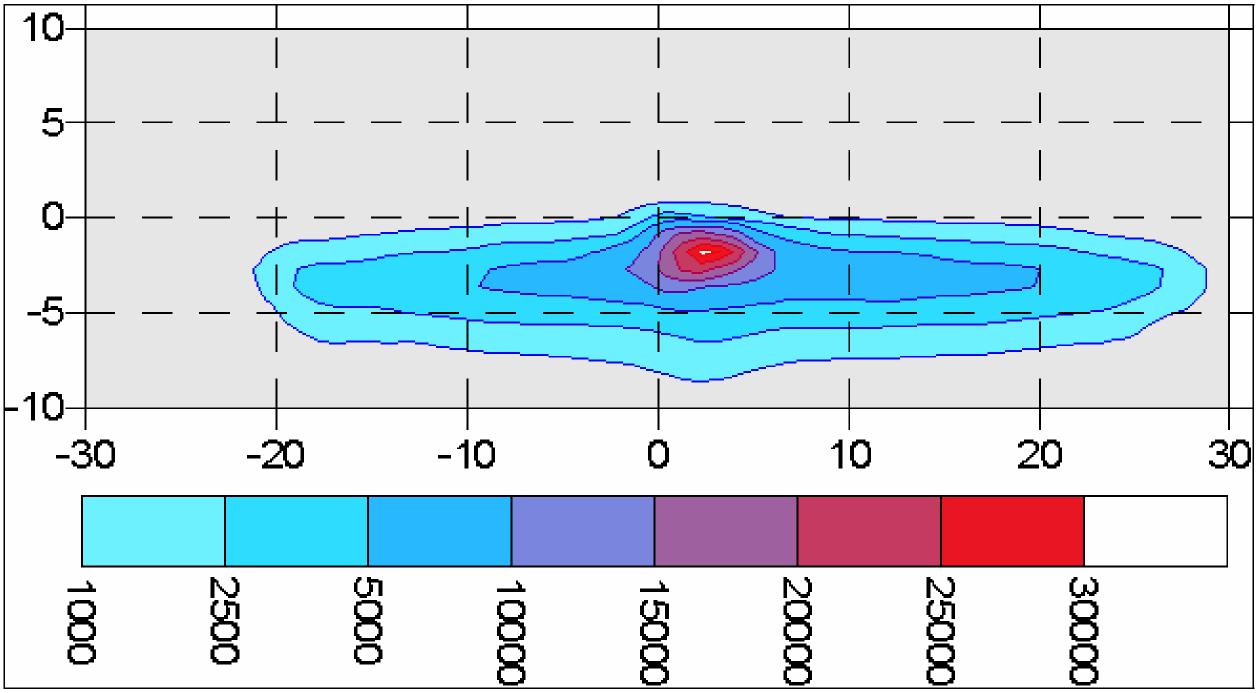


Figure 5. Headlamp Isocandela Plot for CARTS Median Headlamp.

VEHICLE TRENDS

The goal of the project was to sample headlamp illumination of vehicles on Texas roads. In order to set a goal for the types and numbers of vehicles tested, the researchers undertook an examination of vehicle sales and registrations. This section also illustrates trends in motor vehicle design and their implications for vehicle lighting and sign brightness.

Vehicle Sales

Motor vehicle sales were examined in an effort to understand the current trends in vehicle preference. A study completed by the Oak Ridge National Laboratory investigated the sales of new automobiles and light trucks. This report shows that while automobile sales have decreased by 15 percent from 1976 to 1997, light truck sales increased by over 170 percent (*27*). Table 1 shows the 10 best-selling vehicles sold in the U.S. during 2000 and reveals that half were either light trucks, vans, or SUVs (*28*).

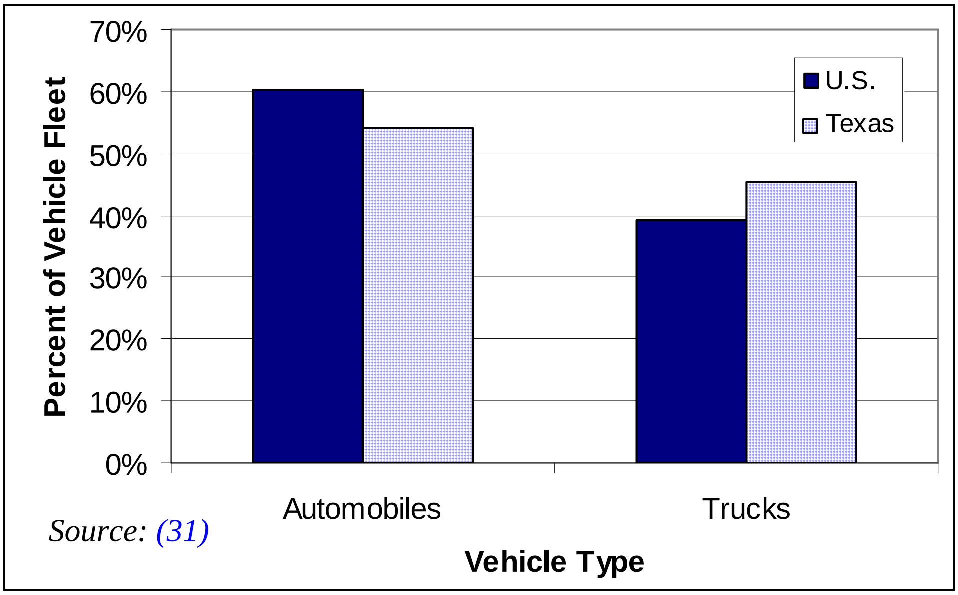
Table 1. Ten Best-Selling Vehicles Sold in the U.S. in 2000.

Make and Model	Number Sold in 2000
Ford F-Series	876,716
Chevrolet Silverado	645,150
Ford Explorer	445,157
Toyota Camry	422,961
Honda Accord	404,515
Ford Taurus	382,035
Honda Civic	324,528
Ford Focus	286,166
Dodge Caravan/Grand Caravan	285,739
Jeep Grand Cherokee	271,723

Source: (30)

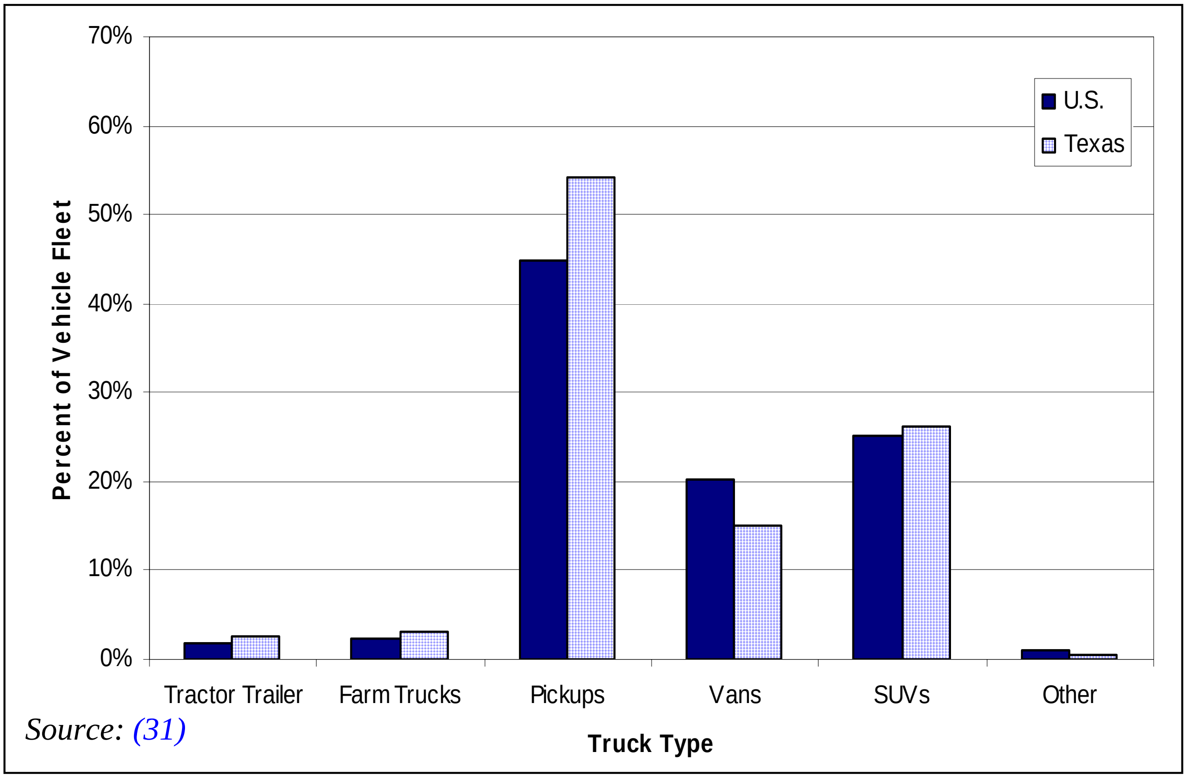
Vehicle Registration

In order to understand how the recent trends in vehicle sales have impacted the vehicle fleet, researchers grouped and compared vehicle registration data by vehicle type (*29*). This comparison was done on a national basis, as well as a state level. Figure 6 and Figure 7 show the results, which indicate that there is a larger portion of trucks on Texas roadways than on the nation's roadways as a whole.



Source: (31)

Figure 6. Vehicle Distribution Based on Sales Data.



Source: (31)

Figure 7. Truck Type Based on Vehicle Registration Data.

Headlamp Trends

Headlamp placement, illumination, and intensity are all significant factors in the nighttime visibility of traffic signs. Headlamp positions are related to the geometry of the viewing system (which incorporates the signing and driver's eye position), which can be somewhat sensitive depending on the sign location and the sheetings used to construct the sign. There are also significant changes underway in terms of headlamp standards that could potentially impact the amount of light available to retroreflect.

The Society of Automotive Engineers (SAE) specification for headlamps was J579 *(31)* but this has been cancelled in lieu of an effort to harmonize headlight design worldwide. Both SAE J579 and the Federal Motor Vehicle Safety Standards (FMVSS 108) standard apply to all vehicles registered in the U.S., regardless of the design of the headlamp filament or light source. The output of two- and four-headlamp systems in the U.S. is limited by these specifications to the following:

- Type 2 or 2A Sealed Beam
  - Upper beam (each lamp): 20,000 - 75,000 candela
  - Lower beam (each lamp): 15,000 - 20,000 candela
- Type 1 or 1A Sealed Beam (upper beam only)
  - Upper beam (each lamp): 18,000 - 60,000 candela

The illumination levels are for the brightest spots within the light distribution. The output decreases quickly as the beam pattern diverges from the nominal hot spot.

There have been two actions in Texas in the last decade that have lead to greater reliance on vehicle headlamps as the source of illumination for large guide signs. In 1993, TxDOT implemented a new policy specifying high intensity sheeting (TxDOT Type C, American Society for Testing and Materials (ASTM) Type III) for freeway guide signs and further stating that independent sign illumination is not needed unless an engineering study indicates a need. More recently, Texas House Bill 916 restricted the ability of government agencies to install lighting which points upward. This eliminated the use of the standard TxDOT sign lighting design in which the light fixtures are located at the bottom of the sign and point up toward the sign. In essence, this virtually eliminated overhead lighting from newly installed or refurbished roadway signs.

The Federal Motor Vehicle Safety Standards (FMVSS 108) includes headlamp intensity and distribution requirements for all vehicles sold in the U.S. (*30*, *31*). Prior to 1997, FMVSS 108 included specifications that allowed a reasonable amount of light to be emitted above the horizontal plane. This is the light that is used to "light up" overhead guide signs when no external illumination is provided. The drawback is that light above the horizontal plane can create a discomforting glare to drivers approaching from the opposite direction (i.e., on a two-lane highway).

Because of efforts to create a global headlamp specification, the FMVSS 108 was revised in 1997. The revision was made to accommodate the U.S. specification along with the European and Japanese specifications. In general terms, the U.S. pattern has traditionally provided substantially more light above the horizontal than the European and Japanese patterns. However, attempts to harmonize these headlamp patterns have resulted in several compromises among all three patterns. For the U.S. pattern, one of the more significant compromises has been the decreased amount of light above the horizontal. In fact, with the 1997 revision to FMVSS 108 allowing visually-optically aimed (VOA) headlamps (including both the visually-optically left [VOL] and visually-optically right [VOR] designs) and GTB's (GROUPE DE TRAVAIL – BRUXELLES 1952, an international group of lighting experts working on worldwide harmonization) 1999 agreement concerning harmonized headlamps (a drastic compromise between the U.S. philosophy of maximizing visibility versus the European philosophy of minimizing glare), the amount of light above the horizontal will decrease. A recent report shows comparisons between U.S. conventional headlamps and the VOL, VOR, and harmonized headlamps. For overhead signs at approximately 500 ft, there are consistent trends showing decreased illumination above the horizontal (*30*). Compared to the conventional U.S. headlamps, the VOR headlamp reduces overhead illumination by 18 percent, the VOL by 28 percent, and the harmonized headlamp by 33 percent (*32*). According to a recent survey, VOR and mechanical-aim low-beams are at least 55 percent predominant in the model year 2000 U.S. on-road fleet (*33*).

One of the more recent headlamp research projects was published in 1998 (*34*). FHWA sponsored this project because of a concern about changes in headlamp performance of the present U.S. vehicle fleet in terms of adequately illuminating traffic signs, especially overhead guide signs. The research was charged with determining the minimum luminance requirements needed for overhead guide signs and then establishing whether the current vehicle fleet was providing enough illumination to create such minimum luminance levels.

Researchers conducted field experiments with 50 different vehicles having a variety of different headlamp types. Based on an assumed minimum luminance of 3.2 cd/m^2 for the legend of overhead signs, the researchers concluded that certain cars in the vehicle fleet do not provide adequate illumination unless Type III sheeting or brighter sheeting is used. The following general conclusions are based on illumination data from over 1500 headlamp distributions:

- Right shoulder-mounted signs receive sufficient illumination to meet the legibility criteria from 99 percent of the vehicles.
- Left shoulder-mounted signs receive enough illumination to meet the legibility criteria from 90 percent of the vehicles.
- Overhead signs receive enough illumination to meet the legibility criteria from only about 50 percent of the vehicles.

High Intensity Discharge (HID) Lamps

Another recent trend in vehicle lighting is the use of high intensity discharge lamps. These lamps, which have a slightly blue color to them, use a gas discharge technology rather than a filament. As with any lamp, it's not the light source that makes the light good or bad for sign illumination. The reflector array, beam pattern, and aim of the headlamps have a greater effect on sign visibility. HID lamps are gaining popularity in the U.S. fleet and are now offered as standard equipment on a few luxury cars and as optional equipment on many more. In order to include the latest lamp designs, TTI sought to include an assessment of these lamps as part of this project.

Photometric data from six HID low-beam headlamps were purchased from Gilbar Technologies. The data included 45,551 photometric measurements per headlamp (from -45 to 45 degrees on the horizontal and -10 to 10 degrees on the vertical, with 0.2 degree intervals). The make and model of the six vehicles represented are listed in Table 2 with the optical system of the headlamps. All vehicles were model year 2000. The median value at each of the 45,551 measurement points was calculated and used to develop a 50th percentile HID headlamp. This median headlamp, which is used in the data analysis section as a comparison lamp, is illustrated in Figure 8.

Table 2. Vehicle and Optical Descriptions of HID Headlamps.

Make	**Model**	**Optical System**
Audi	A8	Polyellipsoidal
BMW	328ci	Polyellipsoidal
Audi	TT	Polyellipsoidal
Honda Acura	3.2	Compound
Mercedes	S500	Paraboloid
Lexus	GS400	Compound

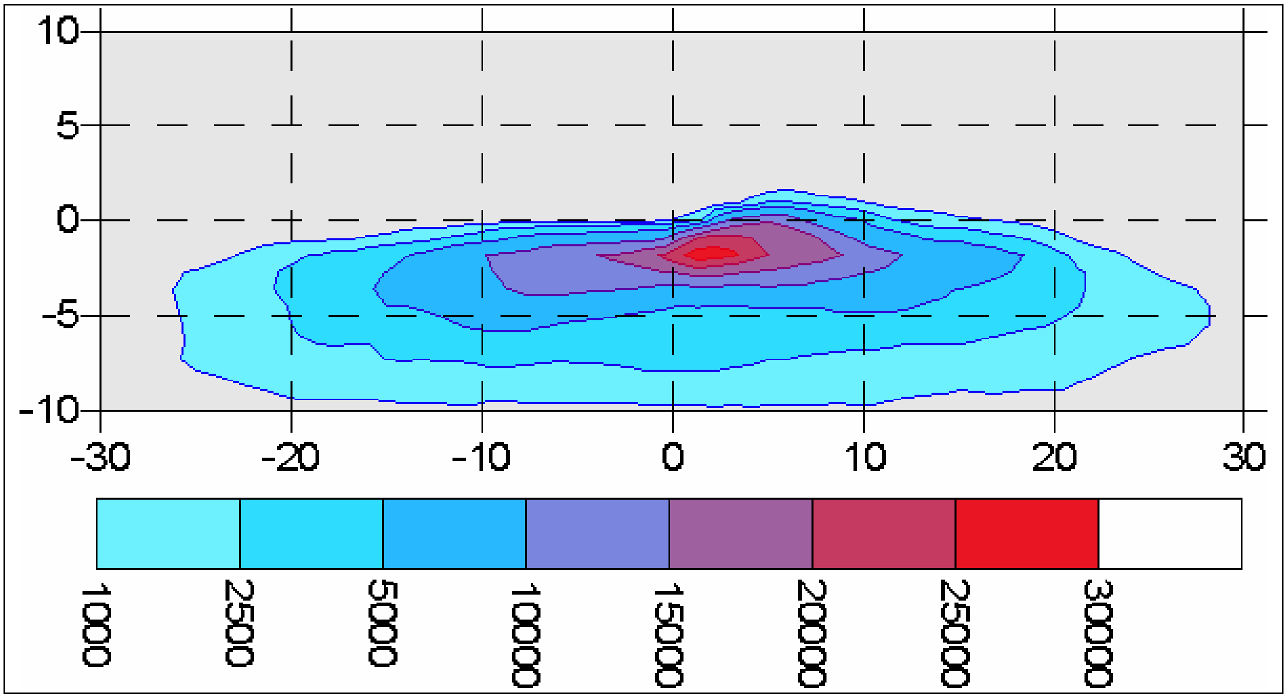


Figure 8. Isocandela Plot of Beam Pattern for Median HID Lamp.

According to Bhise, formerly at the Ford Motor Company, headlamp illumination levels encountered on the highway can vary by as much as a factor of two (33). Low voltages and the use of in-vehicle accessories decrease illumination levels. High charging rates and overvoltages increase illumination levels but to the detriment of lamp life. Another factor is dirt accumulation. A 1996 study by UMTRI found that dirt generally decreases illumination below the horizon. The light scattering created by the dirt actually *increases* the light above the horizon (*35*).

The other major trend in vehicles and lighting that affects sign luminance is vehicle size. The observation angle is generally larger when viewing a sign from a larger vehicle. Observation angle is dependent on the distance between the observer and the signs and on the vertical separation between the observer and the lamp. In 1997, Fambro et al. collected driver eye height and headlamp height for several thousand vehicles around the country (*36*). Table 3 summarizes their efforts. Note that the range of headlamp mounting heights is fairly narrow, since this is a vehicle design parameter that is regulated by the U.S. Department of Transportation (US-DOT). However, the driver eye height varies largely across vehicle type. It is this change that creates the increased observation angles. Retroreflective material varies by type in its ability to return light at these larger observation angles.

Table 3. Headlamp and Driver Eye Height.

Descriptive Statistic	**Passenger Cars**		**Multipurpose Vehicles[1]**		**Heavy Trucks[2]**	
	Driver Eye	**Headlamp**	**Driver Eye**	**Headlamp**	**Driver Eye**	**Headlamp**
Sample size	875	1318	629	992	163	337
Mean (ft)	3.77	2.13	4.86	2.76	8.03	3.68
Standard deviation (ft)	0.18	0.13	0.43	0.31	0.35	0.29
High value (ft)	4.67	3.11	6.67	3.85	9.24	4.43
Low value (ft)	3.13	1.77	3.45	1.87	6.90	3.00
Range (ft)	1.53	1.33	3.22	1.98	2.34	1.43
5th percentile	3.48	1.94	4.15	2.27	7.56	3.19
10th percentile	3.55	1.98	4.28	2.34	7.64	3.31
15th percentile	3.59	1.99	4.37	2.39	7.68	3.35

NOTE: [1] Includes pick-up trucks, sport utility vehicles, minivans, and vans.
[2] Includes tractor-trailer combinations only.

CHAPTER 3. FIELD HEADLAMP MEASUREMENTS

As described in the first chapter, the need to add a headlamp measurement task to this project was identified during the nighttime sign evaluation portion of the sign training task of the project. As part of the TTI sign crew workshop, researchers measured the illuminance of the vehicles participating in the inspections. The results of this effort showed that the range of recorded headlamp illumination was surprisingly large. Some vehicles produced a small amount of illuminance while others produced large illuminance levels. This, of course, would translate to the same sign appearing much brighter to observers in one vehicle than in another, everything else being equal.

MEASUREMENT PROCEDURE

A total of 105 vehicles participated in the evaluation. The vehicles were the same vehicles that the participants brought to the workshop. They were primarily TxDOT vehicles, but 25 were personal vehicles or were not identified as TxDOT vehicles. Before participants began the sign evaluation, the researchers made illuminance measurements of the vehicle headlights. Measurements were made with a Minolta T-1 illuminance meter. Measurements were made on a level section of road, with the instrument positioned 9 ft above the pavement and offset 12 ft from the right edge of the travel lane. This was intended to represent the approximate center of a 30-inch warning sign. Illuminance values were obtained with the vehicles positioned 500 ft and 250 ft from the sign location. Drivers were asked to try to align their vehicles perpendicular to the sign, but no extraordinary measures were taken to assure alignment. Measurements represent the illuminance from the combined headlights. As shown in the table, there was significant variability in the illuminance of the vehicles taking part in the evaluation. Of particular note is the fact that the standard deviations for most of the vehicle groups are equal to the mean values.

RESULTS

The results of the illuminance measurements in units of lux are provided in Table 4. The values in the table are corrected values for the headlights (i.e., the ambient illumination has been subtracted from the measured illuminance).

Table 4. Field Headlamp Illuminance Measurement Results (lux).

Statistic	All Vehicles (N=105)		Car Only (N=28)		Truck, Van, SUV (N=77)	
	500 ft	250 ft	500 ft	250 ft	500 ft	250 ft
Min	0.01	0.13	0.01	0.13	0.06	0.16
Avg	0.25	0.52	0.31	0.65	0.22	0.48
Max	1.72	4.22	0.99	4.22	1.72	2.53
Std Dev	0.25	0.59	0.27	0.91	0.24	0.42

For comparison, illuminance was calculated for the sign position (9 ft offset, 13 ft height) using the ERGO computer model. Headlamps from three different eras were selected as comparisons. Table 5 shows the results of this modeling for the two measurement distances and two vehicle types.

Table 5. Predicted Illuminance Used in Retroreflectivity Modeling.

Headlamp Data Set	Vehicle Model Year	UMTRI Car Dimensions		UMTRI Light Truck Dimensions	
Viewing Distance		500 ft	250 ft	500 ft	250 ft
CARTS	1985-1990	0.08	0.157	0.085	0.169
UMTRI 1997 [1]	1997	0.05	0.116	0.07	0.10
UMTRI 2000 [2]	2000	0.04	0.09	0.04	0.09

[1] UMTRI-1997- 50c lamp used for Car and UMTRI-1997-50v lamp used for Light Truck
[2] UMTRI-2000-low-beam for all passenger vehicle lamps used for both Car and Light Truck

The field measurements indicated a wide variability in the performance of the headlamps of the vehicles that took part in the evaluations. This variability could lead to inconsistencies in sign inspection results. It also indicated a need to conduct further evaluations to determine if the general vehicle fleet demonstrated the same degree of variability in illuminance. The controlled illuminance measurements are described in the next chapter.

CHAPTER 4. INDOOR HEADLAMP MEASUREMENTS

The field study conducted as part of the sign crew workshop gave a glimpse into the variability of headlamp illumination. The field study was limited in that the majority of the vehicles were pickup trucks (77 out of 105), which is not representative of the Texas registered vehicle distribution as discussed in the introduction. Another limitation of the field study was that a single sign position was measured. While the majority of signs do occur on the right shoulder, there are many critical signs that occur overhead and on the left side of the road. Trends in headlamp design indicate that there may be less light available to overhead sign positions with the newer lamp designs. At least one other limitation was that the field measurements were not terribly precise because the vehicles were not aligned carefully.   Therefore, a follow-up study was initiated to address these limitations. However, it should be noted that in some ways the validity of the field measurements is strong because they represent the variety of imperfections that one would find in the real world.

The follow-up study involved indoor headlamp measurements, which were planned to address the field study limitations. The main purpose of the follow-up study was to develop a set of real-world illuminance data that could be used in developing guidelines for the use of retroreflective sign materials as a function of sign position. In addition, it was anticipated that the headlamp illuminance data gathered through the follow-up study could be used to compare the headlamp output data used by the computer models.

METHOD

Illuminance was measured directly using an array of photometers positioned at locations equal to the angular position of road signs viewed from three distances. The research team designed and constructed a special measuring apparatus for this project.

Subject Vehicles

A variety of passenger cars, light trucks, and vans were measured. The research team obtained vehicles through the TTI fleet and from employees' personal vehicles. An attempt was made to measure the widest variety of vehicle types, ages, conditions, and headlamp types. In addition, several examples of the same make and model were measured to assess variability across vehicle type. The vehicles were measured in the condition in which they were obtained. Measurements were made after cleaning the lamps with a rag and window cleaner solution. The lamps were not aimed prior to the measurements. Each headlamp was measured independently by placing an opaque cloth over each lamp in succession to block the light from the lamp not being measured.

Apparatus

A measuring system was developed which allowed illuminance values to be measured at specific sign locations. Horizontal and vertical (H/V) placement for left shoulder, overhead, right shoulder, and right guide signs were calculated for three viewing distances for the left and right headlamp separately. The sign positions were deemed typical placements for that series of signs. All placements met current TxDOT sign specifications. The three viewing distances were selected to be representative of a braking distance (350 ft), legibility distance for a large guide sign (650 ft), and legibility distance for a small sign (200 ft). The H/V points for these sign placements were calculated based on the UMTRI 1997 passenger car dimensions for each individual headlamp. The fact that a composite vehicle was used to determine the sign positions is one drawback to the procedure. However, due to time constraints, it was not feasible to determine measuring test points based on each individual vehicle's separate headlamp positions. The H/V points are determined by headlamp mounting height and separation. These dimensions are limited to a prescribed range by Federal rule so the error introduced by this assumption in calculation is limited.

Table 6 gives the dimensions of sign placement simulated and illumination position for each of the three viewing distances. These dimensions are illustrated on a roadway scene in Figure 9. Figure 10 shows the corresponding photometer positions on the aiming screen assuming a 25 ft distance between the screen and the vehicle. Figure 11 illustrates the measuring screen in the darkened hangar.

Table 6. Sign Positions and H/V Points.

Sign Type	Viewing Dist (ft)	Right Lamp Horiz. (degree)	Right Lamp Vert. (degree)	Left Lamp Horiz. (degree)	Left Lamp Vert. (degree)	Offset (ft)	Height (ft)	Sign Descrip-tion
Right Guide	200	14.04	2.36	15.11	2.34	46 10 ft shoulder 30 ft offset 6 ft to center	11 7 ft to bottom 4 ft to center	8 x 12 ft, mounted far on right shoulder
	350	8.13	1.37	8.77	1.37			
	650	4.40	0.75	4.75	0.75			
Right Warning	200	5.17	1.88	6.30	1.87	14.1 12 ft offset 2.1 ft to center	9.1 7 ft to bottom 2.1 ft to center	36 inch diamond, mounted close on right shoulder
	500	2.96	1.08	3.61	1.08			
	650	1.60	0.58	1.95	0.58			
Overhead Guide	200	-0.57	6.41	0.57	6.41	-6 6 ft to center of lane	25 19 ft to bottom 6 ft to center	12 x 20 ft, mounted over center of travel lane
	500	-0.33	3.68	0.33	3.68			
	650	-0.18	1.98	0.18	1.98			
Left Shoulder	200	-10.23	1.86	-9.12	1.86	-40.1 24 ft (2 lanes) 10 ft shoulder 4 ft offset 2.1 ft to center	9.1 7 ft to bottom 2.1 ft to center	36 inch diamond, mounted on left shoulder
	500	-5.89	1.07	-5.24	1.07			
	650	-3.18	0.58	-2.83	0.58			

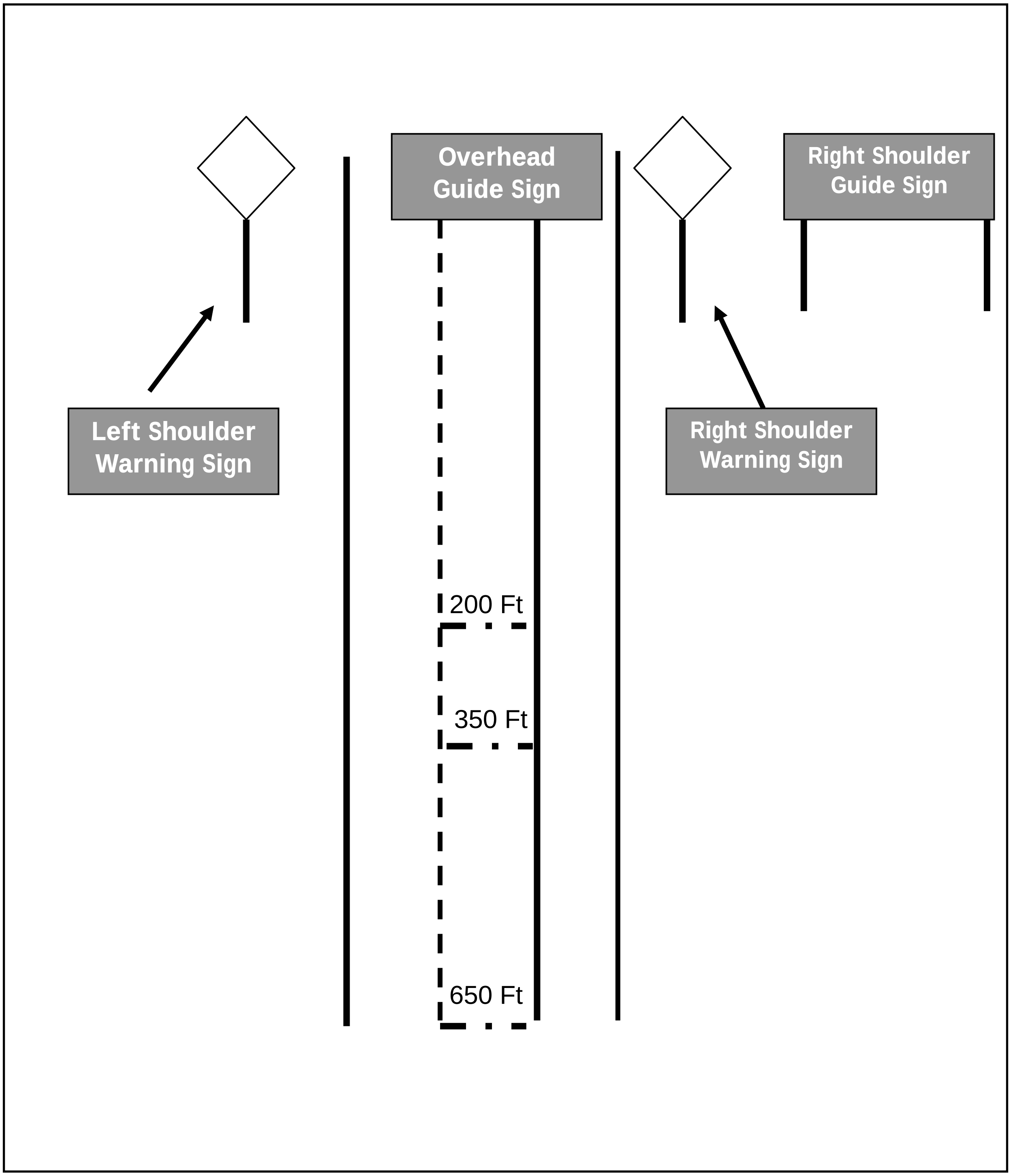


Figure 9. Illustration of Road Sign Positions and Viewing Distances.

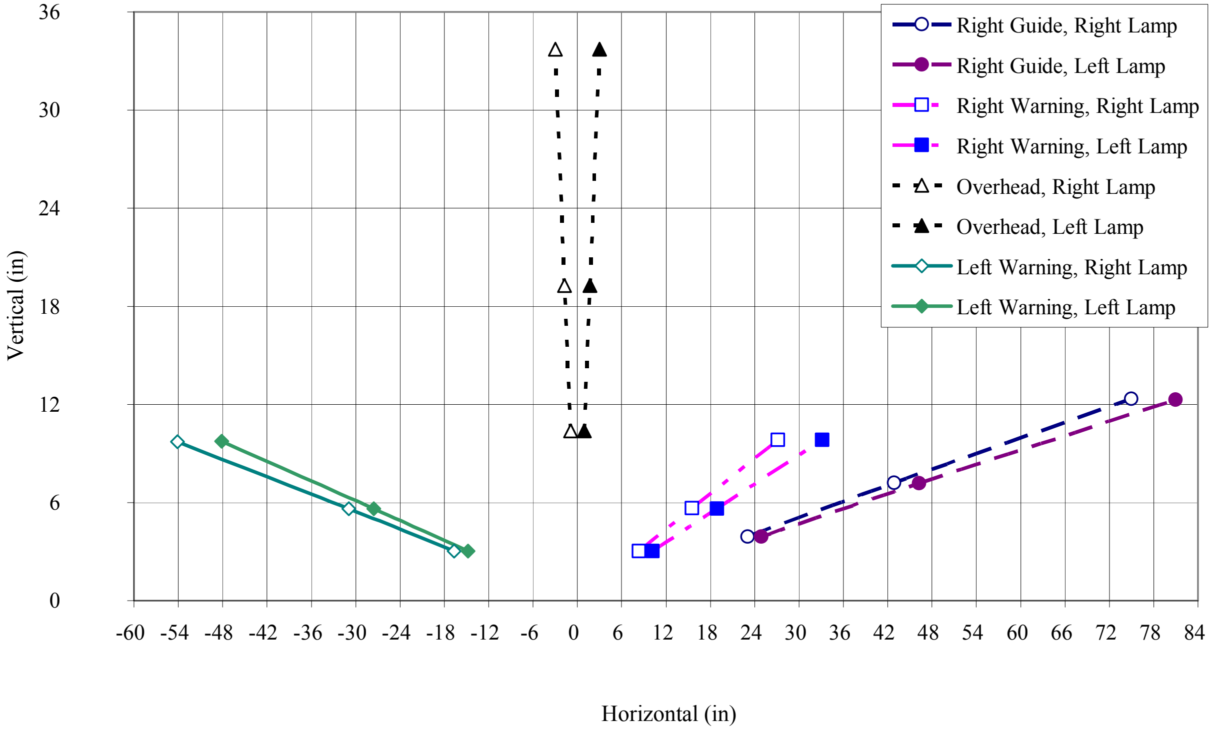


Figure 10. Sign Positions Marked as H/V Points on the Measuring Screen.

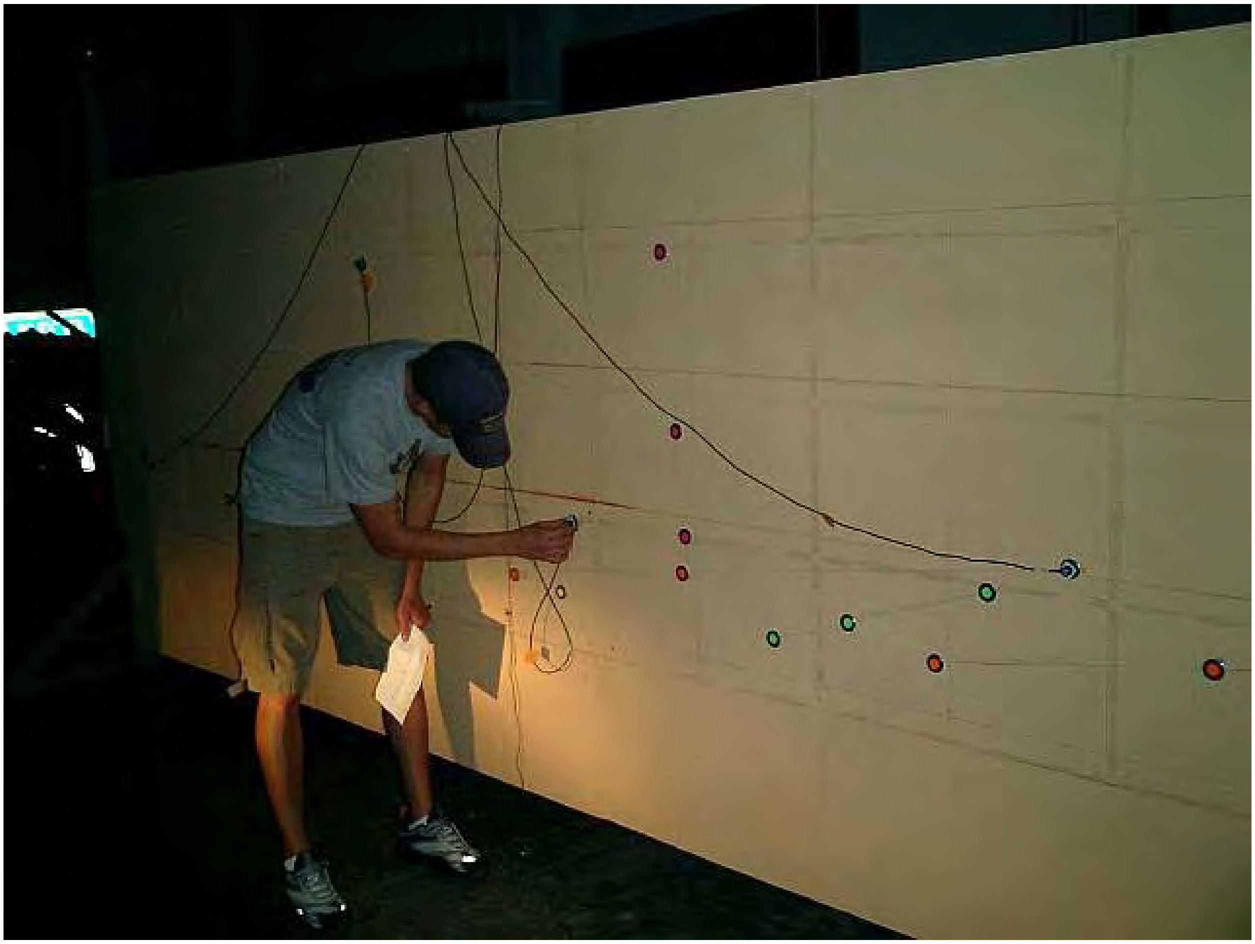


Figure 11. Measuring Screen.

Procedure

Researchers conducted the headlamp tests for this project in a vacant hangar on Texas A&M University's Riverside Campus. Most vehicles were tested during the afternoon hours, with a few tested in the evening. Before testing began, all the windows in the hangar were covered in black plastic to create a dark atmosphere for accurate headlight readings. Ambient illumination measurements were taken before each vehicle was tested. The ambient illumination was never greater than 0.07 lux, and in the majority of cases was between 0.01 and 0.02 lux.

A special measuring screen was constructed for this project and is shown in Figure 11. The screen was made of plywood bolted to a metal frame and was painted flat beige. It measured 16 X 8 ft. The screen was mobile and had a height adjustment range of 22 inches. The 24 measurement positions were marked on the screen by adhering a steel washer to the board in the proper location. Minolta illuminance meters with remote photometer heads (model T12) were equipped with magnets so that they could quickly be moved from one spot to the next. The light meter was operated on AC current throughout the study. All cords and the handheld display were placed behind the screen so as not to cast any shadows. A floor mat was placed between the vehicle and the measuring screen to reduce any light bouncing off the concrete floor.

The measuring screen was placed parallel to one wall of the hangar, about 30 ft from the wall. The screen was less than 1 yard from a wall perpendicular to the screen. A line of duct tape was placed on the floor 25 ft from the measuring screen for use in lining up the test vehicle's headlights. Several sections of pavement marking material mounted on aluminum strips were temporarily placed on the floor on the approach to the tape line to aid vehicle alignment.

When a vehicle arrived for testing, it entered the hangar through a garage door on the opposite wall of the measuring screen. Once the vehicle entered the hangar, the garage door was closed, as well as all other doors in the building. The researcher guided the test vehicle toward the screen by centering it over the temporary stripes. Once the front of the vehicle's headlights was directly over the center of the tape line, the researcher parked the vehicle and turned off the engine. At this point, the vehicle's hood was opened and headlights were turned on. To simulate a voltage equal to what would be produced when a vehicle is running, a power supply of 13.8 volts was applied to each test vehicle's battery (see Figure 12).

Before taking measurements, the researcher recorded the test vehicle's make, model, model year, and mileage on the data form in the designated spaces as well as the date and the starting time. Then, the headlights had to be identified based on the markings found on the headlights themselves. These markings were recorded as the type of headlamp. The researcher asked the vehicle owner if the headlights were original equipment and recorded changes that had been made, if any.

A series of physical measurements were taken for each vehicle. All measurements were taken in inches. First, the distance from the floor to the center of the test vehicle's headlights was recorded as the lamp height (see Figure 13). Next, the lateral headlight separation was measured by taking the distance from the center of the vehicle to the center of the driver side headlamp. This distance was multiplied by two and recorded as the lateral separation between headlamps. Now the measuring device was laid on the floor beside the driver's side of the car with the zero end at the center of the tape line. For this purpose, a measuring tape was attached to a wooden 1 X 2 inch board approximately 8 ft long. The researcher then sat in the driver's seat of the test vehicle and glanced at the measuring device on the floor to see how far his eyes were from the front of the headlight. The seat position was not adjusted; rather the measurement was made where the vehicle owner had positioned the seat. This distance was recorded as the longitudinal setback of the driver's eye from the front of the headlamp. Then the researcher took the measuring device, stood it upright with the zero end on the floor, and measured his eye height while seated in the driver's seat by sitting normally in the seat and turning his head to read the distance from the ground to a height level with his eye and recording it as the driver eye height. The experimenter was 5 ft 8 inches tall. The measuring device was then held inside the vehicle with the zero end even with the center of the vehicle, usually judged to be the rearview mirror mounting on the windshield. The researcher, seated normally in the driver's seat and holding the measuring device in front of himself at the indicated position, read the number even with his nose and recorded it as the driver eye lateral offset.

Figure 12. Attachment of Voltage Regulator to Battery.

Figure 13. Physical Measurements of the Vehicle.

To make sure the center of the measuring screen was aligned with the center of the test vehicle, a tape measure was used to measure the distance from the wall to the center of the vehicle. The screen was moved, if necessary, by measuring this new distance from the wall and aligning the centerline of the screen to it by rolling the screen away from or toward the wall.

Illuminance values for each of the sign positions were recorded separately for each lamp. An opaque cloth was placed over the lamp which was not being measured (see Figure 14). Measurements took approximately 25 minutes per vehicle.

Figure 14. Covering One Lamp for Independent Measurement.

RESULTS

The results of the physical measurements of the vehicle dimensions are presented next. The illumination results are presented later in this section.

Vehicle Characteristics

The make, model, and year of the vehicles tested are listed in Table 7. The total number of vehicles tested was 46; 25 were sedans and 21 were pickups, vans, or sports-utility vehicles. This 55 percent sedan / 45 percent light truck mix mirrors the Texas passenger vehicle registrations.

The average age of the vehicles was 1998 and the average mileage was 70,341. The spread of vehicle ages is shown in Figure 15.

The vehicle dimensions and driver eye position measurements are summarized in Table 8. In addition to the vehicles tested by TTI, the median dimensions from the 1997 market weighted passenger sedan calculated by UMTRI are provided (*2*). In general, these figures show that the sample was quite similar to the 1997 market weighted vehicle dimensions.

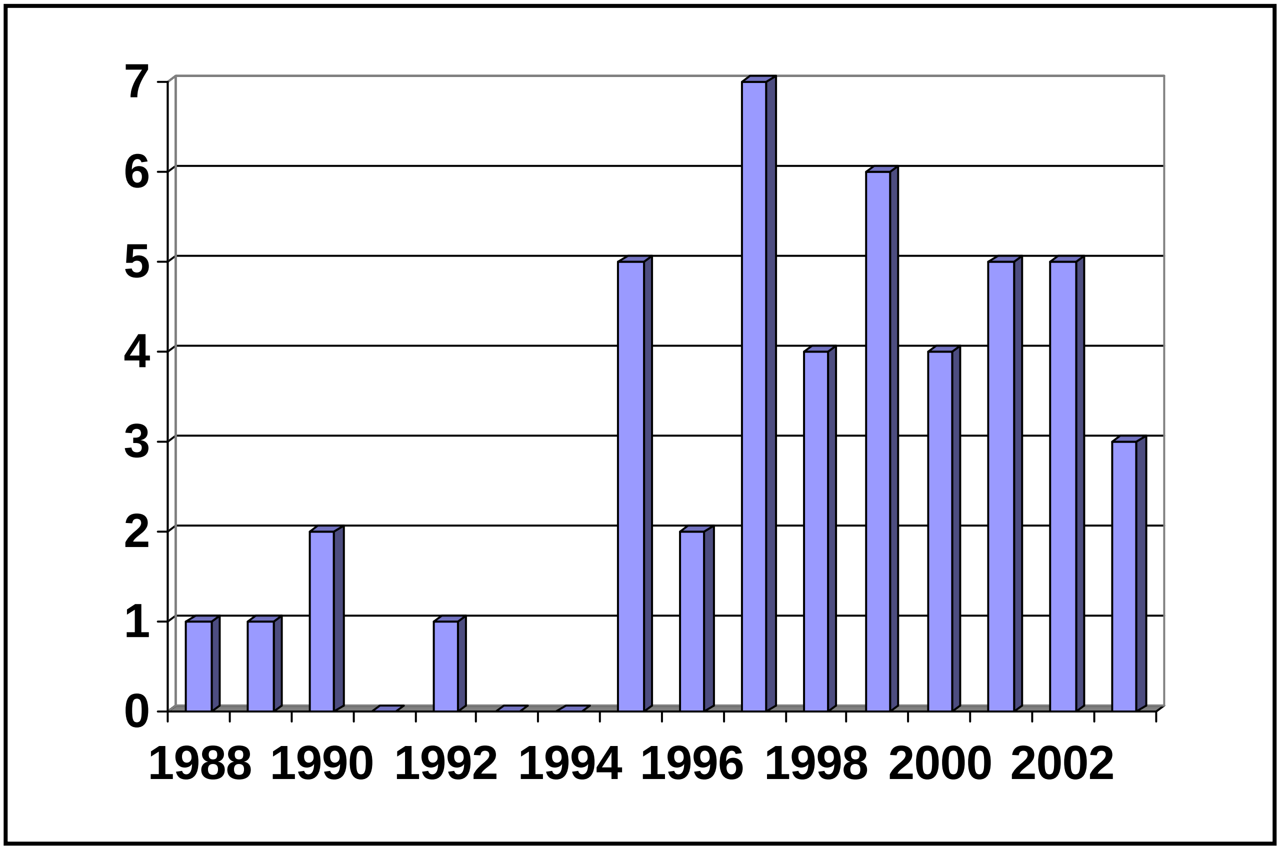


Figure 15. Age Distribution of Vehicles Tested.

Table 7. Vehicle Make, Model, Year, and Class.

	Year	Make	Model	Class
1	1988	Chevrolet	1500	LTV
2	1989	Nissan	Pathfinder	LTV
3	1990	Ford	F-150 XFT	LTV
4	1995	Chevrolet	3500	LTV
5	1995	Ford	Explorer	LTV
6	1996	Ford	Ranger	LTV
7	1997	Chrysler	Caravan	LTV
8	1997	Chevrolet	Suburban 1500	LTV
9	1998	Dodge	Durango	LTV
10	1998	Toyota	RAV 4	LTV
11	1999	Ford	F-150	LTV
12	2000	Ford	F-150	LTV
13	2000	Ford	F-250	LTV
14	2000	Jeep	Grand Cherokee	LTV
15	2001	Dodge	Caravan	LTV
16	2001	Nissan	Pathfinder	LTV
17	2002	Dodge	Ram 1500	LTV
18	2002	Dodge	Ram 1500	LTV
19	2002	Chevrolet	Trail Blazer	LTV
20	2002	Dodge	Ram	LTV
21	2003	Kia	Sedona	LTV
22	1990	Pontiac	Grand AM	Sedan
23	1992	GM	Saturn	Sedan
24	1995	Ford	Mustang	Sedan
25	1995	Toyota	Corolla	Sedan
26	1995	Chevrolet	Lumina	Sedan
27	1996	Ford	Contour	Sedan
28	1997	Ford	Taurus	Sedan
29	1997	Mazda	Miata	Sedan
30	1997	Nissan	Maxima	Sedan
31	1997	Ford	Taurus	Sedan
32	1997	Buick	Skylark	Sedan
33	1998	Chevrolet	Lumina	Sedan
34	1998	Mazda	626	Sedan
35	1999	GM	Saturn	Sedan
36	1999	Toyota	Corolla	Sedan
37	1999	Ford	Taurus SE	Sedan
38	1999	Hyundai	Elantra	Sedan
39	1999	Chevrolet	Cavalier	Sedan
40	2000	Ford	Taurus	Sedan
41	2001	Ford	Taurus	Sedan
42	2001	Ford	Taurus	Sedan
43	2001	Chevrolet	Monte Carlo	Sedan
44	2002	Audi	A4	Sedan
45	2003	Ford	Taurus	Sedan
46	2003	Subaru	Baja	Sedan

Table 8. Physical Dimensions of Vehicles Tested.

	Minimum	Mean	Median	Maximum
Headlamp Height (inches)				
All TTI sampled vehicles	23.5	29.5	27.8	41.0
TTI Passenger cars only	23.5	26.0	26.0	29.0
UMTRI 1997 Passenger Car			24.4	
TTI Light Trucks & Vans only	28.0	33.7	34.0	41.0
Headlamp Separation (inches)				
All TTI sampled vehicles	32.0	48.3	47.0	64.0
TTI Passenger cars only	32.0	43.9	45.0	48.0
UMTRI 1997 Passenger Car			44.0	
TTI Light Trucks & Vans only	42.0	53.4	54.0	64.0
Driver Eye Height (inches)				
All TTI sampled vehicles	38.0	50.5	47.5	66.0
TTI Passenger cars only	38.0	44.5	45.0	48.0
UMTRI 1997 Passenger Car			43.7	
TTI Light Trucks & Vans only	52.0	57.7	57.0	66.0
Driver Eye Lateral Offset (inches)				
All TTI sampled vehicles	12.0	14.5	14.0	18.5
TTI Passenger cars only	12.0	13.5	13.5	15.0
UMTRI 1997 Passenger Car			13.8	
TTI Light Trucks & Vans only	13.0	15.8	15.5	18.5
Driver Eye Setback (inches)				
All TTI sampled vehicles	67.0	83.1	84.0	94.0
TTI Passenger cars only	74.0	83.5	84.0	94.0
UMTRI 1997 Passenger Car			84.0	
TTI Light Trucks & Vans only	67.8	82.8	84.0	94.0

Illuminance Data

Several vehicles were photographed as part of an earlier phase of this project. A few of these photographs are included here for illustrative purposes. Figure 16 compares two vehicles. On the top is a 1999 Chevrolet Tahoe, on the bottom is a 2002 Chevrolet 2500 4X4 Truck that produced the highest illumination at this point.

Note: Top photograph is of a 1999 Chevrolet Tahoe; bottom photograph is of a 2002 Chevrolet 4X4 2500 Truck.

Figure 16. Photographs of Headlamp Patterns from Two Vehicles.

The lux values in this project were obtained at a distance of 25 ft from the headlamp. In order to extrapolate to other viewing distances, these lux values were first converted back to candela (luminous intensity) values by multiplying by 25^2. This operation essentially creates a raw candela value that we can then convert back to lux at varying distances by dividing by the distance-squared for each respective viewing distance. So, for instance, the measured lux value for the photometer in the geometric position corresponding to the right lamp for a right warning sign at 500 ft was multiplied by $1 / 500^2$. Once this distance correction was performed for each measured value, descriptive statistics were obtained for the various measurement positions. Table 9 through Table 12 presents these summary statistics for each sign class.

Table 9. Summary Illuminance Statistics for Right Guide Sign.

		All Vehicles			**Cars**			**Light Trucks**		
Viewing Distance (ft)	**Statistic**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**
200	Min	0.0441	0.0288	0.0728	0.0459	0.0288	0.0747	0.0441	0.0633	0.1073
	Average	0.2564	0.3152	0.5716	0.2623	0.3637	0.6260	0.2493	0.2575	0.5068
	Median	0.1737	0.1830	0.3566	0.1891	0.2158	0.4048	0.1103	0.1780	0.2883
	Max	0.8953	1.6469	2.5422	0.8953	1.6469	2.5422	0.8734	0.8563	1.7297
	Std Dev	0.2269	0.3317	0.5586	0.2302	0.4077	0.6380	0.2283	0.2039	0.4323
350	Min	0.0086	0.0000	0.0086	0.0089	0.0060	0.0149	0.0086	0.0000	0.0086
	Average	0.0327	0.0373	0.0700	0.0307	0.0402	0.0709	0.0351	0.0339	0.0690
	Median	0.0237	0.0247	0.0485	0.0252	0.0246	0.0498	0.0229	0.0263	0.0492
	Max	0.1571	0.1883	0.3454	0.0817	0.1883	0.2699	0.1571	0.1185	0.2756
	Std Dev	0.0260	0.0325	0.0585	0.0183	0.0367	0.0550	0.0332	0.0273	0.0605
650	Min	0.0011	0.0010	0.0021	0.0013	0.0010	0.0023	0.0011	0.0026	0.0037
	Average	0.0040	0.0044	0.0083	0.0042	0.0043	0.0086	0.0036	0.0044	0.0080
	Median	0.0031	0.0038	0.0070	0.0029	0.0038	0.0067	0.0035	0.0040	0.0075
	Max	0.0167	0.0086	0.0253	0.0167	0.0078	0.0245	0.0077	0.0086	0.0162
	Std Dev	0.0027	0.0017	0.0045	0.0034	0.0018	0.0052	0.0016	0.0017	0.0033

Table 10. Summary Illuminance Statistics for Right Warning Sign.

		All Vehicles			Cars			Light Trucks		
Viewing Distance (ft)	**Statistic**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**
200	Min	0.0659	0.0000	0.0659	0.0659	0.0000	0.0659	0.0861	0.0000	0.0861
	Average	0.4417	0.5015	0.9432	0.5194	0.6001	1.1195	0.3492	0.3841	0.7333
	Median	0.2892	0.3018	0.5910	0.3877	0.2697	0.6573	0.2419	0.3022	0.5441
	Max	2.2219	4.0531	6.2750	2.2219	4.0531	6.2750	1.1797	1.1203	2.3000
	Std Dev	0.4154	0.7012	1.1166	0.4901	0.9039	1.3939	0.2889	0.3151	0.6040
350	Min	0.0191	0.0137	0.0328	0.0213	0.0137	0.0351	0.0191	0.0277	0.0468
	Average	0.0878	0.1127	0.2004	0.1020	0.1356	0.2376	0.0708	0.0854	0.1562
	Median	0.0639	0.0659	0.1298	0.0669	0.0886	0.1555	0.0528	0.0651	0.1178
	Max	0.4842	0.6939	1.1781	0.4842	0.6939	1.1781	0.1857	0.2724	0.4582
	Std Dev	0.0816	0.1258	0.2074	0.1007	0.1593	0.2600	0.0476	0.0609	0.1085
650	Min	0.0037	0.0026	0.0063	0.0043	0.0026	0.0069	0.0037	0.0055	0.0093
	Average	0.0125	0.0148	0.0273	0.0138	0.0161	0.0299	0.0110	0.0133	0.0243
	Median	0.0095	0.0106	0.0201	0.0091	0.0111	0.0202	0.0099	0.0104	0.0203
	Max	0.0470	0.0423	0.0893	0.0470	0.0423	0.0893	0.0279	0.0415	0.0694
	Std Dev	0.0086	0.0097	0.0183	0.0101	0.0105	0.0206	0.0062	0.0087	0.0149

Table 11. Summary Illuminance Statistics for Overhead Sign.

		All Vehicles			Cars			Light Trucks		
Viewing Distance (ft)	**Statistic**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**
200	Min	0.0434	0.0406	0.0841	0.0434	0.0406	0.0841	0.0452	0.0552	0.1003
	Average	0.1344	0.1977	0.3321	0.1593	0.2654	0.4246	0.1048	0.1172	0.2220
	Median	0.1046	0.1040	0.2086	0.1152	0.0847	0.1998	0.0978	0.1048	0.2027
	Max	0.7469	1.8250	2.5719	0.7469	1.8250	2.5719	0.2311	0.2539	0.4850
	Std Dev	0.1100	0.3205	0.4305	0.1400	0.4236	0.5636	0.0449	0.0568	0.1017
350	Min	0.0088	0.0082	0.0169	0.0098	0.0082	0.0180	0.0088	0.0096	0.0184
	Average	0.0274	0.0287	0.0561	0.0319	0.0330	0.0649	0.0221	0.0235	0.0456
	Median	0.0229	0.0214	0.0443	0.0247	0.0195	0.0443	0.0207	0.0219	0.0426
	Max	0.1353	0.1194	0.2547	0.1353	0.1194	0.2547	0.0415	0.0515	0.0930
	Std Dev	0.0204	0.0217	0.0420	0.0260	0.0276	0.0535	0.0082	0.0098	0.0179
650	Min	0.0015	0.0016	0.0030	0.0018	0.0016	0.0034	0.0015	0.0018	0.0033
	Average	0.0046	0.0044	0.0091	0.0052	0.0047	0.0100	0.0039	0.0041	0.0080
	Median	0.0041	0.0038	0.0079	0.0048	0.0036	0.0085	0.0039	0.0039	0.0078
	Max	0.0177	0.0099	0.0276	0.0177	0.0099	0.0276	0.0073	0.0094	0.0167
	Std Dev	0.0086	0.0097	0.0183	0.0101	0.0105	0.0206	0.0062	0.0087	0.0149

Table 12. Summary Illuminance Statistics for Left Shoulder Sign.

		All Vehicles			Cars			Light Trucks		
Viewing Distance (ft)	**Statistic**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**	**Left Lamp (lux)**	**Right Lamp (lux)**	**Sum (lux)**
200	Min	0.0544	0.0000	0.0544	0.0544	0.0000	0.0544	0.0772	0.0820	0.1592
	Average	0.2058	0.1896	0.3954	0.2310	0.1833	0.4143	0.1758	0.1970	0.3728
	Median	0.1663	0.1487	0.3150	0.2114	0.1234	0.3348	0.1650	0.1652	0.3302
	Max	0.6469	1.3094	1.9563	0.6469	1.3094	1.9563	0.4228	0.6250	1.0478
	Std Dev	0.1369	0.2001	0.3371	0.1663	0.2509	0.4172	0.0851	0.1204	0.2055
350	Min	0.0154	0.0165	0.0319	0.0154	0.0177	0.0330	0.0165	0.0165	0.0331
	Average	0.0395	0.0488	0.0883	0.0433	0.0581	0.1015	0.0348	0.0377	0.0726
	Median	0.0357	0.0331	0.0688	0.0360	0.0305	0.0665	0.0351	0.0349	0.0699
	Max	0.1211	0.2383	0.3594	0.1211	0.2383	0.3594	0.0542	0.0913	0.1455
	Std Dev	0.0194	0.0506	0.0699	0.0238	0.0658	0.0896	0.0110	0.0181	0.0291
650	Min	0.0032	0.0024	0.0057	0.0034	0.0024	0.0058	0.0032	0.0027	0.0059
	Average	0.0070	0.0070	0.0139	0.0075	0.0073	0.0149	0.0063	0.0065	0.0128
	Median	0.0066	0.0052	0.0118	0.0068	0.0052	0.0120	0.0062	0.0061	0.0123
	Max	0.0200	0.0210	0.0410	0.0200	0.0210	0.0410	0.0091	0.0128	0.0219
	Std Dev	0.0031	0.0044	0.0075	0.0038	0.0054	0.0092	0.0018	0.0028	0.0046

SIGN SHEETING RECOMMENDATIONS BASED ON MEASURED ILLUMINATION VALUES

The data collected for this project are exclusively illumination values. In order to make recommendations about sign sheeting, these illumination values must be applied to coefficients of retroreflection to determine luminance. For this project the median value of all the measured vehicles was used to determine the illumination value. The luminance calculation also requires assumptions to be made about the retroreflective characteristics of different sheeting products. For this project, the retroreflectivity data provided in the ERGO 2001 computer program distributed by the Avery-Dennison Corporation were used. This program provides photometric range measurements of the coefficient of retroreflection (R_A) for materials which meet the specifications for ASTM Types I, II, III, VII, VIII, and IX. The creators of the program state that measurements were made across a sample of at least 10 lots of white sheeting meeting each ASTM type during 1998. Within each ASTM Type, a single manufacturer's material was sampled. The following section should be interpreted with this limitation in mind. Because manufacturing processes change, and new vendors of the various approved types of sheeting are in the market place, the R_A values from 1998 may not represent material purchased now or in the future. The ASTM Type classification is intended to generically describe the photometric performance of materials. The actual measurements that are done, must use an actual piece of manufactured material. Though this report uses the phrase "ASTM Type x," the reader should keep in mind that 10 samples of a single manufacturer's material meeting that type specification are the data source.

Once the theoretical luminance of a sign that is being illuminated by the median TTI vehicle is determined, it must be evaluated against some target luminance value. The determination of this target value is described in the following section. The calculation of sign luminances based on the data obtained in this project follow that discussion.

Minimum Luminance Threshold

One of the first issues in this approach is defining the threshold luminance that will be used to compare the results. Fortunately, research has been recently completed that documents the minimum luminance needs for nighttime drivers. In a recent FHWA study, Carlson and Hawkins worked to determine minimum guide sign luminance needs for elderly drivers (*23*). Figure 17 shows the cumulative distribution results for 30 drivers aged 55 to 81. These curves represent the minimum luminance needed to read overhead guide signs. They developed another set of curves for street name signs. The overhead signs had 16/12-inch Series E(Modified) legend and the street name signs had 6-inch Series C legends.

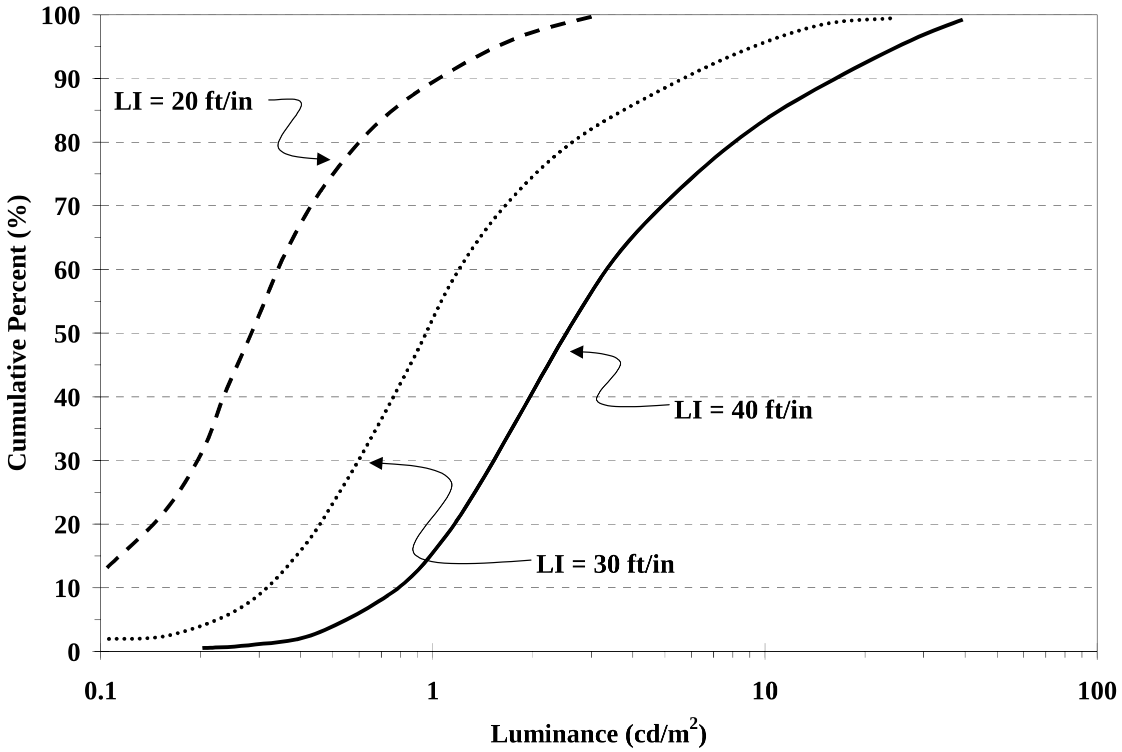


Figure 17. Required Luminance for Different Legibility Indices.

Figure 17 shows that the luminance needed to read an overhead sign decreases as the distance to the sign decreases. At a distance of 640 ft (i.e., a legibility index of 40 ft/inch of letter height with Series E(Modified) letters), 50 percent of the elderly drivers would be accommodated with a luminance of 2.3 cd/m^2. Using the same legibility index of 40 ft/inch of letter height for Series C letters, the 50th percentile legibility luminance level was 3.9 cd/m^2. The legibility index of 40 ft/inch meets the current design standard laid out in the MUTCD. Some work suggested using a standard of 30 ft/inch legibility index to be inclusive of a wider range of older drivers. For this project, the current standard of 40 ft/inch is selected. These resulting luminance values accommodate only half the drivers. A more inclusive accommodation may be desired for engineering purposes. The required minimum luminance levels increase as a larger portion of the driving population is accommodated. Table 13 shows an example of the sensitivity of the luminance requirements depending on accommodation level and distance for large overhead signs viewed from a passenger car.

Table 13. Threshold Luminance Values for Overhead Signs (cd/m^2).

Distance (ft)	Accommodation Level (percent)		
	50	75	85
300	0.27	0.45	0.75
470	0.80	1.63	3.05
640	2.30	5.70	11.7

For the present project, the researchers chose to use the 50th percentile legibility luminance levels from this recent FHWA study *(23)*. Data from the National Personal Transportation Survey of 1995 can be used to estimate the actual levels of nighttime driver accommodation that these 50th percentile levels represent. According to Figure 18, approximately 89 percent of the nighttime drivers are under 55 years. Therefore, the legibility accommodation levels assumed herein actually correspond to levels well above 90 percent (89 percent plus 50 percent of drivers over age 55).

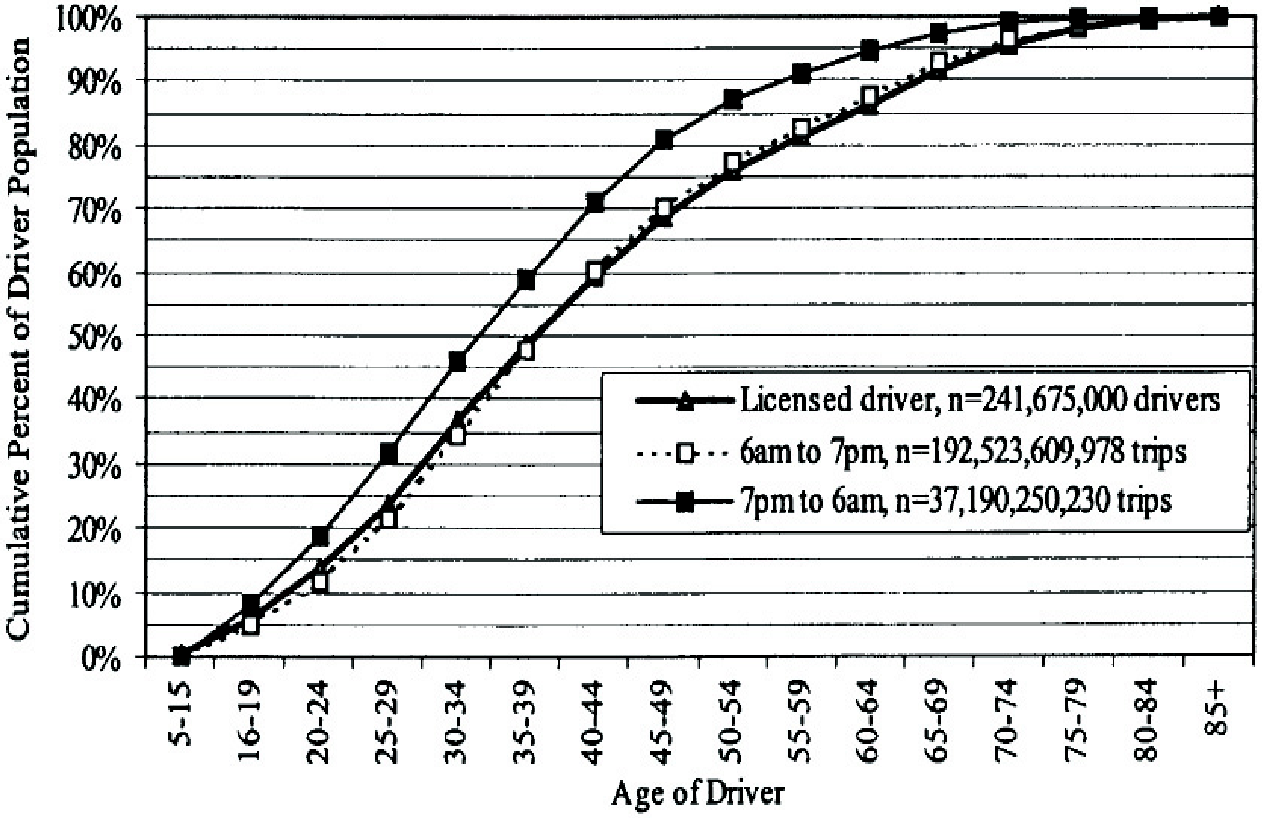


Figure 18. Cumulative Percentage of Driver Population as a Function of Driver Age.

Theoretical Sign Luminance Calculations

Using the recorded illuminance and vehicle dimension data, the researchers analyzed how various types of retroreflective sheeting performed against assumed threshold luminance data. The purpose of this analysis was to provide results that could be used to help develop guidelines to select retroreflective sheeting types based on sign position.

The median lux values for the 46 vehicles were used for all calculations. These lux values represent the total illumination provided by both lamps. In order to properly calculate luminance, the lamps must be considered independently. The coefficients of retroreflection at the geometry presented by the left and right headlamps are different from each other as well. Again using ERGO, the separate R_A values at each distance were determined. The vehicle dimensions of the UMTRI Car were used which represents a passenger sedan. The illuminance was then multiplied by the corresponding R_A to determine luminance for that lamp. The independent luminances were then summed to give total sign luminance. This procedure was applied to the R_A values for each of the ASTM types represented in ERGO. The selection of the UMTRI Car for this modeling is a necessary simplification because it is impractical to make sheeting recommendations based on vehicle type when signs are viewed by a variety of vehicles.

For the ground-mounted and overhead guide sign positions, the target luminance value of 2.3 cd/m^2 is used. This represents how bright a sign would need to be at 640 feet in order for 50 percent of older drivers to be able to read it with Series E(Modified) letters. Guide signs typically have 16-inch Series E(Modified) letters so this target is most appropriate for these two sign types. Table 14 shows the calculated sign luminance for the median TTI vehicle for right-shoulder guide signs. This table shows that only microprismatic materials would meet the minimum target luminance values under the assumptions itemized above.

Table 14. Theoretical Sign Luminance Values for a Right-Shoulder Guide Sign.

ASTM Sheeting Type (TxDOT Type)	Theoretical Sign Luminance (cd/m^2)
I (A)	0.65
II (B)	1.12
III (C)	2.08
VII (D)	7.44
VIII (D)	5.83
IX	2.84
Note: The target minimum luminance value for legibility of a 16 inch Series E(Modified) letter at 640 feet for the 50th percentile older driver is 2.3 cd/m^2.	

The same calculations were applied to the overhead sign position. Table 15 shows the results of this modeling. For overhead signs, as well, the minimum luminance threshold is met by only microprismatic materials, though Type C is just barely below the threshold of 2.3 cd/m^2.

Table 15. Theoretical Sign Luminance Values for an Overhead Guide Sign.

ASTM Sheeting Type (TxDOT Type)	Theoretical Sign Luminance (cd/m^2)
I (A)	0.72
II (B)	1.24
III (C)	2.29
VII (D)	7.99
VIII (D)	6.92
IX	3.97
Note: The target minimum luminance value for legibility of a 16 inch Series E(Modified) letter at 640 feet for the 50th percentile older driver is 2.3 cd/m^2.	

For the smaller shoulder-mounted signs, the minimum luminance threshold determined for 6 inch Series C letters at a legibility distance of 240 ft was used. This value is 3.9 cd/m^2. The illumination levels measured at the 200 ft viewing distance position were used as an approximation for this legibility distance. Table 16 shows the theoretical sign luminances for the right-shoulder mounted warning sign. For right shoulder warning signs, the minimum luminance threshold is met by Type I sheeting. The same data for the left shoulder mounted warning sign position are shown in Table 17. In this case, the minimum threshold is again met by Type I sheeting.

Table 16. Theoretical Sign Luminance Values for a Right Shoulder Warning Sign.

ASTM Sheeting Type (TxDOT Type)	**Theoretical Sign Luminance (cd/m^2)**
I (A)	17.13
II (B)	17.26
III (C)	23.99
VII (D)	61.11
VIII (D)	56.63
IX	121.14
Note: The target minimum luminance value for legibility of a 6 inch Series C letter at 240 feet for the 50th percentile older driver is 3.9 cd/m^2.	

Table 17. Theoretical Sign Luminance Values for a Left Shoulder Warning Sign.

ASTM Sheeting Type (TxDOT Type)	**Theoretical Sign Luminance (cd/m^2)**
I (A)	10.19
II (B)	14.36
III (C)	22.46
VII (D)	67.85
VIII (D)	45.91
IX	60.48
Note: The target minimum luminance value for legibility of a 6 inch Series C letter at 240 feet for the 50th percentile older driver is 3.9 cd/m^2.	

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

LIMITATIONS OF CURRENT RESEARCH AND FUTURE DIRECTIONS

This project is one of the very few research studies that measured headlamp illumination in a field environment. The researchers have demonstrated that it is possible to construct a system that allows for measurements in the field.

One way to validate the present project would be to take field luminance measurements of actual signs. These measurements have proven to be quite difficult due to the difficulty in aligning the vehicle consistently at large viewing distances. In addition, aiming a telephotometer, even with the smallest aperture, at distances greater than 200 ft is very difficult in the field, particularly inside a vehicle. Field measurements of luminance taken from inside a vehicle also must be adjusted for windshield and atmospheric transmissivity factors before comparisons to theoretical modeling can be made.

Other factors exist that affect headlamp output and sign illumination quality. In selecting vehicles for nighttime inspection, these characteristics should be taken into consideration. These include:

- headlamp aim,
- dust and dirt,
- electrical system voltage,
- yellowing or clouding of plastic lenses,
- one lamp not working, and
- after-market bulb replacements (e.g,“blue bulbs”).

Most of these factors would tend to reduce the amount of illumination provided to road signs and other traffic control devices.

CONCLUSIONS

This research project sought to assess the amount and variability of illumination provided to sign positions by a sample of Texas vehicles. The results showed that there is considerable variability among vehicles that make precise predictions of sign visibility difficult.

With regards to predicted sign luminance of different sign sheeting, the analysis showed that the current TxDOT standards regarding retroreflective sheeting for ground-mounted signs placed close to the lane of travel are adequate. For larger, freeway guide signs which are mounted further away from the lane of travel, TxDOT may want to consider using a material with a higher retroreflectivity value. The luminance achieved by Type III sheeting in this sign position fell just below the minimum. For the overhead sign position, Type III was again just below the threshold while all the microprismatic materials produced sign luminance values above the threshold.

Many assumptions and simplifications were necessary in determining the sign luminance values reported here. The retroreflectivity values used for the computer modeling were all based on new material and all on white material which would tend to overestimate the sign luminance in practice. In addition, the threshold values were computed for the median value of illumination from the vehicles measured. This implies that half the vehicles would produce sign luminance values less than those reported in this project. In addition, the target threshold luminance levels are based on legibility research conducted on a closed course where the observers could devote a great deal of attention to the legibility task which would tend to underestimate the actual value. This course is also in a very dark environment. Higher ambient light levels, increased driver workload, and higher speeds all contribute to higher minimum threshold values. The threshold values were based on visibility requirements of the 50th percentile older driver which leads to retroreflectivity values in the higher range. The fact that TxDOT sign sheeting standards require retroreflectivity values greater than Type I in most cases is an appropriate and necessary safety factor. It also allows for sign degradation due to weathering and dirt accumulation.

Since the vehicle sample was not chosen randomly, it may not be representative of headlamp performance of all vehicles on the roadway. The current report represents one task in a much larger project examining many aspects of sign retroreflectivity. A large sample of vehicles closely matched in make, model, and year to the Texas fleet was beyond the scope of the project. A more detailed research project would need to be undertaken to examine in detail important factors such as headlamp aim and headlamp light source. As vehicle design and lighting technology continues to evolve, sign illumination provided by these new systems should be assessed periodically.

RECOMMENDATIONS

- The evaluation of headlamps indicated that Type C sheeting (high intensity) is sufficient for ground-mounted signs near the shoulder to meet the luminance needs for most drivers based on the sample of vehicles tested. Type D sheeting (microprismatic) should be used for the legend of overhead signs and large guide signs located further from the shoulder.
- The information provided by computer models appears to be adequate and appropriate for modeling and selecting sign sheeting.
- TxDOT should encourage districts to aim and clean vehicle headlamps prior to conducting nighttime sign inspections.
- Headlamp design has changed significantly in the last few years and will continue to evolve in the near future. More detailed evaluations need to be conducted in the near future to assess the impacts of new headlamp performance with regards to sign luminance.

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