Updates to Research on Recommended Minimum Levels for Pavement Marking Retroreflectivity to Meet Driver Night Visibility Needs

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FOREWORD

In 1992, the Congress directed the Secretary of Transportation to revise the Manual on Uniform Traffic Control Devices to include a standard for minimum levels of retroreflectivity that must be maintained for pavement markings. While previous research has been undertaken to recommend minimum pavement marking retroreflectivity levels, the need existed to update the earlier research in light of changes in roadway user characteristics, vehicle preferences, headlamp performance, and available research tools. Based on a newer, more powerful analytical tool, the following document provides updated recommended minimum levels for pavement marking retroreflectivity to meet driver night visibility needs.

This report will be of interest to State and local agencies with responsibility for pavement marking and people involved in pavement marking maintenance.

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Director, Office of Safety
Research and Development

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16. Abstract

This study was aimed at completing the research to develop and scrutinize minimum levels for pavement marking retroreflectivity to meet nighttime driving needs. A previous study carried out in the 1990s was based on the CARVE model developed at Ohio University and resulted in a table of minimum levels of pavement marking retroreflectiviy values. Since then, a newer, more powerful analytical tool, Tarvip, which was developed at the Operator Performance Lab of the University of Iowa, overcomes a lot of limitations of the CARVE model and uses updated data that reflect the current states of vehicles and roadways in the United States.

In this study, the Pavement Marking Visibility Module of the Tarvip model was validated by comparing field data from various studies to prediction results under similar conditions from Tarvip. Next, a comprehensive survey on the factors that affect pavement marking visibility and minimum R_L levels was performed, with key factors identified, including pavement marking configuration, pavement surface type, vehicle speed, vehicle type, and presence of RRPMs. From these key factors, a methodology of using Tarvip to do a sensitivity analysis on factors modeled in it was developed. The plan was executed, and resulting R_L values under typical conditions on United States roadways formed the basis of new recommendations. Finally, limitations of the recommendations were analyzed, and a plan for future research was presented.

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CARVE, Detection Distance, Illuminance, Night, Pavement marking, Pavement Surface, Retroreflectivity, RRPM, TARVIP, Visibility

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1. INTRODUCTION

As traffic control devices, pavement markings relay a wide variety of information to drivers. They are unique in terms of traffic control devices because drivers do not have to shift their attention away from the roadway in order to receive continuous information. Properly implemented longitudinal pavement markings convey the following information:(1)

- Directional information.
- Location of the road center and edges.
- Presence of passing or no-passing zones.
- Indication that a driver is occupying the correct lane.

Pavement markings become one of the key methods of conveying this information to the driver at night, so their proper placement and maintenance are critical for safe driving.(2) In order for pavement markings to be seen by drivers at night, they must be retroreflective. Retroreflectivity is a measure of an object's ability to reflect light back towards a light source along the same axis from which it strikes the object. In the case of retroreflective pavement markings, incoming light from vehicle headlamps is reflected back towards the headlamps and, more importantly, the driver's eyes. The retroreflective property of pavement markings is what makes the pavement markings visible to nighttime drivers. Pavement markings are made retroreflective by embedding glass beads in the marking material (sometimes called the binder material). Rather than scattering light, as the pavement marking material would do without the glass beads, the beads refract the incoming light in such a way that it is returned back towards the driver's headlamps. The most common measurement of retroreflectivity is the Coefficient of Retroreflected Luminance (R_L), which can be described as "the ratio of the luminance of a projected surface of retroreflective material to the normal illuminance at the surface on a plane normal to the incident light."(3) Retroreflective measurements can be used to assess the efficiency of pavement markings in terms of their ability to retroreflect headlamp illumination.

Retroreflective measurements are made with a standard geometry that represents what a driver in an average passenger car would see during inclement weather conditions at night. The standard geometry is based on a viewing distance of 30 m (98 ft). Handheld and mobile pavement marking retroreflectometers used in the United States must be based on the standard 30-m (98-ft) geometry. This includes the minimum retroreflectivity levels recommended in this report.

Pavement markings, like many other roadway materials, deteriorate over time. As pavement markings deteriorate, they lose their ability to retroreflect headlamp illumination. As a result, retroreflective measurements of pavement markings decrease over time. There is general agreement that this reduced performance may be a causative agent in the rate and severity of nighttime crashes, although previous research has not yet quantified the relationship. It should be pointed out that a recent study found no safety difference between high and low retroreflectivity for longitudinal nonintersection markings.(4)

Several surveys have shown that "brighter" markings provide a higher comfort level and are preferred by nighttime drivers. Drivers of all ages and from all parts of the United States feel that markings that are bright and easy to see are important to driver safety and that agencies should make marking visibility a priority. Many drivers believe that pavement marking visibility could be improved and that such improvement would make them more comfortable while driving at night.[(5)]

While the *Manual on Uniform Traffic Control Devices* (MUTCD) requires that pavement markings be illuminated or retroreflective, it contains no minimum maintenance retroreflective requirements.[(6)] In 1992, Congress mandated that such standards for signs and pavement markings be developed, and research to develop these standards has been ongoing. The research for minimum in-service retroreflective requirements for traffic signs was accelerated, leading to a Notice of Proposed Rulemaking that was posted in the Federal Register in July 2004. Currently, the Federal Highway Administration (FHWA) is conducting research to develop a standard for minimum levels of pavement marking retroreflectivity. The FHWA expects to initiate the pavement marking retroreflectivity rulemaking process once the research is concluded and the results are analyzed and considered. While previous research has been undertaken to recommend minimum pavement marking retroreflectivity levels, the need exists to update the earlier research due to changes in roadway user characteristics, vehicle preferences, headlamp performance, and available research tools.

1.1. Problem Statement

In the early 1990s, the FHWA sponsored research in which the Ohio University's Computer-Aided Road-Marking Visibility Evaluator (CARVE) model was used to determine driver night visibility needs for various pavement marking treatments.[(1)] This model was developed and calibrated using results of various pavement marking studies published in the literature. Using CARVE, a table of recommended minimum levels of pavement marking retroreflectivity was developed as a function of posted roadway speed and the presence of retroreflective raised pavement markers (RRPMs).[(1)] However, the CARVE model is limited because it has not been updated to reflect changes in roadway marking materials, headlamps, or types of roadway surfaces. Subsequently, the Target Visibility Predictor (TARVIP) model was developed based on the CARVE model by the University of Iowa to address these shortcomings, with additional features that allow the user to define roadway profiles, adjust headlamp configurations, and use newer roadway marking materials.

With this new modeling tool, an opportunity exists to analyze and recommend updated minimum maintained pavement marking retroreflectivity levels. These recommendations will consider what minimum retroreflectivity levels will best serve drivers operating in a broad range of visibility scenarios.

1.2. Research Objectives

The objective of this research is to develop updated minimum maintained pavement marking retroreflectivity levels. The following goals were pursued to accomplish this objective:

- Identify and understand the key factors that affect the visibility of pavement markings.
- Ascertain the ability of TARVIP to generate reasonable measures of pavement marking visibility under various scenarios by comparing its outputs to data from various pavement marking visibility studies.

- Use TARVIP to analyze driver visibility requirements for pavement markings.
- Conduct sensitivity analyses to evaluate the impacts incremental changes in key pavement marking visibility factors upon recommended minimum pavement marking retroreflectivity levels.
- Develop recommended minimum in-service retroreflectivity levels for longitudinal pavement markings based on findings from previous goals.

The project scope was limited to the investigation of dry, dark, rural, straight roads and longitudinal pavement markings. Transverse pavement markings, horizontal and vertical curves, and wet conditions are outside the scope of this project.

2. LITERATURE REVIEW

Over the past two decades, there has been a variety of research evaluating pavement marking retroreflectivity, with the results leading to several proposals from government agencies and professional organizations recommending minimum pavement marking retroreflectivity levels. This literature review first traces these proposals and then examines the underlying minimum retroreflectivity research upon which these proposals are based. Finally, it examines many key factors affecting driver visibility of pavement markings.

2.1. Minimum Pavement Marking Retroreflectivity Proposals

Turner authored a 1999 internal FHWA report in which the first government-based recommended minimum pavement marking retroreflectivity levels were crafted based mostly on research results available at that time.(*7*) The 1999 research-proposed values are shown in table 1 along with the rationale for each value. The recommended minimum retroreflectivity values rely heavily on the CARVE-produced values in Zwahlen's research.(*1*)

Zwahlen's CARVE input included a fully marked (yellow center line skip with white edge lines), two-lane, straight roadway. The road surface used was old asphalt, as the majority of roads in the United States have an old asphalt surface, either as the original surface or as an overlay. The vehicle-driver geometry used was an average-sized adult in an average passenger sedan using a General Electric H6054 low-beam headlamp (i.e., a sealed-beam headlamp representing those typically found on vehicles in the 1970s and early half of the 1980s). A 62-year-old driver was used in order to accommodate an estimated 95 percent of the nighttime motorists in the United States. Zwahlen created two sets of data, shown in table 2. The first set is minimum retroreflectivity recommendations for fully marked roads without RRPMs, which used a 3.65-second preview time in the CARVE model. The second set is for fully marked roads with RRPMs, which used a 2.0-second preview time in the CARVE model.(*1*) It should be noted that the 3.65-second preview time is one of the longest preview times recommended in the literature.

Table 1. FWHA research recommendations for minimum pavement marking retroreflectivity.(7)

Option 1		**Non-Freeway, ≤ 40 mi/h**	**Non-Freeway, ≥ 45 mi/h**	**Freeway, ≥ 55 mi/h**
Option 2		**≤ 40 mi/h**	**≥ 45 mi/h**	**≥ 60 mi/h, >10K ADT**
Option 3		**≤ 40 mi/h**	**45–55 mi/h**	**≥ 60 mi/h**
With RRPMs	**White**	30, per Zwahlen	35, per Zwahlen	70, per Zwahlen
	Yellow	30, per Zwahlen	35, per Zwahlen	70, per Zwahlen
Without RRPMs	**White**	85, per Zwahlen	100, subjectively chosen to accommodate many drivers while minimizing impact.	150, increased from lower speed category to accommodate increase in required preview time. Recommended that such roads be outfitted with RRPMs since older drivers may have difficulty with this retro value.
	Yellow	55, lowered by 35% from White value since drivers primarily use white edge line, reflecting field data.	65, lowered by 35% from White value since drivers primarily use white edge line, reflecting field data.	100, lowered by 35% from White value since drivers primarily use white edge line, reflecting field data.

Note: Retroreflectivity values are in mcd/m^2/lux
1 mi/h = 1.61 km/h

Table 2. Zwahlen's recommended minimum R_L values.(1)

Vehicle Speed [mi/h]	**Minimum Required R_L [mcd/m^2/lux]**	
	Without RRPMs 3.65 s Preview Time	**With RRPMs 2.0 s Preview Time**
0–25	30	30
26–35	50	30
36–45	85	30
46–55	170	35
56–65	340	50
66–75	620	70

1 mi/h = 1.61 km/h

FHWA presented the results of Turner's research in three workshops held for public agencies in 1999. Consensus from these workshops was incorporated into an unpublished report that recommended two preferred alternatives for the format of minimum retroreflectivity guidelines.(8) One format was based on color and speed; the other based on color and roadway classification. It should be noted that no additional research was used to adjust the earlier FHWA research recommendations shown in table 1. Rather, the adjustments made as a result of the three workshops reflect the consensus of the workshop participants. The two alternatives are shown in table 3 and table 4.

Table 3. Workshop-proposed speed-based minimum pavement marking retroreflectivity values.(8)

Marking Color	Minimum R_L [mcd/m^2/lux] for Indicated Speed Limit		
	≤ 30 mi/h	35–50 mi/h	≥ 55 mi/h
White	Presence	80	100
Yellow	Presence	65	80

1 mi/h = 1.61 km/h

Table 4. Workshop-proposed classification-based minimum pavement marking retroreflectivity values.(8)

Marking Color	Minimum R_L [mcd/m^2/lux] for Class of Roadway		
	Local and Minor Collector	Major Collector and Arterial	Highways, Freeways and all roads ≥ 88.5 km/h (55 mi/h)
White	Presence	80	100
Yellow	Presence	65	80

The American Traffic Safety Services Association (ATSSA) undertook a similar effort in 2004, with the ATSSA Pavement Marking Committee developing minimum retroreflectivity recommendations that were then approved by the ATSSA Board of Directors.(9) As with the recommendations from the FHWA agency workshops, the ATSSA recommendations (shown in table 5) are not based on any specific research; instead, they are based on the consensus of traffic safety professionals. The most significant element of this proposal is that the minimum maintained pavement marking levels are the same for both yellow and white pavement markings.

Table 5. ATSSA recommended minimum R_L values.(9)

Posted Speed [km/h] ([mi/h])	≤ 80.5 (50)	≥ 88.5 (55)
Minimum R_L [mcd/m^2/lux]	100	125

2.2. Minimum Pavement Marking Retroreflectivity Research

The above proposals take into account the results of several studies that attempt to identify the minimum pavement marking retroreflectivity that is needed by drivers. These studies recommend a range of minimum retroreflectivity values, depending on the research protocol. The following section provides a summary of some of the key studies that have shaped these proposed minimum pavement marking retroreflectivity levels.

In 1986, the 3M Company conducted a study where subjects drove a test road marked similarly to one side of a four-lane freeway. The markings applied to the roadway ranged in retroreflectivity from 30 to 1,700 mcd/m^2/lux. Participants viewed the markings at distances of 30 m (98.4 ft) and 100 m (328.0 ft) and were asked to rate the markings on a scale of one to seven, with one being “very poor” and seven being “superior.” The minimum acceptable rating was three. The researchers fit a regression curve to relate the average rating to the retroreflectivity of the pavement markings and found that a minimum acceptable rating corresponded with a retroreflectivity value of 90 mcd/m^2/lux. A minimum value of 100 mcd/m^2/lux was suggested as a conservative recommendation due to instrument variability.(10)

In a 1991 University of North Carolina study, 59 participants were driven over a 32-km (20-mile) test course. The participants made 20 observations of pavement markings with various retroreflectivity levels and evaluated them as less than adequate, adequate, or more than adequate. The participants also made subjective evaluations of markings presented to them in a laboratory setting. Markings with a retroreflectivity value of 93 mcd/m^2/lux were rated as adequate or more than adequate by 90 percent of the participants. The researchers noted that the participants were mostly younger drivers and that older drivers would likely need a higher retroreflectivity value than 93 mcd/m^2/lux.(*11*) Therefore, the researchers performed a similar study in 1996 that focused on older drivers, finding that 85 percent of drivers aged 60 or older rated markings with a retroreflectivity of 100 mcd/m^2/lux as adequate or more than adequate.(*12*)

The Minnesota Department of Transportation (MnDOT) sponsored a 1998 study that used a sample of drivers (200 in total) with an age distribution comparable to the age distribution in the state. Each participant drove a designated route on existing roads and was asked to rate the quality of the pavement markings. The study found that 90 percent of the participants rated markings with a retroreflectivity of 100 mcd/m^2/lux as acceptable. Additionally, the researchers found that the acceptability ratings of the pavement markings increased dramatically as the retroreflectivity increased from 0 to 120 mcd/m^2/lux, much less as the retroreflectivity increased from 120 to 200 mcd/m^2/lux, and almost none as the retroreflectivity increased beyond 200 mcd/m^2/lux. The researchers recommended that MnDOT use 120 mcd/m^2/lux as the threshold between acceptable and unacceptable pavement marking retroreflectivity in its pavement marking maintenance program.(*13*)

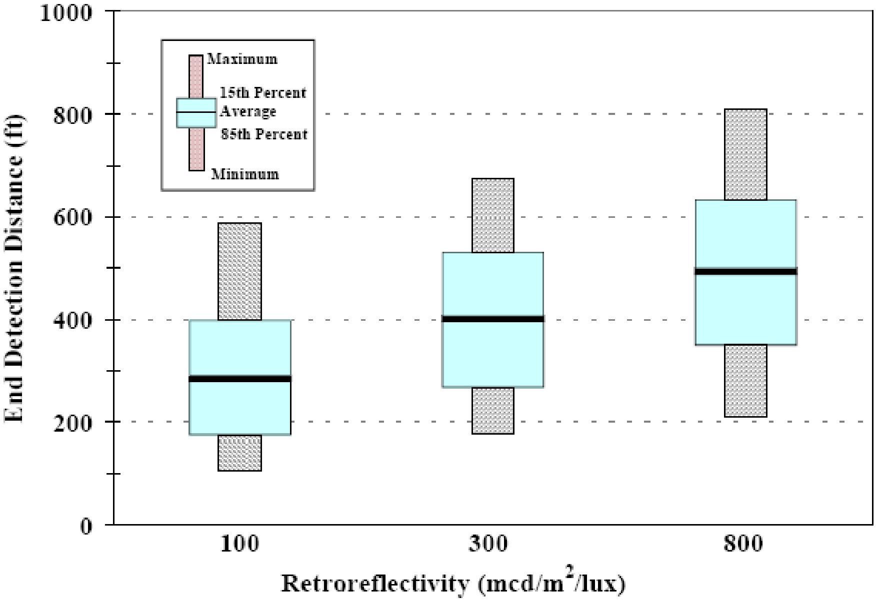
In a 2002 study for the New Jersey Department of Transportation (NJDOT), 64 participants drove a 52-km (32-mile) course laid out on existing roadways in their own vehicles and were asked to rate the markings as acceptable or unacceptable. For drivers younger than 55 years of age, the retroreflectivity threshold of an acceptable pavement marking was between 80 and 130 mcd/m^2/lux while the threshold for drivers older than 55 years of age was between 120 and 165 mcd/m^2/lux. Pavement markings deemed acceptable by participants ranged from 70 to 170 mcd/m^2/lux. The analysis further suggested that NJDOT should concentrate on re-marking roadways with pavement marking retroreflectivity less than 130 mcd/m^2/lux rather than those with a retroreflectivity greater than 130 mcd/m^2/lux to achieve "a greater relative increase in driver satisfaction."(*14*)

2.3. Key Factors Affecting Pavement Marking Visibility

Several factors affect the ability of a driver to see a pavement marking. Key research investigating the effects that these factors have on pavement marking visibility is summarized in the flowing sections.

2.3.1. Pavement Marking Retroreflectivity

Research has shown that increasing the retroreflectivity of a pavement marking will increase the detection distance—the distance at which a driver will initially see an approaching pavement marking (or its end). The Texas Transportation Institute (TTI) conducted a study evaluating the visibility of signs and pavement markings from the perspective of commercial vehicle drivers.(*15*) Two tape products were investigated, one of which was used both in new condition and with a clear mask applied. Thus, three different markings were tested, representing low, medium, and high retroreflectivity coefficients. Pavement marking detection distance data were collected in a 1998 Chevrolet Lumina and a 1986 Freightliner traveling at 48.3 km/h (30 mi/h). Participants were following a solid white right edge line and asked to indicate to the researcher in the vehicle with them when they could clearly see the end of the pavement marking. The results showed that as the retroreflectivity increased from 100 to 800 mcd/m^2/lux, average detection distance also increased from 86.9 m (285 ft) to 152.7 m (502 ft), respectively, as shown in figure 1.



1 ft = 0.305 m

Figure 1. Bar graph. Detection distance versus pavement marking retroreflectivity.([*15*])

2.3.2. Pavement Surface Material

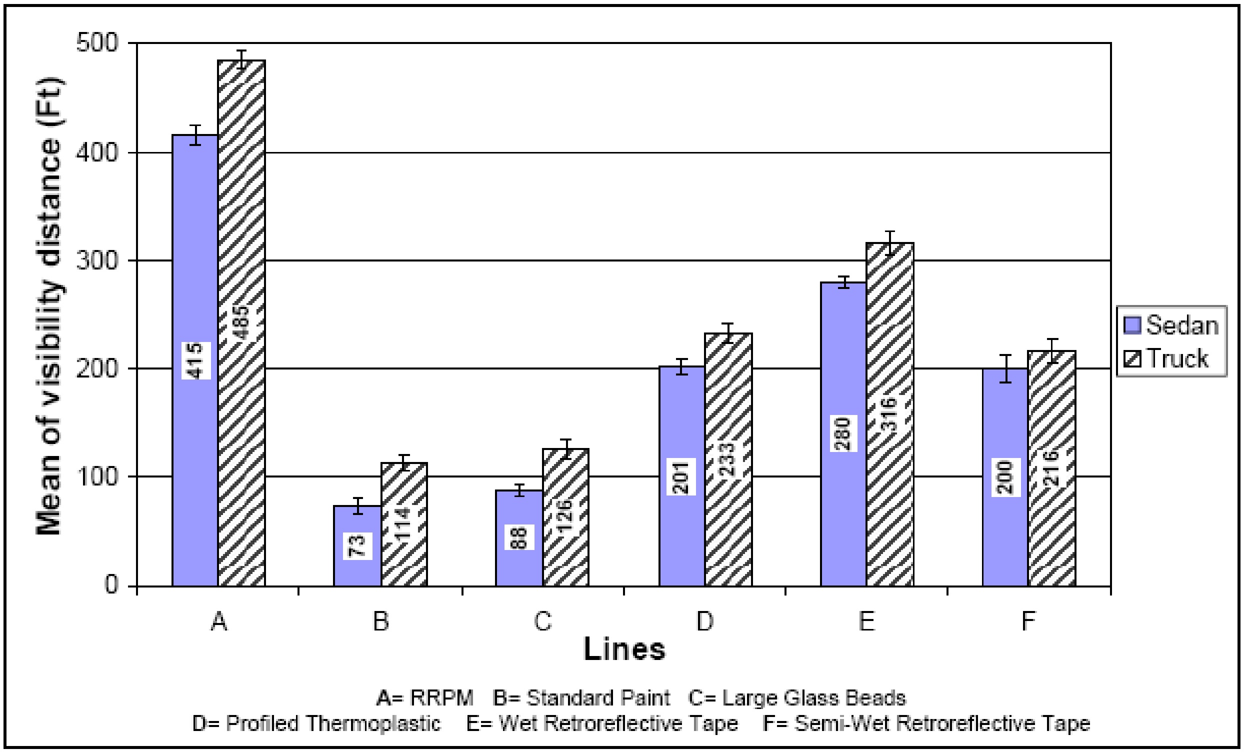
One of the key factors that determine whether a pavement marking will be seen is its contrast with the surrounding pavement. The same pavement marking will be more easily seen when applied to material with which it has a greater luminance contrast than when applied to one with which it has a lower luminance contrast. Computer-based visibility models such as CARVE and TARVIP evaluate the visibility of a pavement marking by comparing this luminance contrast between the marking and the surrounding road surface with a minimum human contrast threshold.([*16*])

In 1999, Schnell et al. developed retroreflectance matrices for old asphalt, new asphalt, old concrete, and new concrete. The researchers designed an apparatus that functioned as a goniometer but did not require the extraction of a road surface sample. Measurements of luminance and illuminance were taken over a range of observation and entrance angles for typical headlamp-pavement-marking-driver geometry, varying from a 5 percent female driver in a small car to a 95 percent male driver in a semi truck. The resulting R_L values were then calculated. The research results showed that the new asphalt surface was substantially less reflective than the old asphalt surface. The old Portland cement concrete surface, however, was found to be less reflective than the new concrete surface, with embedded rubber, dirt, and grease leading to a darker surface. New concrete and old asphalt were found to have similarly high reflectance levels. The new asphalt had the lowest reflectance levels, therefore providing better luminance contrast for optimal pavement marking visibility.(16)

2.3.3. Vehicle Type

The geometry of the subject vehicle has several influences on the driver's visibility of pavement markings. The height of the headlamps above the pavement surface determines the entrance angle of the headlamps' light for a given distance away from the pavement marking. This height can also determine how far the headlamps' light travels away from the vehicle before meeting the road surface. The vertical separation between the driver's eyes and the headlamps determines the observation angle for a given distance away from the pavement marking. Finally, the height of the driver's eyes above the pavement determines the size of the projected area of the pavement marking on a plane perpendicular to the driver's line of sight for a given distance away from the pavement marking.

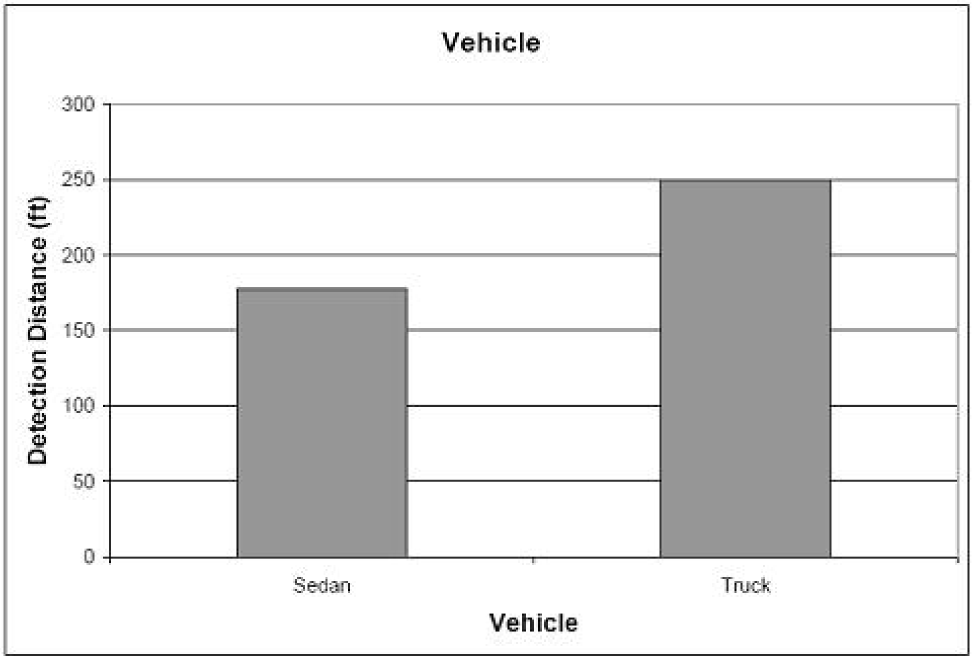
In a 2005 static study of the visibility of wet pavement markings, Gibbons et al. had 33 participants over the age of 60 evaluate the visibility of six different pavement markings in simulated rain conditions by counting the number of skip lines they could see from both a stationary Volvo Class 8 tractor and a stationary Ford Crown Victoria. One of the findings of the study showed that under saturated conditions, the visibility distance from the semi truck was between 8 percent and 56 percent greater than the visibility distance from the Ford Crown Victoria, as shown in figure 2. The researchers theorized that because the skip line looks larger from the truck than it does from the sedan, the larger visual target creates a lower contrast threshold for a given skip mark in the truck compared with the sedan.(17)



1 ft = 0.305 m

Figure 2. Bar graph. Saturated condition visibility distance versus marking type and vehicle type.(*17*)

In a 2006 study of the impact of pavement marking width on visibility distance, Gibbons et al. had 19 truck drivers and 19 sedan drivers operate a vehicle at 40.3 km/h (25 mi/h) on a course at the Virginia Smart Road Facility. When the research participants detected an approaching pavement marking, they notified the researcher seated next to them. The researchers found that the semi truck drivers had a significantly larger average detection distance than the sedan drivers, as shown in figure 3.(*18*)



1 ft = 0.305 m

Figure 3. Bar graph. Average skip line detection distance versus vehicle type.(*18*)

The University of Michigan performed a study where the mounting height of a low-beam headlamp and driver eye height were varied. Participants were stationary and asked to state when they detected a retroreflective pavement marking moving toward them. The researchers found that as the mounting height increased from 0.6 m (2 ft) to 1.2 m (4 ft), the detection distance increased by 19 percent, suggesting that pavement markings are more visible for truck drivers than for car drivers.(*19*)

2.3.4. Vehicle Headlamps

The changing nature of vehicle headlamps and their beam patterns have had an effect on driver visibility of pavement markings. This can be illustrated using the Exact Road Geometry Output (ERGO) software. ERGO calculates entrance and observation angles based on the exact location and orientation of headlamps, visual targets such as signs or pavement markings, and the driver's eye. ERGO then determines the illuminance reaching the visual target as well as the luminance reaching the driver's eyes.(*20*) For this study, ERGO was used to estimate the illuminance reaching pavement markings as a function of four different headlamps. A total of four distances were selected for evaluation purposes: 30 m (98 ft), 60 m (197 ft), 100 m (328 ft), and 150 m (492 ft) from a vehicle, for both the right edge line and the center line (see table 6). The 2A1 headlamp is a sealed beam headlamp that was found in vehicles sometime before 1985.(*21*) The CARTS50 headlamp is a conglomeration of the 50th percentile of 26 sealed beam and replaceable bulb headlamps from vehicles sold from 1985–1990.(*22*) Two vehicle headlamp conglomerations developed by the University of Michigan Transportation Research Institute (UMTRI), the 1997 and 2004 U.S. market weighted headlamps, were included as well.(*23*) The four headlamps represent the progression of vehicle headlamp technology from the 1970s to now.

The results of the ERGO modeling, shown in table 6, indicate that each evolution of newer headlamps casts more light upon edge lines and center lines at distances past 30 m (98 ft) than the older headlamps. Therefore, the trend in headlamp design generally improves pavement marking visibility.

Table 6. Headlamp illuminance along edge lines and center lines.

Headlamp Information		Illuminance on Pavement Marking [lux]							
		Edge Line				Center Line			
Name	Represented Years	30 m	60 m	100 m	150 m	30 m	60 m	100 m	150 m
2A1	Pre mid 1980s	43.5	5.9	1.4	0.5	5.9	1.1	0.5	0.3
CARTS50	1980s–1990s	33.7	6.6	1.5	0.5	6.2	1.2	0.4	0.2
UMTRI97	1997	40.2	9.5	2.3	0.7	11.3	2.0	0.6	0.3
UMTRI04	2004	33.5	10.4	3.4	1.3	16.3	3.9	1.5	0.7

Note: Lane width = 3.66 m (12 ft)
1 m = 3.28 ft

2.3.5. Overhead Lighting

Research has shown that overhead roadway lighting can improve the visibility of retroreflective pavement markings. For example, in an industry-sponsored study, participants drove through a closed course and viewed the pavement markings with levels of retroreflectivity varying from 30 to 1,700 mcd/m^2/lux with 15.2-m (50-ft) high luminaires to the left of the roadway. The luminaires contained 250-watt mercury-vapor lamps and were spaced at 76.2 m (250 ft). The researchers found that none of the markings were rated below a minimum acceptable level in the lighted condition (in the unlighted condition a 100 mcd/m^2/lux minimum acceptable level was derived). Adequate line luminance was provided by the roadway lighting without any contribution from the pavement marking retroreflectivity. Therefore, lines of similar retroreflectivity received higher ratings from the participants under the illuminated condition than they received under the dark condition.(*10*)

2.3.6. Edge Line Presence

Research suggests that the additional marking material provided by white edge lines over a road marked with only a center line improves driver visibility of the roadway, providing longer end detection distances. In a 1997 study,(*24*) researchers at Ohio University had 40 healthy college students drive a 1989 Dodge Aries sedan through a closed course on an unused airport runway. The subjects were asked to inform the researcher seated in the car with them when they saw the end of various pavement markings treatments. The first part of the experiment consisted of five center line only markings: two single dashed lines of different widths, two single solid lines of different widths, and a double solid line. The second part of the experiment consisted of two fully marked roads: one with two solid white edge lines and a double solid yellow center line, and the other with two solid white edge lines and a single dashed yellow center line. On average, the pavement marking treatments with solid white edge lines and single dashed or double solid yellow center lines resulted in end detection distances that were approximately twice those of the pavement marking treatments consisting of the corresponding yellow center line alone. The researchers also found that the addition of a yellow center line only marginally increased the detection distance (8.5 percent) of a road marked with only a solid white edge line on the right shoulder, implying that the edge lines predominantly govern the detection distance of a fully marked road.

2.3.7. Wider Longitudinal Markings

Past research efforts have been inconclusive in determining the effect of wider longitudinal markings on driver visibility. In the 1997 Ohio University study mentioned previously, the researchers found that for dashed center lines, increasing the line width from 0.05 m (0.16 ft) to 0.1 m (0.3 ft) provided a 6.6 percent increase in average end detection distance. For a single solid center line, the researchers found that the same increase in line width provided a 47 percent increase in average end detection distance.(*24*) Gibbons et al. found that increasing marking widths from 102 mm (4 inches) to 152 mm (6 inches) increased detection distance, but there was no increase in detection distance when widening the markings from 152 mm (6 inches) to 203 mm (8 inches).(*18*)

However, researchers in Virginia evaluated the effects of replacing 102-mm (4-inch) edge lines with 203-mm (8-inch) edge lines on rural two-lane roads. Twelve sections of roadway were outfitted with speed and lateral position detectors to collect speed and lane position data from passing vehicles in the before (102-mm (4-inch) edge lines) and after (203-mm (8-inch) edge lines) conditions. The researchers found that increasing the edge line width from 102 mm (4 inches) to 203 mm (8 inches) produced no statistically significant difference in lateral placement variance, encroachment by autos and trucks, mean speed, or speed variance. They concluded that the wider edge lines did not practically effect lateral placement or speed.(*25*)

In another study, researchers identified 853 km (530 mi) of rural two-line highways in New Mexico that had high run-off-the-road (ROR) crashes. Of these roads, 283.3 km (176 mi) were treated with 203-mm (8-inch) edge lines while the remainder was treated with 102-mm (4-inch) edge lines for control purposes. The researchers compared 42 months worth of “before” crash data and 17 months of “after” crash data at the two sites and found that the treatment sites did not perform any better than the comparison sites in terms of ROR crashes.(*26*)

TTI researchers conducted an investigation of the visibility of various pavement marking materials under wet and dry conditions, including 102-mm- (4-inch-) and 152-mm- (6-inch-) wide materials. In Phase I, participants drove down an isolated test track in a passenger sedan at 48.3 km/h (30 mi/h) and were asked to inform the researcher in the vehicle with them when they could see isolated skip lines in the center of the travel lane ahead. Subjects repeated their observations while driving down the test track in a simulated rain environment. Although not a focus of the Phase I work, the researchers noted that the detection distances for one of the materials tested (a wet-weather tape, which happened to be one of the best performers in the Phase I study) increased approximately 30 percent under wet conditions when the width was increased from 102 mm (4 inches) to 152 mm (6 inches).(*2*) This finding led the research team to a more focused effort on detection distances of wider lines under dry and wet conditions. For Phase II of the research, the research team designed a robust experimental protocol to ensure adequate statistical power for testing the potential differences between 102-mm (4-inch) and 152-mm (6-inch) lines (the Phase I finding related to wider lines was based on limited empirical results and not robust statistical testing). In Phase II of the study, the researchers tested the effect of width on the dry and wet detection distances for five different pairs of 102-mm (4-inch) and 152-mm (6-inch) pavement markings. Under wet conditions, two of the 152-mm (6-inch) markings had longer average detection distances (but only by 4.9 m (16 ft) and 4.6 m (15 ft) while one of the 102-mm (4-inch) markings had an average detection distance 3.4 m (11 ft) longer than its 152-mm (6-inch) counterpart. Under dry conditions, three of the 152-mm (6-inch) markings had longer average detection distances (by 5.5 m (18 ft), 5.5 m (18 ft), and 4.6 m (15 ft)), and two of the 102-mm (4-inch) markings had longer average detection distances than their 152-mm (6-inch) counter parts (3.0 m (10 ft) and 4.3 m (14 ft)). The average detection distances did not vary more than 6.1 m (20 ft), and the researchers found that the differences in average detection distances were no greater than 5 percent.(*27*)

Despite the lack of conclusive evidence supporting wider markings, a survey of state departments of transportation conducted in 2001 showed that at the time, 29 out of 50 states indicated that they were using wider markings to some degree.(*28*) Fifty-seven percent of the respondents indicated that they used wider lines to improve visibility. Most agencies using wider markings were satisfied with their use, and no agency indicated planned discontinuation of its use. However, the crash-reduction benefits of wider lines are unknown as 10 states indicated that they had performed or taken part in crash studies and found inconclusive results. Therefore, the cost-effectiveness of wider markings is currently unknown.

Conclusive evidence that the use of wider pavement markings reduces crashes is not available in the literature, although some positive impacts have been found when using detection distance as a surrogate for safety. However, even those findings are inconclusive in showing that wider lines can increase detection distance or otherwise benefit drivers.

2.3.8. RRPM Presence

There are many studies that investigate the visibility of striping and RRPMs separately but few that investigate the interaction between the two and if less line luminance is required of a pavement marking by the driver if RRPMs are present.

Researchers with the FHWA conducted driving simulator studies to determine the relative luminance of RRPMs and pavement markings. Participants were shown combinations of RRPMs and pavement markings with low, medium, and high luminance and asked to state when they detected an upcoming curve. The researchers used the data to develop discount factors for required pavement marking luminance when RRPMs were present. Of primary interest are the discount factors for pavement markings with low luminance for low, medium, and high RRPM luminance (23 percent, 48 percent, and 79 percent, respectively). While RRPM luminance drops off rapidly from the "new" condition, it should be noted that due to limitations in the simulation technology, even the high RRPM luminance condition had a luminance well below that which would be expected from a new RRPM (4.06 cd/m^2 versus 41.2 cd/m^2). Therefore, the medium and high RRPM luminance discount factors should not be dismissed.(*29*)

The researchers also conducted field validation studies of the discount factors derived from the simulation studies. Participants drove on a newly-constructed two-lane roadway and were asked to identify when they detected a simulated curve ahead. The curves were delineated with combinations of RRPMs and pavement markings with low, medium, and high luminance. The RRPMs were deployed in conformance with the MUTCD along the center line only. The results showed that the RRPMs had a powerful effect, washing out any influence that pavement markings could exert on curve recognition distance. The results indicated that pavement markings could deteriorate to less than 1 percent of their original luminance before creating any detrimental effect on curve recognition distance. The researchers noted that the weaker RRPMs in the simulator study might be comparable to worn, dirty, or weathered RRPMs that have been in use for some length of time on a roadway. Also of interest, the data showed a 59 percent discount factor in center line pavement marking luminance when white edge lines are also present.(*30*)

Other research shows that RRPMs in good condition far out perform new pavement markings of any material in terms of detection distance, especially in wet weather. In the previously mentioned TTI study by Carlson et al., the researchers found that under rainy conditions, RRPMs had an average detection distance of more than 168 m (550 ft), or more than 61 m (200 ft) further than the next best pavement marking material investigated.(*2*)

Before and after studies investigating the safety effects of RRPMs have shown mixed results. Analysis of crash data from six states showed that nonselective implementation of RRPMs on two-lane highways created no significant reduction or increase in nighttime crashes. However, when RRPMs were deployed based on nighttime crashes in wet conditions in New York, the data showed a nearly 24 percent reduction in crashes of this type. The researchers also found a reduction in wet-night crashes on freeways with RRPM deployment.(*31*)

2.3.9. Driver Age

In humans, aging causes several elements of the vision system to degrade, which ultimately reduces older driver visibility. Consequently, younger drivers do not need as much light as older drivers to see the same object on a roadway, and older drivers will require pavement markings to have higher retroreflectivity in order to see them as well as younger drivers. Because of this, several studies investigating minimum pavement marking retroreflectivity have based their recommendations on the needs of older drivers.

Zwahlen and Schnell investigated the effects of aging on pavement marking visibility.(*32*) Two groups of participants were used: 10 older drivers with an average age of 68.3 years and 10 younger drivers with an average age of 23.2 years. The subjects performed runs along an old unused airport runway marked as a two-lane road with solid white edge lines and dashed yellow center lines. Subjects informed researchers in the vehicle with them when they saw the end of the pavement marking treatment. The data showed that driver age had a significant effect on the visibility of the pavement marking. Depending on whether low beams or high beams were used and on what pavement marking material was used, the increase in detection distance for the younger drivers over the older drivers ranged from 49.1 percent to 61.6 percent. In the Carlson et al. TTI study of pavement marking visibility under wet conditions, participants were divided according to age into a younger group (18–54 years old) and an older group (55 years and older). Overall, the average detection distance for older drivers was found to be 14 percent less than that for younger drivers. Additionally, drivers with high visual acuity had significantly higher average detection distances than those with lower visual acuity when a vehicle with low headlamp illumination output was used. It should be noted, however, that the difference was not significant in a vehicle with higher headlamp illumination output.(*27*)

2.3.10. Preview Time

A driver must be able to see pavement markings at a certain distance down the road in order to receive adequate information to safely guide the vehicle. This distance allows the driver adequate time to perceive, process, and react to the information that the pavement marking presents. Since the required distance increases as the speed of the vehicle increases, it is often expressed as a constant preview time.

The FHWA conducted a 1988 study that recommended two separate preview times for adequate marking of a roadway. For long-range guidance preview time, 3 seconds was recommended, which makes the driving task much easier and allows the driver to make quick adjustments. For short-range extreme driving conditions, 2 seconds of preview time was recommended as the safe minimum acceptable limit, allowing enough time for the driver to perceive and react to the pavement marking in hazardous conditions, such as heavy rain or fog.(*33*)

Driving simulator studies reported in *COST 331*, a European Union study tasked with recommending optimum pavement marking design, showed that the absolute minimum preview time required for safe driving is 1.8 seconds; otherwise, drivers will have trouble maintaining steady lane keeping. The authors emphasized that this was the bare minimum and that a higher value should be used, although they did not go as far as to recommend what that value should be.(*34*)

2.3.11. Summary of Key Factors

A summary of the key factors affecting pavement marking visibility identified above is presented in table 7. Other factors not addressed here are summarized in table 8.

Table 7. Summary of key factors affecting pavement marking visibility.

Factor	Impact on Pavement Marking Visibility
Pavement Marking Retroreflectivity	Increased pavement marking R_L will increase driver detection distance.
Pavement Surface Material	In general, new asphalt provides the best luminance contrast with pavement markings, therefore providing the best visibility. Old concrete, old asphalt, and new concrete follow, in order of pavement marking decreasing visibility.
Vehicle Type	In general, vehicles with headlamps and driver eye heights that are further from the pavement provide better pavement marking visibility.
Vehicle Headlamps	Newer headlamps improve pavement marking visibility.
Overhead Lighting	Overhead lighting to a roadway improves pavement marking visibility.
Edge Line Presence	Adding edge lines improve pavement marking visibility.
Wider Longitudinal Markings	Increasing line width may increase the detection distance of the pavement marking, but the results to date are inconclusive. There has been no strong link to safety.
RRPM Presence	RRPMs have much longer detection distances than other pavement marking materials and can reduce the required preview time of pavement markings.
Driver Age	Older drivers generally have decreased visual performance, and therefore, require more retroreflectivity to see a pavement marking at the same distance as a younger driver.
Preview Time	Longer preview times provide greater driver comfort but also require higher pavement marking retroreflectivity.

Table 8. Other factors affecting pavement marking visibility.(35)

Factor
Pavement Color
Pavement Wear
Pavement Marking Degree of Obliteration
Center Line Configuration
Lateral Separation Between Double Lines
Available Retroreflective Area in PM
Windshield Transmission
Driver Workload
Driver Attention
Horizon/Sky Luminance
Atmospheric Transmissivity
Weather Conditions
Oncoming Vehicle Glare

3. RESEARCH METHODOLOGY

The scope of this research effort did not include the collection of additional human factors data from the field. The focus of this research was to examine the body of pavement marking visibility research in order to understand how different factors affect pavement marking visibility. Using the understanding gained from existing research, a visibility model (TARVIP) was employed to evaluate the effect that various pavement marking visibility parameters have upon the minimum retroreflectivity required by nighttime drivers. Some factors were analyzed in the TARVIP model while others were held constant to represent either reasonably worst-case visibility conditions (such as the absence of roadway lighting or the driver being of advanced age) or the conditions most likely faced by drivers on the roadway (such as conventional markings consisting of paint with beads). The results of the TARVIP analysis were then used, in conjunction with previous research findings reported herein, to provide recommended minimum pavement marking retroreflectivity levels.

3.1. Description of Tarvip

TARVIP is a deterministic model for evaluating the nighttime visibility of retroreflective objects from a driver's perspective.[1] TARVIP has a physical subsystem and a human factors subsystem. The physical subsystem determines the actual luminance contrasts of retroreflective objects on the roadway and is influenced by the following factors:

- Three-dimensional spatial locations of the vehicle headlamps, driver eyes, and pavement markings.
- Two-dimensional matrices of headlamp luminous intensity with respect to vertical and horizontal beam angle.
- Two-dimensional matrices of pavement surface and pavement marking retroreflectivity coefficients (R_L) with respect to entrance and observation angle.
- Environmental data such as windshield transmission, atmospheric transmissivity, and ambient luminance.

The human factors subsystem uses Blackwell contrast threshold data to determine the average contrast detection ability of a human observer of a certain age under specific lighting and luminance contrast scenarios. The actual luminance contrast from the physical subsystem is compared with the average luminance contrast threshold from the human factors subsystem to determine how well the driver can see a pavement marking in the given geometric scenario, and what the driver's needs are in terms of retroreflectivity for that scenario.(36)

3.2. Using the TARVIP Model

The process used in creating TARVIP models for the purpose of recommending minimum pavement marking retroreflectivity is detailed in the following paragraphs. In creating a visibility scenario, the first geometric component to create is the road itself. The user may select the width

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[1] The latest version of TARVIP may be obtained from the University of Iowa's Operator Performance Laboratory website at http://opl.ecn.uiowa.edu/tarvip.

of roadway available on either side of the road center line and the geometry of the road in terms of plan and profile.

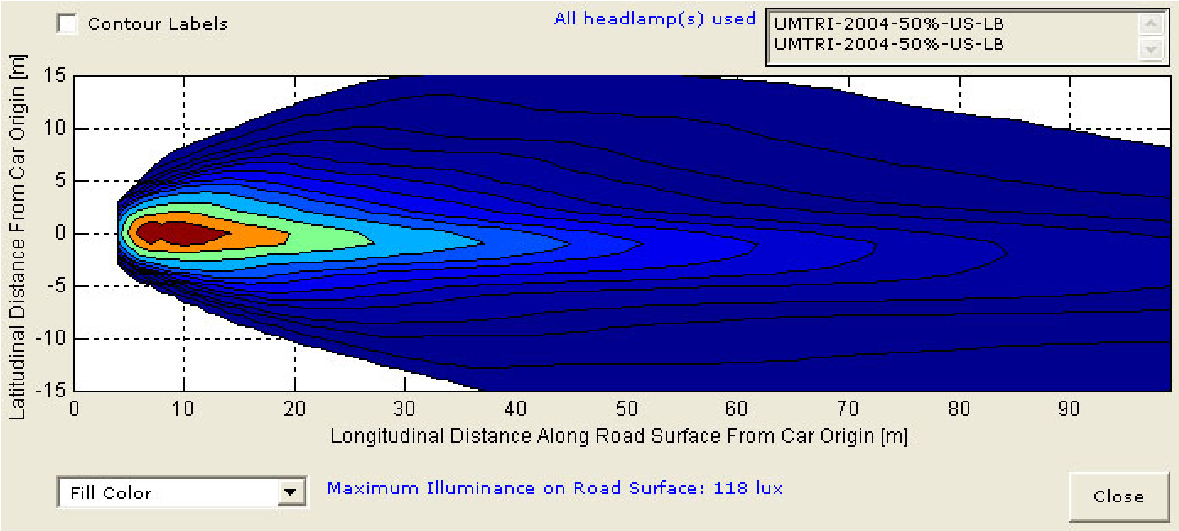
The user is then asked if the visibility of pavement markings, signs, or a diffuse (non-retroreflective) target is to be analyzed. Once pavement markings are selected, the user can choose which pavement marking configuration is to be analyzed. The three choices on the left are for center line configurations without edge lines. The “Combined” choice is for a single solid plus a single dashed center line (such as for a one-way no-passing zone). The final two options are for a single dash or double solid center line with solid white edge lines.

If the “Full + Dash” option is selected, the user is then prompted to define the widths of each pavement marking line and its lateral location on the roadway. The user is also asked for the longitudinal cycle length and the longitudinal gap length for the center line skip. If the “Full + Double Solid” option had been selected, the latter two would have been replaced with a prompt for the lateral separation between the two lines. The user is also asked to supply ASCII files containing tab-delimited text of the retroreflectivity matrices for the pavement surface and the pavement marking material. The efficiency of the material can be adjusted to represent old or worn marking materials.

The user may then define the length of the road and the location of a point of interest for use in tracking changes in photometric relationships as the vehicle moves along the roadway. Once this has been done, the vehicle and headlamp details can be selected. The user can select the speed of the vehicle, the ability of the windshield to allow light to pass, the location of the vehicle on the roadway, and the increments at which calculations should be performed. The user is also asked to supply ASCII files containing tab-delimited text of the luminous intensity matrices of the vehicle’s headlamps.

Once the file is supplied, the user can adjust the dimensions of the headlamp locations relative to a point halfway between the two headlamps on the pavement surface (termed the car origin), as well as adjusting the headlamp efficiency to represent deficient headlamps. TARVIP uses the headlamp luminous intensity matrices to project the headlamp beams onto the road surface for the visibility analysis (figure 4).

In the “Driver” window, the user may set the driver age, exposure time, minimum preview time, and the driver’s eye location relative to the car origin. If visibility under glare conditions is to be modeled, the user may enter the horizontal and vertical angle components of the driver’s glance away from the center of the traveled way.



All headlamp(s) used
UMTRI-2004-50%-US-LB
UMTRI-2004-50%-US-LB

Maximum Illuminance on Road Surface: 118 lux

Figure 4. Screen shot. Plot of iso-lux curves on road surface (TARVIP screen shot).

The “Environment” window allows the user to adjust ambient luminance (cd/m^2) and atmospheric transmissivity (km^{-1}). The user can also enable fog luminance calculations and specify a fog droplet diameter if such analysis is to be undertaken.

Once the scenario is modeled in TARVIP to the user’s specifications, the visibility analysis may be performed. TARVIP provides a variety of data options for the output of the visibility analysis, including photometric angles, luminous intensity, illuminance, luminance, and contrast as the vehicle travels along the roadway toward the point of interest. TARVIP also includes a “Material Performance Summary” window that provides a minimum required R_L for the scenario and allows for adjustments to be made to a few parameters without recalculating the entire model. The user can obtain the minimum required R_L for any desired preview time and recalculate for changes in vehicle speed and the driver age. The user can also obtain the required preview time given a certain R_L value as well as input a preview time to determine, on average, the oldest driver who would be able to see the pavement marking under the modeled conditions.

3.3. Validation of the TARVIP Model

The ability of TARVIP to generate reasonable measures of pavement marking visibility under various scenarios was ascertained by comparison of its outputs to data from various pavement marking visibility studies. The validation was performed using the study data from two Texas Transportation Institute (TTI) studies, reported in TTI Technical Report 5008-1*(2)* and TTI Technical Report 4269-1.*(15)* In those two studies, dry, nighttime pavement marking detection distances were collected. The data were used to compare to TARVIP predictions. The comparison showed that the TARVIP curve fell within the 95 percent confidence range of the TTI study data under most conditions.

3.3.1. TTI Report 5008-1 Study Comparison

TTI Report 5008-1 was for a study evaluating the performance of several varieties of pavement markings in wet weather. However, as part of this research, dry detection distance data for each marking were also collected. Subjects drove a 2004 Ford Taurus with a researcher in the passenger seat. The research was conducted on an isolated test track. The subjects drove with the cruise control set at 48.3 km/h (30 mi/h) and told the researcher when they could see a pavement marking (white lines, yellow lines, or RRPMs). Distracter markings were located outside the travel lane to minimize the possibility of the subjects becoming accustomed to the pavement marking locations and guessing their location before actually seeing them. The markings of interest to the researchers were isolated skips located in the center of the travel lane. When the subject alerted the researcher when he/she could identify a pavement marking and its type, the researcher recorded the location values from a distance-measuring instrument.(*2*)

The research conditions used by Carlson et al. were duplicated as closely as possible in the TARVIP software; however, some assumptions were required. The pavement surfaces that were available in TARVIP when this analysis was conducted did not include an old or weathered asphalt pavement (after this phase of the research, the research team was able to add pavement-marking retroreflectivity files for old asphalt, which were ultimately used to generate the final recommendations in this report). However, the TTI study was conducted on old asphalt. Therefore, for the purposes of this validation effort, old concrete was used. Old concrete would most likely provide the nearest approximation of old asphalt in terms of contrast with pavement markings of any of the available pavement surfaces. Because old concrete has a lower retroreflectivity than old asphalt in the TARVIP pavement surface files, it will provide more luminance contrast with the pavement marking than old asphalt. Therefore, the resulting detection distances from the TARVIP analysis will be higher with old concrete than they would be with old asphalt, so the reported detection distances are more liberal than they would have been had an old asphalt pavement surface file been used in the analysis.

When comparing a tape product's performance in TARVIP to its performance as reported by Carlson et al.,(*2*) it was assumed that the product used in the TTI study had similar retroreflective characteristics to the pavement-marking file in TARVIP. To adjust for any differences, a material efficiency is used. This material efficiency is a ratio between the R_L reading of the actual marking used and the 30-m (98-ft) geometry R_L contained in the TARVIP pavement marking file. Such an adjustment assumes that this ratio is valid across the entire viewing matrix based on one R_L value.

For the TARVIP thermoplastic marking files (as well as any of the other nonmanufactured markings), no information is available regarding the thickness, application method, binder, or bead gradation of these markings. Therefore, it was necessary to assume that the TARVIP thermoplastic marking file was similar to the material used in the TTI study.

It should be noted that the researchers used a 2003 Ford Taurus headlamp for the modeling, and the TTI study used a 2004 Ford Taurus. It was confirmed with a local Ford dealership that the headlamps of these two model years are compatible. The locations of the headlamp relative to the car origin and the driver's eye relative to the headlamps were measured using the original vehicle from the study.

The TARVIP default values for windshield transmission, ambient luminance, and atmospheric transmissivity were retained since no data for these values are available from the TTI study.

The results of the comparison showed that the TARVIP curve fell within the 95 percent confidence range of the TTI study data (see figure 5 and figure 6).

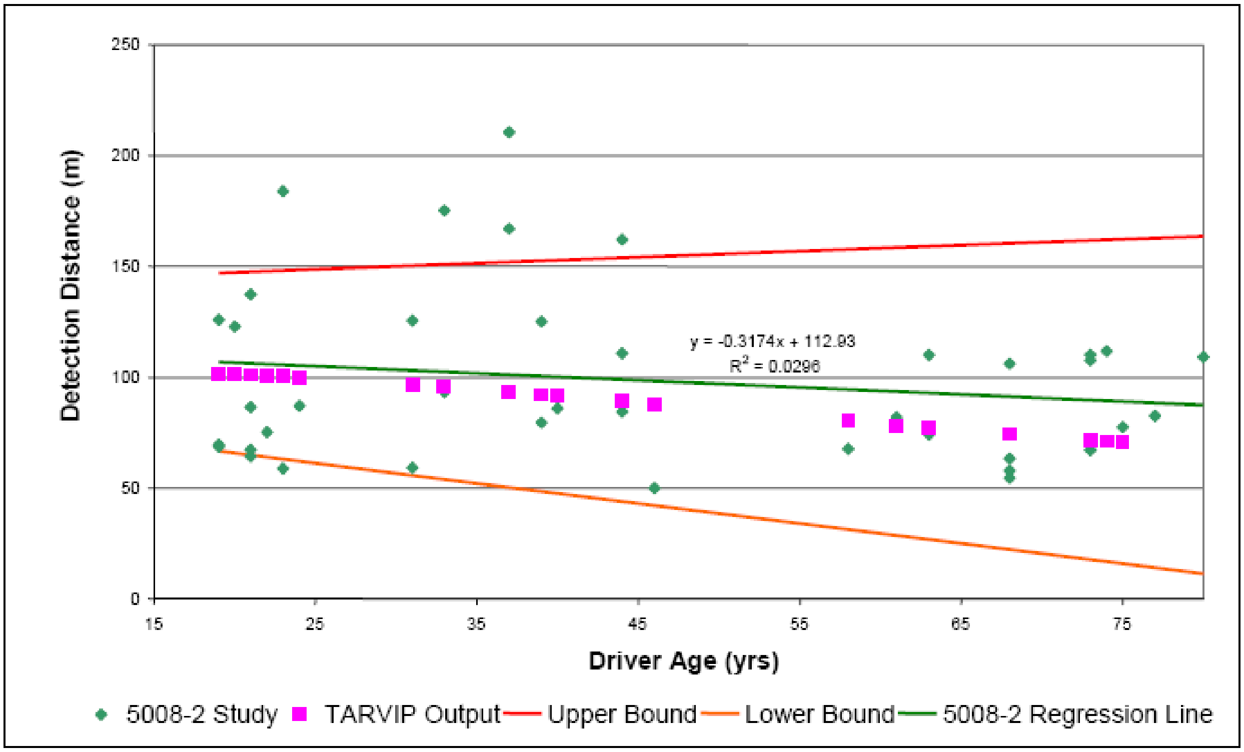


Figure 5. Scatter diagram. Detection distance versus driver age—Structured tape.

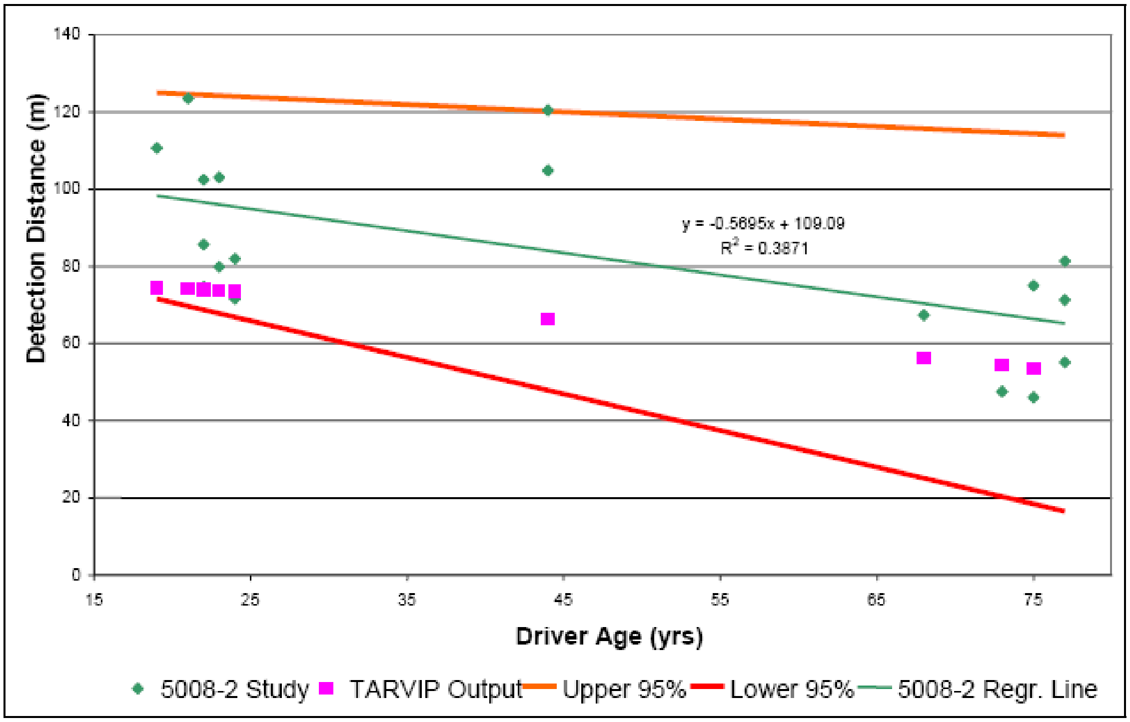


Figure 6. Scatter diagram. Detection distance versus driver age—Thermoplastic.

3.3.2. TTI Report 4269-1 Study Comparison

TTI Report 4269-1 was for a study evaluating the visibility of signs and pavement markings from the perspective of passenger car drivers and commercial vehicle drivers (only the results from the passenger car drivers are reported herein). Two different types of pavement marking tape products were investigated, one of which was used both in new condition and with a clear mask applied. Thus, three different markings were tested, representing low, medium, and high retroreflectivity coefficients. Pavement marking detection distance data were collected in a 1998 Chevrolet Lumina traveling at 48.3 km/h (30 mi/h). Data were recorded similarly to that recorded by Carlson et al., except that participants were following a solid white right edge line and asked to state when they could clearly see the end of the pavement marking. The course also had signs that they were asked to identify during each run.(*15*)

The TTI study was performed on old concrete, so that pavement marking file was used. Assumptions regarding material efficiencies and TARVIP default values were the same as those made for the TTI Report 5008-1 study comparisons.

The most problematic assumption involved the vehicle headlamps, as TARVIP contains no Chevrolet Lumina headlamp file. TARVIP does have a 2001 UMTRI 50 percent low-beam headlamp file—the only headlamp that it has in common with the ERGO software used for sign visibility. Using ERGO, the luminance values recorded in the sign luminance portion of the study by Finley et al. and the output of scenarios modeled in ERGO were compared. From these two values, a headlamp efficiency value for each point was obtained. These efficiencies were then averaged to obtain one efficiency value. The two obvious limitations are

- It is assumed that the average obtained is an effective method for comparing the Chevrolet Lumina headlamp to the UMTRI 50 percent low-beam headlamp.
- The points of comparison are all located above the horizontal while the points of interest are below the horizontal.

The results of the comparison showed that the TARVIP curve fell within the 95 percent confidence interval for older drivers but slightly below the interval for younger drivers (approximately 50 years old and younger). See figure 7.

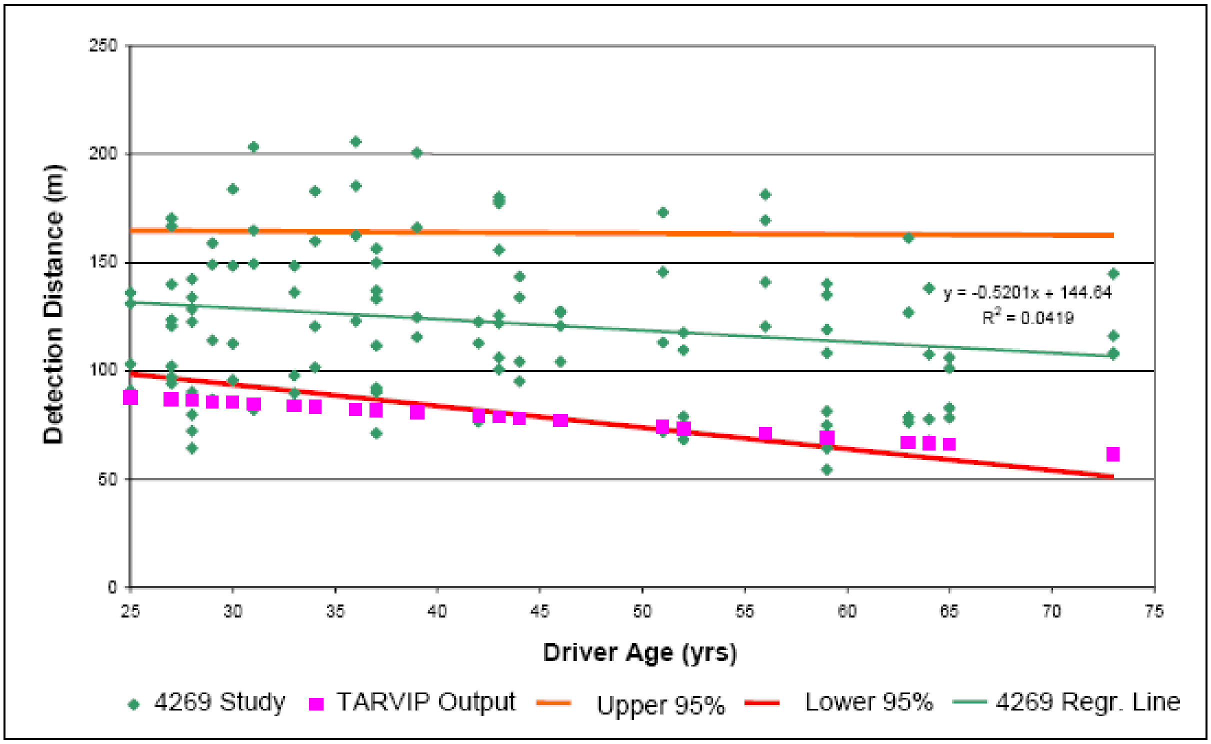


Figure 7. Scatter diagram. Detection distance versus driver age—Standard tape.

4. ESTABLISHING CRITERIA FOR MINIMUM PAVEMENT MARKING RETROREFLECTIVITY

In order to develop recommended minimum in-service pavement marking retroreflectivity values, TARVIP models were constructed to determine driver needs under various scenarios. A matrix was constructed using factors that affect pavement marking visibility and could be adjusted in TARVIP. Reasonable values for each factor were chosen to test minimum required retroreflectivity sensitivity to those parameters. As not all factors affecting pavement marking visibility can be accounted for using TARVIP, care was taken to ensure that the modeled scenarios conservatively modeled those factors.

A list of the factors varied in the TARVIP analyses is shown below with the levels studied. Further justification is provided below.

- Pavement surfaces (2 levels: old asphalt, old concrete).
- Pavement marking configurations (3 levels: yellow dashed center line with white edge lines, yellow dashed center line, white left lane line).
- Vehicle type (2 levels: passenger sedan, commercial truck).
- Vehicle speed (3 levels: 64 km/h (40 mi/h), 88.5 km/h (55 mi/h), 112.7 km/h (70 mi/h)).

Factors held constant in the TARVIP analysis are

- Pavement marking material (alkyd paint with standard glass beads).
- Overhead lighting (none).
- Line width (102 mm (4 inches)).
- Required preview time (2.2 seconds).
- Pavement wear (old surfaces).
- Center line configuration (3.0-m (10-ft) skip with 9-m (30-ft) gaps).
- Windshield transmission (0.7).
- Atmospheric transmissivity (0.86 km^{-1}).
- Weather conditions (dry).
- Oncoming vehicle glare (none).
- Headlamp type (UMTRI 2004 50 percent low beam).
- Driver age (62 years old).
- Pavement marking degree of obliteration (none).
- Lateral separation between double lines (no double lines were investigated).
- Driver workload (not distracted/low workload).
- Driver attention (full).
- Horizon/sky luminance (none).

4.1. Selection of Pavement Surfaces

The pavement surfaces used in the TARVIP models were old concrete and old asphalt. The pavement surface retroreflectivity matrices used for these surfaces were developed by Schnell et al. by using a portable device that acted as a goniometer in recording luminance and illuminance over a range of entrance and observation angles for a variety of pavement surfaces.(16) Old concrete and old asphalt were chosen for analysis, as new concrete and new asphalt make up a small percentage of road surfaces in the United States. New concrete and new asphalt surfaces will also have new pavement markings, which are unlikely to be the focus of scrutiny in terms of minimum retroreflectivity.

4.2. Selection of Pavement marking Configurations

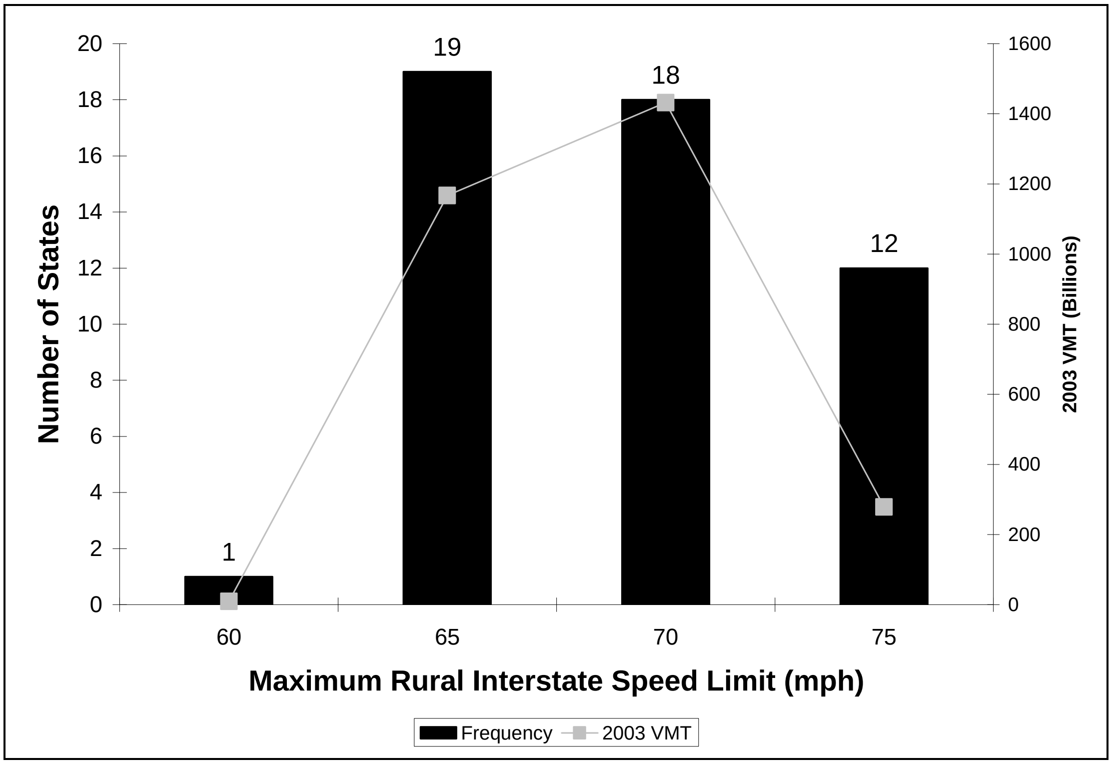
Three pavement marking configurations were included in the model: a single white dashed lane line to the left of the vehicle, a single yellow dashed center line to the left of the vehicle, and a single yellow dashed center line to the left of the vehicle with a solid white edge line to the right of the vehicle. For all dashed lines, a standard 3-m (10-ft) skip line was used with a 12-m (40-ft) cycle length. The two dashed line only scenarios provide the driver with minimal pavement marking surface and are located to the left of the vehicle (opposite the typical aiming direction of most U.S. headlamps, as shown in figure 4). The use of the two colors provided useful information on the difference in driver retroreflectivity needs between white and yellow lines. Additionally, the scenario including the edge lines serves to show the additional benefit drivers obtain from a fully marked roadway.(24).Twelve-foot lane widths were chosen, as the vast majority of travel lanes in the United States are no wider than 3.7 m (12 ft). With larger lanes, the pavement markings are farther away laterally from the vehicle headlamps. Therefore, using larger lanes as a default yields a conservative visibility scenario.

4.3. Selection of Vehicle Types

Two vehicle types were included in the model: a passenger sedan and a large commercial vehicle. The dimensions used were those of the 1998 Chevrolet Lumina and the 1986 Freightliner from the TTI study.(15) Many of the vehicles in the United States are either similar to one of these vehicles or somewhere in between them in terms of driver and headlamp locations.

4.4. Selection of Operating Speeds

The TARVIP model was evaluated at three vehicle speeds: 64.4 km/h (40 mi/h), 88.5 km/h (55 mi/h) and 112.7 km/h (70 mi/h). This loosely follows the recommendations of the Turner research, which recommended one minimum retroreflectivity level for all speeds below 64.4 km/h (40 mi/h), as drivers will always need close-proximity vehicle placement information, no matter how slow they are traveling. Turner also showed that nearly 68 percent of the rural two-lane highways in the United States have a speed limit of 88.5 km/h (55 mi/h), creating another natural investigation speed.(7) Finally, 112.7 km/h (70 mi/h) was chosen as the final investigation speed as 38 of 50 U.S. states have a maximum rural interstate speed limit of 112.7 km/h (70 mi/h) or less (see figure 8). The 12 states with a speed limit of 120.7 km/h (75 mi/h) accounted for only 9.6 percent of annual vehicle miles traveled in the United States in 2003.(37, 38)



1 mi/h = 1.61 km/h

Figure 8. Bar graph/line graph. Maximum speed limits in U.S. states and associated VMT.(*37, 38*)

4.5. Consideration of Roadway Lighting

Determining the effect of roadway lighting on minimum pavement marking retroreflectivity values is desirable. TARVIP contains an ambient luminance option that allows the user to account for luminance that originates from nonheadlamp sources. However, as described in the previous section, TARVIP works by calculating the luminance contrast between the pavement marking material and the road surface. The ambient luminance option adds an equal amount of luminance to the pavement marking material and the road surface, which serves to reduce the luminance contrast ratio. Increasing the ambient luminance in TARVIP decreases pavement marking visibility when research has shown that the opposite is true.(*10*) Therefore, a dark roadway was used exclusively in the TARVIP model.

4.6. Selection of Pavement marking Materials

The TARVIP pavement marking described as alkyd paint and beads was selected for analysis, as Turner found that markings composed of paint with beads make up the vast majority of pavement marking material used by state and local agencies in his survey of those agencies.(*7*) Pennsylvania Transportation Institute researchers also surveyed nine state agencies and found that 98 percent of the lane-miles of pavement markings in those states are either water-based or epoxy-based paints.(*39*)

4.7. Selection of Vehicle Headlamp Performance

The headlamp used for the TARVIP analysis was the 2004 UMTRI 50th percentile market weighted headlamp. This headlamp file comprises a luminous intensity matrix that represents the latest available market-weighted average representation of the U.S. vehicle fleet. It is a conglomerate of the 20 best-selling 2004 model year passenger vehicles in the United States, representing 39 percent of all vehicles sold in the United States. The photometric information for each headlamp was weighted according to how many vehicles of that type were sold.(*23*)

4.8. Establishment of Required Preview Time

COST 331 states that the absolute minimum driver preview time is 1.8 seconds and established a recommended preview time of 2.2 seconds.(*34*) Other research has used preview times ranging from 2.0 to as high as 3.65 seconds in recommending minimum pavement marking retroreflectivity, the latter producing relatively high R_L recommendations.(*1*) For the purpose of this research, a preview time of 2.2 seconds was used, aligning with the value recommended and used in *COST 331*.

4.9. Selection of Driver Age and Visual Performance

Research sponsored by the FHWA to establish minimum in-service retroreflectivity levels for traffic signs has shown that about 90 percent of the nighttime driving population is 62 years of age or less.(*21*) The human factors study to support the minimum retroreflectivity levels for traffic signs used drivers aged 55 and older, with an average age of 62 years. Therefore, in order to maintain consistency with previous FHWA-sponsored work on minimum retroreflectivity, a driver age of 62 years was used in the TARVIP models. By selecting age in TARVIP, the visual abilities of the drivers are also set.

4.10. Consideration of RRPMs

Accounting for RRPMs in minimum pavement marking retroreflectivity recommendations is desirable because their superior retroreflective performance during wet night conditions can reduce the luminance required of pavement markings by drivers. However, TARVIP does not currently have a module built in to directly model RRPMs or for determining the relative efficiency of two different pavement marking materials deployed under the same scenario. Zwahlen and Schnell were the only previous researchers who have made minimum pavement marking retroreflectivity recommendations and attempted to account for RRPM presence. Their methodology involved reducing the required preview time from 3.65 seconds without RRPMs to 2.0 seconds with RRPMs. While there is little support for this value, it is still greater than the absolute minimum driver preview time established by *COST 331*. It was the first attempt to establish a "discount" factor for pavement marking retroreflectivity in the presence of RRPMs.(*1*)

The methodology developed for determining minimum pavement marking retroreflectivity when RRPMs are present does not generate minimum retroreflectivity levels for the RRPMs themselves and assumes that the RRPMs are in adequate working condition. This approach is based on the driver being able to receive enough information from the pavement markings to identify the nature of curves in the roadway and the configuration of the pavement markings. As most pavement markings become unreliable sources of driver information under wet night conditions, RRPMs are designed to aid drivers under these conditions. However, they are not continuous linear devices like pavement markings; the information provided by RRPMs is intermittent. Therefore, understanding their ability to provide advanced roadway alignment information is critical. A literature review identified work by Zwahlen and Park, which shows that drivers need a minimum of three cues to detect changes in the horizontal alignment.(*40*) Using this information, the researchers developed a criterion such that the recommended minimum retroreflectivity levels for pavement markings when RRPMs exist will be based on a requirement that drivers be able to detect at least three RRPMs. Note, these RRPMs do not have to be continuously spaced, but three should be visible. In other words, there is allowance for missing or damaged RRPMs as long as there are still three within view to the nighttime driver.

Because drivers also need to receive close-proximity information from pavement markings (for peripheral vision tasks such as lane keeping and regarding passing zone information on two-lane highways), a second criterion was also developed. This second criterion was established to supplement the initial criterion of having a preview time of at least 2.2 seconds. With this additional criterion, it was felt that the recommended minimum maintained pavement marking retroreflectivity levels could accommodate both the near range visibility needs of nighttime drivers as well as their long range visibility needs. The near range criterion was based on a 24.4-m (80-ft) detection distance. This distance was chosen based on the close-proximity information markings provide while considering the occluded distance caused by the hood of typical vehicles. It provides about 1 second of preview time traveling at 88.5 km/h (55 mi/h).

4.11. Determining Minimum Pavement marking Retroreflectivity

Based on the information outlined above, 48 scenarios were developed for use with TARVIP to produce an array of retroreflectivity levels that could be used in conjunction with previous research and previous recommendations to put forth an updated set of recommendations that incorporate the best-known scientific findings and expertise currently available. Thirty-six of the 48 scenarios were used to compute the required retroreflectivity of pavement markings without RRPMs. The remaining 12 scenarios included RRPMs. There were an additional 18 scenarios developed to evaluate the sensitivity of required R_L to preview time.

5. RESULTS

The results of the TARVIP runs are shown in table 9. Each cell contains the required R_L for a unique set of vehicle type, vehicle speed, pavement surface, and pavement marking configurations. The minimum R_L values for the scenarios that included RRPMs are also shown in table 9. Table 10 shows the results of the TARVIP runs that were generated to evaluate the sensitivity of R_L to preview time. These runs were made by varying the preview time and speed while keeping the vehicle (passenger sedan), pavement surface (old asphalt), and pavement marking configuration (yellow center line with white edge lines) constant.

Table 9. Minimum retroreflectivity levels in [mcd/m^2/lx].

RRPM Scenario	**Marking Configuration**	**Pavement Surface**	**Vehicle Speed [km/h] ([mi/h])**	**Vehicle Type**	
				Sedan	Freightliner
None (2.20s Preview Time)	YCL-WEL	Asphalt	64.4 (40)	32	37
			88.5 (55)	52	56
			112.7 (70)	92	86
		Concrete	64.4 (40)	26	30
			88.5 (55)	47	47
			112.7 (70)	88	79
	WLL	Asphalt	64.4 (40)	88	86
			88.5 (55)	223	188
			112.7 (70)	492	379
		Concrete	64.4 (40)	81	77
			88.5 (55)	215	176
			112.7 (70)	491	363
	YCL	Asphalt	64.4 (40)	94	83
			88.5 (55)	249	189
			112.7 (70)	577	391
		Concrete	64.4 (40)	87	75
			88.5 (55)	241	176
			112.7 (70)	575	374
Present and in good working order (at least 3 in view)	YCL-WEL	Asphalt	N/A	25	35
		Concrete	N/A	19	29
	WLL	Asphalt	N/A	40	55
		Concrete	N/A	33	48
	YCL	Asphalt	N/A	39	49
		Concrete	N/A	32	43

Table 10. Required R_L values for TARVIP scenarios with varying preview time in [mcd/m^2/lx].

Preview Time (s)	Speed [km/h] ([mi/h])		
	64.4 (40)	88.5 (55)	112.7 (70)
1.5	25	30	40
2.0	29	43	72
2.5	37	69	135
3.0	51	112	248
3.5	72	184	441
4.0	102	294	735

The results in table 9 show good agreement with recent research. For instance, in many cases, the retroreflectivity levels associated with the Freightliner vehicle are less than they are for a passenger vehicle. Gibbons et al., as well as Rumar et al., discovered the same finding in their recent works.(17, 19) On a fully marked roadway, this visibility advantage for the Freightliner was slight, and there was even an advantage for the passenger sedan at lower speeds. In such cases, the height advantage provided by a larger vehicle does not overcome the larger observation angle in a large vehicle. However, in scenarios with the center line only configuration, the Freightliner required R_L values ranging from 2 percent to 53 percent less than those required for the passenger sedan. This wide range of values is due to the previously discussed interaction between speed and vehicle type.

The results in table 9 show that the required R_L increases as the speed of the vehicle increases. This is in agreement with previous minimum pavement-marking retroreflectivity recommendations(1, 7, 9) that roadways with higher speed limits should have pavement markings with higher retroreflectivity. This is expected, as higher speeds require longer detection distances for the same preview time. In other words, longer detection distances are needed when driving at higher speeds in order to perceive and react to the information provided by the pavement markings.

The results in table 9 also correlate well with previous research that shows that old concrete should provide better visibility than old asphalt.(16) This advantage ranged from nearly negligible at higher speeds to approximately 20 percent at lower speeds. This was also expected as at higher speeds, the preview distances are longer, resulting in larger entrance angles. At large entrance angles, the retroreflectivity values of old asphalt and old concrete measured by Schnell et al. converge.(16)

As expected, the fully marked road scenarios produced much lower required R_L values than the center line only scenarios. For the fully marked road scenario (noted as YCL-WEL in table 9), the detection distance used to generate the retroreflectivity levels is based almost entirely on the visibility of the solid white edge line. For this configuration, TARVIP calculates the detection distance for the white edge line and then multiplies by a factor, which varies with geometry, to add additional detection distance due to the presence of the yellow center line, as shown by Zwahlen and Schnell in their previous research.(24) Therefore, the required R_L of a white edge line is slightly reduced by the presence of a yellow center line. On the other hand, the addition of solid white edge lines provides a 66 percent reduction in the required R_L values for a dashed yellow center line and a dashed white lane line at 64.4 km/h (40 mi/h) and an 85 percent reduction at 112.7 km/h (70 mi/h). The reason that solid white edge lines provide for greater reduction in the required luminance of center lines and lane lines at high speeds may be deduced from the distribution of headlight illuminance on the road surface, presented in figure 4. At greater distances from the vehicle, the difference in the headlamp illuminance on the right edge line to that incident on other lines becomes proportionally greater, increasing the visibility advantage that the solid white edge lines offer to drivers.

Also, when RRPMs are present (and in good working order so that at least three are in view at any time), the required R_L values decrease substantially, ranging from 18 to 34 mcd/m^2/lux for fully marked roads and 31 to 48 mcd/m^2/lux for center line only roads. The results indicate that, at most, R_L values no greater than 55 mcd/m^2/lux are necessary for the driver to determine the color and configuration of pavement markings. These results also concur with the Molino et al. work, which recommended retroreflectivity discount factors when RRPM are present.(*29, 31*) The TARVIP results were compared to that research in order to recommend minimum values for pavement marking retroreflectivity when RRPMs are deployed.

The results shown in table 10 indicated that required R_L is highly sensitive to preview time, especially at higher speeds. Increasing either speed or required preview time increases the detection distance. For a vehicle speed of 112.7 km/h (70 mi/h) and a preview time of 4.0 seconds, this equates to a detection distance of 125.3 m (411 ft), thus the relatively high required R_L of 735 mcd/m^2/lux. These results show that selecting a reasonable preview time is critical when determining minimum pavement marking retroreflectivity.

6. RECOMMENDATIONS AND CONCLUSIONS

Recommendations for minimum levels of pavement marking retroreflectivity were developed using the results described in the previous section. The recommended levels are shown in table 11. They should apply to MUTCD warranted center line and edge line pavement markings, including lane lines on Interstate highways and freeways, measured under dry conditions in accordance with the 30-m (98.4-ft) geometry described in ASTM E1710.(41) The levels in table 11 apply to both yellow and white pavement markings. The reduction factor recommended for RRPMs assumes that the RRPMs are in good working condition and that at least three of them are visible to nighttime drivers at any point along the road. On two-lane highways with RRPMs along the center line only, the reduction factor applies to both center lines and edge lines. The recommended minimum R_L values shown in table 11 are not intended to apply to every combination of geometry, speed, and pavement marking configuration that may be encountered on a roadway. Drivers may require a higher R_L in certain situations and engineering judgment should be used to determine if conditions warrant higher R_L values. Additional information concerning the basis of these recommendations is described below.

Table 11. Recommended minimum R_L values in [mcd/m^2/lux].

Roadway Marking Configuration	Without RRPMs			With RRPMs
	≤ 50 mi/h	55–65 mi/h	≥ 70 mi/h	
Fully marked roadways (with center line, lane lines, and/or edgeline, as needed)*	40	60	90	40
Roadways with center lines only	90	250	575	50

* Applies to both yellow and white pavement markings.
1 mi/h = 1.61 km/h

A key item under consideration was the pavement surface. The TARVIP analysis showed that the required R_L values are higher for an old asphalt pavement surface. As the majority of the roads in the United States are surfaced with old asphalt at any point in time,(7) the recommended minimum retroreflectivity levels are based on aged asphalt surfaces.

Another key item to consider is the vehicle type. Passenger sedans accounted for 57 percent of vehicle miles traveled in the United States in 2003,(42) not including pick-up trucks, vans, and sport- utility vehicles. The TARVIP analysis showed that the required R_L values are generally higher for the passenger sedan than the commercial vehicle. The literature shows that the higher the driver eye height (and headlamp height), the lower the needed retroreflectivity. Therefore, the minimum retroreflectivity levels recommended in table 11 are based on a passenger sedan.

Another factor that was considered is pavement marking configuration. The MUTCD includes warrants for center lines and edge lines based on roadway classification, roadway width, and average daily traffic (ADT).(6) The application of longitudinal pavement markings beyond that required by the warrants in the MUTCD is optional. In order to gain some perspective on the presence of edge lines on rural two-lane highways, a recent report from Texas was reviewed which shows that about 40 percent of the rural, two-lane, two-way, state-maintained highway miles in the state have no edge lines.(43)

The recommendations in table 11 are based on different marking configurations. An obvious outcome is that roadways with only a center line need more retroreflectivity than roadways marked with edge lines. Previous research has shown similar results in terms of visibility as a function of marking configuration.(*24*)

The results in table 10 agree that for a constant preview time, required pavement-marking retroreflectivity is sensitive to speed. Therefore, for roadways without RRPMs, the recommendations in table 11 are based on the three roadway speeds investigated in the analyses.

The final factor to consider is RRPM presence. The results of the analyses confirm that a discount factor of approximately 45 percent suggested by Molino et al.(*29*) for a combination of lines with low luminance and RRPMs with medium luminance is reasonable. Therefore, the minimum retroreflectivity recommendations reflect an approximately 45 percent discount factor when RRPMs are deployed and maintained.

7. LIMITATIONS

The minimum retroreflectivity levels presented in this study are the product of computer models and simplifying assumptions based on numerous other research efforts. Therefore, these recommendations are subject to the following limitations:

- The TARVIP analysis used a preview time of 2.2 seconds. It was assumed that this was an adequate preview time for drivers to safely and comfortably navigate their vehicles. Drivers requiring a higher preview time will need pavement markings with higher R_L values than those recommended herein.
- The TARVIP analysis considered only straight roadways and longitudinal pavement markings. Curved roadway segments, especially those with small low radii, place the approaching pavement markings in a different location in the projected headlamp beam pattern than they would be on a straight roadway. Consequently, pavement markings in a curved roadway segment may be more or less visible to drivers than those on a straight segment.
- Only dry, clear weather conditions were considered. Standing water, rain, snow, and fog can all have a significant negative impact upon pavement marking visibility and require much higher retroreflectivity levels than dry and clear conditions to achieve the same visibility distance.
- This analysis assumes that vehicle headlamps are in good working condition and windshields are clean.
- The only pavement marking material that was modeled was white alkyd paint with beads. Although TARVIP provides the capability to model other materials, there is no available information regarding crucial details such as bead quality and size or the marking material thickness associated with the retroreflectivity matrices used in the TARVIP models of alternative materials. As a result, alternative pavement marking materials that cannot be adequately modeled with existing information may exhibit different visibility performances with respect to distance, when compared to white alkyd paint with beads.
- The TARVIP analysis used pavement surface retroreflectivity matrices developed by researchers at the University of Ohio based on readings taken from specific surfaces. It was assumed that these matrices are representative of road surfaces in use throughout the United States.
- It was assumed that the 50th percentile UMTRI-2004 headlamp is representative of the headlamps in the U.S. vehicle fleet. There may be a significant number of vehicles operating in the United States using headlamps with inferior performance to that of the UMTRI-2004 headlamp.
- The RRPM analysis assumes that the deployed RRPMs on a roadway provide long detection distances, and thus, long preview times. However, RRPM visibility can deteriorate quickly from the “new” condition. Therefore, it was assumed herein that the RRPMs are in adequate working order when applying the discount factor of 45 percent to the pavement marking minimum retroreflectivity levels.
- Drivers older than 62 years old may require greater pavement marking retroreflectivity than the minimum levels presented here.

- The retroreflectivity levels were developed without consideration of driver needs when encountering glare from oncoming vehicles.

The retroreflectivity values recommended by this research should be considered minimum maintenance levels, and markings should be replaced or scheduled for replacement before falling below these recommended levels. The retroreflectivity values recommended by this research are not intended to account for worst-case conditions or all possible combinations of roadway geometry, speed, and pavement marking configurations. In summary, engineering judgment should be used to evaluate whether or not conditions warrant the use of pavement markings with higher maintained retroreflectivity.

It should also be noted that winter maintenance activities can severely damage the retroreflective performance of pavement markings. In addition, nonconcentric driving behavior around horizontal curves can also wear markings faster along the length of the curves than on adjacent tangent sections. The recommended minimum retroreflectivity levels presented in this report should be considered as applicable to sections of the marking representative of the marking over the length of the roadway and not to specific points along the roadway.

8. FUTURE RESEARCH NEEDS

The results of this study indicate that it would be beneficial to conduct additional research before implementing minimum pavement marking retroreflectivity values. This research effort did not include the collection of any field data to support the findings. Therefore, the recommendations should be validated by field testing to determine if the recommended minimum retroreflectivity levels provide adequate information to drivers under various speeds, roadway geometries, lighting conditions, and vehicle geometries.

This study determined minimum pavement marking retroreflectivity for straight roadways. The need exists for research showing how these values are affected by horizontal and vertical curves. Under such geometric conditions, the pavement markings will be located in different areas of a projected headlamp beam, having a significant impact upon their visibility.

Most of the pavement marking nonsubjective visibility research has been conducted with research participants viewing markings in a static condition or while driving at relatively slow speeds (48.3 km/h (30 mi/h), for example). There is little research showing what drivers need in terms of preview time and pavement marking luminance under high-speed conditions. Such research could help determine if assuming one required preview time for all speeds is necessary. As such, methodology tends to produce relatively high minimum retroreflectivity values for high speeds using preview times in the middle of the typical range used. Additional research into preview time required by drivers would also be beneficial, as previous recommendations of minimum pavement marking retroreflectivity have used a wide range of preview times, resulting in a wide range of recommended values. Utilizing a reasonable preview time is critical in determining minimum pavement marking retroreflectivity.

While some research shows that increasing line width can increase detection distance, other research on this issue has been inconclusive. Further research is needed to determine if widening pavement marking lines does, in fact, enhance visibility and if that enhancement translates to lower required pavement marking retroreflectivity. The Texas DOT is planning to commission a study starting in September 2007 that provides an opportunity to direct further research on the effectiveness of line width.

Research findings do show that roadway lighting increases the visibility of pavement markings. However, this research is qualitative and subjective in nature. A need exists to quantify the interaction between pavement marking visibility and the presence of roadway lighting as well as to understand the optimum roadway lighting deployment strategy that maximizes pavement-marking visibility.

Research findings from TTI and 3M show that there are differences in the performance of marking materials as a function of geometry.(44) Markings with similar 30-m (98-ft) R_L values can have very different visibility distances because of very different luminance levels beyond the standard 30-m (98-ft) measurement geometry. Therefore, a need exists to better characterize different types of pavement markings to better understand how different marking materials behave when the geometry is varied.

Finally, there have been a few research efforts that provide insight into the interaction between pavement markings and RRPMs. While the quantitative simulator research and the qualitative field research completed to date have increased understanding in this area, further research is necessary to understand driver information needs from pavement markings when RRPMs are used. Also, better information regarding the degradation of RRPM visibility would aid in developing more refined discount factors for pavement marking retroreflectivity.

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