Roadway Visibility Research Needs Assessment

U.S. Department of Transportation
Federal Highway Administration

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16. Abstract

This report focuses on a review of issues related to nighttime visibility and assessment of how the Federal Highway Administration (FHWA) Office of Safety's three safety program areas—roadway departure safety, intersection safety, and pedestrian and bicycle safety—address concerns for nighttime visibility, as well as a review of fatality data and a gap analysis for research needs.

In addition to the assessment of the three program areas, this report summarizes a survey of practices and policies of highway design, traffic engineering, and highway safety that are based on daytime conditions and may neglect issues and concerns that arise from nighttime conditions

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SI* (MODERN METRIC) CONVERSION

FACTORS 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 1,000 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)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°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

*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).

SI* (MODERN METRIC) CONVERSION

APPROXIMATE CONVERSIONS TO 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)				
°C	Celsius	1.8C+32	Fahrenheit	°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

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1. INTRODUCTION

This report focuses on a review of issues related to nighttime visibility and assessment of how the Federal Highway Administration (FHWA) Office of Safety's three safety program areas—roadway departure safety, intersection safety, and pedestrian and bicycle safety—address concerns for nighttime visibility, as well as a review of fatality data and a gap analysis for research needs. Within the framework of the Office of Safety's focus areas (roadway departure safety, intersection safety, and pedestrian and bicycle safety), the researchers identified potential ways future research, advancing technologies, and changes to current practices may address nighttime visibility concerns from a perspective of highway design, traffic operations, and highway safety. The strategic narratives from the roadmaps for intersection safety and roadway departure safety were evaluated to identify the extent to which they address nighttime conditions and issues of visibility, retroreflectivity, and lighting. These strategic plans were updated in February 2015. Information about the pedestrian and bicycle safety program was obtained from the strategic plan with recommended research for pedestrian safety, updated in 2010. The Office of Safety's three program areas are described in detail on line (https://safety.fhwa.dot.gov/).

In addition to the assessment of the three program areas, this task included a survey of practices and policies of highway design, traffic engineering, and highway safety that are based on daytime conditions and may neglect issues and concerns that arise from nighttime conditions. The topics identified are divided into the three safety program areas.

2. CURRENT RESEARCH AND PRACTICES

PRINCIPLES OF VISIBILITY

Approximately 90 percent of the information that drivers use is visual.(1) For nighttime driving, two of the most important factors that affect vision are visual acuity and contrast sensitivity. Visual acuity is the ability for drivers to discern details at a distance. The ability to detect differences in luminance and discern an object from its background is contrast sensitivity.(2)

A visual acuity of 20/20 is considered normal vision. In ideal conditions, a person with normal vision can read letters that subtend an angle of 5 minutes of arc. A person with 20/40 vision needs letters of 10 minutes of arc. A driver with poor vision must be closer to signs or roadway hazards to see them.(2) Contrast sensitivity is noted as being more impactful on vehicular crashes than is visual acuity. Regardless of a driver's visual acuity, an object that cannot be distinguished from its background will not be seen. This could involve any number of roadway hazards, from debris to a crossing pedestrian. Drivers typically misjudge the distance at which pedestrians are seen,(3) which often leads to crashes. The use of lighting can increase contrast in most cases and make objects in the roadway more discernible.(2)

For pedestrians and bicycles, it is important that conspicuity be increased to promote visibility. Lighting is one way to increase conspicuity. Although street lighting can help drivers see these vulnerable road users, a lack of uniformity can create dark spots, improper lighting can create glare, and changes in asphalt color can create areas of poor contrast.(2)

Color vision is a result of three types of color-sensitive cones in the eye. These three cones respond in general to red, green, and blue components of the visual spectrum. Abnormal color vision (or color blindness) refers to an aspect of vision where shades of color are confused by the observer. This is typically a result of low or missing levels of pigment in one of the cones in the retina. Color deficiencies can be red confusion, green confusion, or blue/yellow confusion (Protanopia, Deuteranopia, and Tritanopia, respectively). Color blindness occurs in approximately 8–9 percent of the population and mostly in males. Colorblind drivers typically use position of traffic signals and other clues to overcome their disability. There are new considerations in universal design that can overcome the limitations of color vision. These approaches are similar to a blue cross embedded in the red signal to aid in the signal identification.

The *FHWA Lighting Handbook* discusses the decline of visual function that often comes with age. Typical aging issues include a reduction in pupil size, which reduces the amount of light entering the eye; the lens losing elasticity, making focus difficult; and a general yellowing of the lens, which reduces both luminance and color contrast. Diseases such as glaucoma affect peripheral vision, and the yellowing of the ocular lens diminishes contrast sensitivity. The handbook also states that people over 60 have a reduced ability to detect movement of objects. Older drivers are also more susceptible to glare because the amount of contrast needed to overcome threshold contrast increases significantly. The concerns of the aging population's vision extend beyond drivers to pedestrians as well. Pedestrians, like drivers, need to accurately read sign messages and detect motion. Even though these concerns are known, the current roadway lighting system design practices are not designed with modifiers for age.(4)

ROADWAY DEPARTURE SAFETY

In the FHWA Safety Program, a roadway departure (RwD) crash is any crash in which a vehicle crosses an edge line, crosses a center line, or otherwise leaves the traveled way. Roadway departures account for over half of fatal crashes in the United States.(5) Harmful events associated with fatal roadway departures are fairly broad; however, the most harmful event in over 70 percent of crashes are rollovers, collisions with other vehicles and collisions with trees. Various factors come into play with roadway departures, including road type, speed limit, roadway geometry, weather, distracted driving, and even pavement. This section contains common practices for lighting various roadway types and concludes with potential areas of research for visibility and lighting that can help prevent roadway departures.

Current Assessment of Nighttime Visibility in Program Area

The strategic narrative for the FHWA roadway departure safety roadmap focuses on the goal of reducing roadway departure fatalities by 50 percent by the year 2030. The principal strategy is a focus on data, and there are some summary statistics of characteristics of roadway departure fatalities. For example, 76 percent of roadway departure rollover fatalities and 70 percent of roadway departure opposite-direction fatalities occur in rural areas. Also, over 70 percent of fatal crashes occur with a posted speed limit of 50 mi/h or greater.(6)

Data for the proportion of roadway departure fatalities that occur at night are notably absent from the strategic narrative. It is well known that nighttime crash rates are disproportionately high, especially for roadway departures. Therefore, any treatment that specifically targets nighttime crashes has a great potential to significantly improve safety. There is little within the strategic narrative that emphasizes the importance of these topics.

The strategic narrative mentions improved delineation as a potential countermeasure and the FHWA *Lighting Handbook* and training as a resource for addressing roadway departure safety.(6) There is limited information about how visibility will be integrated into the future of the roadway departure program area. Online, however, there is more information about retroreflectivity, lighting, and visibility within the current roadway departure safety program. That information relates to *Manual on Uniform Traffic Control Devices* (MUTCD) regulations, research, funding for visibility improvements, and other resources for implementing the objectives of the program. In general, however, there is not a direct link between these visibility topics and safety. Without evidence of a direct link, it may be difficult to persuade agencies to change their practices and policies.

Along the same lines, the national guides have found deficiencies in design practice. The lighting needs for different roadways are highlighted in the American Association of State and Highway Transportation Officials' (AASHTO's) lighting guidance in *A Policy on Geometric Design of Highways and Streets* (Green Book).(7) Because fixed-source lighting tends to reduce crashes, and most crashes occur at critical points such as interchanges, curves, and junctions, AASHTO recommends lighting many urban and suburban areas. Rural lighting is rarely justified except for critical areas like intersections, railroad crossings, bridges, or sharp curves.[7]

There are several issues that result in a difference in design between rural and urban zones. Rural areas may have higher speed limits due to fewer conflicts such as intersections, curbs, and pedestrians. The levels in background luminance may be different since by definition rural areas are less populated, so there will be less surrounding illumination.[8]

Recent and Ongoing Research

Within the area of roadway departure safety, there are several research projects that have recently been completed or are ongoing that relate to visibility and the use of traffic control devices and lighting. Examples of these are described below.

Pavement markings provide roadway alignment information that helps drivers maintain their position in the lane and identify upcoming features such as curves and ramps. Recent research conducted for the Texas Department of Transportation and FHWA has identified the benefits of using wider (greater than 4 inch) edge lines,[9, 10, 11] which leads to improvements in lane position, reductions in encroachments across the edge line, and reductions in observed crashes. A key finding from the work on wider edge lines is that they are shown to significantly reduce crashes on two-lane highways but not on multilane divided highways (which is where they are generally used). A pooled fund study recently showed that upgrading pavement markings so they are retroreflective when wet can result in significant crash reductions for multiple types of crashes, especially on multilane highways.[12]

In addition, there have been recent studies on how pavement marking retroreflectivity may be associated with nighttime crashes (see13, 14, 15,16, and 17). While there is not yet an established link that has been widely accepted, research has been making progress on identifying thresholds of pavement marking retroreflectivity where improvement in nighttime safety may be achieved.

Complementing the research on wider and brighter pavement markings and on markings designed for performance in wet weather, the Texas A&M Transportation Institute (TTI) is currently leading a project funded through the National Cooperative Highway Research Program (NCHRP) on retroreflective pavement markers (RPMs). RPMs provide the most notable benefit during wet weather events at night because their construction and shape prevent water from accumulating on the marker. The objectives of the NCHRP project include addressing where RPMs should be used and developing specifications for spacing and maintenance (i.e., retroreflectivity and retention).

Regarding traffic signs that can prevent roadway departure crashes, a recently completed NCHRP project developed guidelines for the use of traffic control devices at changes in alignment.[18] Researchers evaluated the safety impacts of traditional devices used at curves (such as advance warning signs and chevrons) and studied how drivers respond to these devices. From the findings, they developed guidelines that promote the consistent use of devices that provide drivers the right information for safe curve negotiation.

Regarding lighting, the Virginia Tech Transportation Institute (VTTI) has recently completed nighttime visibility projects involving adaptive lighting, light-emitting diode (LED) sign board visibility in fog, and fog and rain visibility with active lane delineators. The adaptive lighting project produced guidelines for adaptive roadway lighting design criteria.

The LED sign board visibility in particular was developed to determine the best color combinations for signs in foggy conditions. These will be used in areas where adaptive speed limits based on weather conditions are implemented. The results indicate that white and black remain the best combination.

The active delineators have shown promise in providing information to control both speed and roadway position of a driver in fog. A variety of flash patterns were tested to investigate the impact on driver behavior. The results show that active delineators can provide lane guidance as well as speed control in low visibility conditions.

Currently in progress at VTTI are research projects concerning the impact of roadside police vehicle and active work zone equipment lighting on visibility. These projects will produce recommendations for equipping vehicles with lighting that promotes traffic and worker safety. The Lighting Research Center and Penn State identified links between visibility and public safety from roadway lighting in a recent research effort. The research was prompted by a recent trend of municipalities removing their lighting in an effort to save money and energy. While lighting is expected to improve safety, little data are available to serve as a link between the two ideas. This research effort attempted to solidify that link and provide information on the consequences of removing or adding lighting to an area.

INTERSECTION SAFETY

An intersection crash is any crash where an intersection or driveway access is identified as the location or one of the influencing factors. Intersections vary widely depending on location, functional class, traffic volume, and use of channelization. While fatal crashes at intersections have declined in recent years, determining how and why crashes continue to occur is still a strong research focus. Most research shows that the addition of roadway lighting and other visible elements can reduce crash frequency at an intersection.

Current Assessment of Nighttime Visibility in Program Area

One of the program strategies for intersection safety is a prioritization of efforts based on data. While fatalities have steadily dropped in recent years, it is clear that continued improvements will be best realized by focusing on the conditions in which crashes occur most frequently. The strategic plan focuses on both signalized and unsignalized intersections, with additional emphasis areas categorized as vulnerable users: pedestrians, bicycles, motorcycles, and older drivers.

Some analysis has been performed for each of these emphasis areas, showing trends and summary statistics. There are also lists with potential treatments, projects, resources, and opportunities for coordination with other areas. For example, the areas for pedestrian and bicycle safety identify road diets and pedestrian-oriented roundabouts as potential methods to facilitate reductions in pedestrian and bicycle fatalities.

Of the topics and practices discussed in the strategic plan for intersection safety, there is only one mention of conditions related to visibility at night. Retroreflective signal backplates are listed as an effective countermeasure at signalized intersections. There are other projects that may have a component of visibility such as the recently completed "Accelerating Roundabout Implementation in the US" however there are few that deal with visibility or lighting as the explicit research focus.

In terms of the lighting, the primary goal is to provide sufficient illuminance so drivers can see their entry and exit points ahead of time. Other goals of intersection lighting include alerting drivers of an intersection ahead of time as well as providing comfort and safety for pedestrians. Many policies provide information on when intersection lighting is warranted, but specifics on implementation can be rare. Often left out of consideration are rural intersections, which are often dimly lit or unlit and designed for higher speeds and typically have other confounding issues such as dark sky considerations and availability of utilities. Currently, guidelines for roundabout lighting is based on policies for signalized or all-way-stop intersections enhanced with additional computer based rendering simulations although roundabouts and intersections are significantly different in their operation and visual areas of concern. Note that some intersections are not controlled in any of the directions, and lighting may impact the safety at these intersections with noticeability of the intersection and potential conflicts.

There may not be a need to include visibility and nighttime conditions as a separate emphasis area in the intersection safety strategic plan, but the typical disproportionate crash rates at night on all roadways justify at least identifying the resources and potential countermeasures that can address safety issues related to nighttime conditions for each of the emphasis areas.

Recent and Ongoing Research

Visibility within the focus area of intersection safety can be impacted by the use of lighting and traffic control devices at intersections. Several recent and ongoing projects investigating these issues are discussed here.

One key concern for safety at intersections is communicating to drivers the presence of intersection control so they properly respond. While the visibility of traditional intersection control devices such as stop signs and traffic signals is adequate in most cases, in some cases the intersection control devices can be made even more visible (or conspicuous) by measures such as added flashing lights, with the use of either beacons or LEDs embedded in stop signs.(19, 20) Improving the sign visibility at the intersection may be another way to obtain similar results. FHWA research has shown that while upgrading stop sign retroreflectivity may lead to only a modest reduction in crashes, the low cost of installing new stop signs produces cost-effective benefits, particularly at lower-volume intersections.(21)

Research completed for an NCHRP project on overhead signs showed that legibility is directly linked to sign luminance, whether provided from internal illumination or with retroreflective sheeting.(22) Increase in retroreflectivity of signs or use of internal illumination can serve to not only enhance legibility but also improve overall conspicuity for alerting drivers to the intersection. TTI is currently evaluating the safety impacts of systemically upgrading signs with a case study in Albuquerque, New Mexico.

A recent study of lighting levels at isolated rural intersections was completed by the University of Minnesota. The study found that lighted intersections had reduced nighttime crashes compared to unlit intersections of comparable traffic volume and configuration. Increasing the horizontal illuminance is effective at reducing nighttime crash rate regardless of source, whether high-pressure sodium (HPS) or LED.[23] Other recent research found lighting at intersections to reduce crashes by 3.6–6.5 percent.[24]

In late 2015, VTTI completed a study investigating the positioning of intersection lighting and how that lighting helps promote the visibility of pedestrians. The study found that lighting the box of the intersection provided the best results in terms of visibility with a plateau of illuminance levels between 8 and 12 lx. This configuration requires fewer luminaires, which may lead to an energy saving solution.[25]

PEDESTRIAN AND BICYCLE SAFETY

Differences in size, speed, and use of safety gear make pedestrians and cyclists the most vulnerable of road users. In fact, pedestrians accounted for approximately 18 percent of all traffic fatalities in 2014.[26] Nearly 70 percent of all pedestrian-related crashes occur at night. There are many policies in place for providing lighting to intersection crosswalks and midblock crosswalks, but typically with little regard for the differences in vehicle headlamps and surrounding illumination.

Current Assessment of Nighttime Visibility in Program Area

The strategic plan for the pedestrian and bicycle safety area, updated in 2010 and available online, discusses the proportion of nighttime fatal crashes that involve pedestrians. Sixty-nine percent of those fatal crashes occur at night. Reduced visibility compared to daytime conditions is clearly a contributing factor in the high number of pedestrian fatalities. The issue of nighttime visibility is clear in the strategic plan for pedestrian and bicycle safety, which lists several FHWA products and topic areas that address pedestrian safety at night. Some of these resources include the Pedestrian Forum Newsletter, the website pedbikeinfo.org, and information for developers to create safe and accessible communities. Other areas of the strategic plan summarize research related to nighttime visibility, such as the effects of lighting on pedestrian crashes.

FHWA sponsored some work assessing crosswalk lighting. In general, based on the level of pedestrian conflict, more lighting is required in areas where pedestrian conflict is greater. Crosswalks are often co-located at intersections, so intersection lighting is often designed to encompass sufficient lighting for crosswalks and pedestrians. Midblock crosswalks can be lit but are at location on a roadways in areas where vehicles do not naturally stop and therefore have different visibility requirements. Pedestrians are more dependent on their own judgement to keep them safe. Since many pedestrians do not cross strictly at marked crosswalks, some consideration must be made to allow for these potential conflicts.

Recent and Ongoing Research

Pedestrian safety from a perspective of visibility focuses on the ability of drivers to see pedestrians and to properly respond to their crossing at an intersection or potentially anywhere in the roadway. In a recent study, a collaborative effort between VTTI and North Carolina State University studied the gaze behavior of drivers entering and exiting roundabouts. Because roundabouts are features that allow vehicles to pass through the intersection without stopping, the ability to see crossing pedestrians at the right time is critical to their safety. Information gathered from this study can inform where pedestrian crossings and bicycle pathways may be best implemented.[27]

New methods that help drivers identify crossing pedestrians include pedestrian hybrid beacons (PHBs) and rectangular rapid-flashing beacons (RRFBs). RRFBs and PHBs are user-activated devices that help notify drivers that pedestrians are crossing or are about to begin crossing. Research has shown that drivers are more likely to yield when these treatments are used.[28, 29] Recent research evaluated drivers yielding to pedestrians when these treatments are used to identify the conditions for which their use may be preferable.[30]

3. REVIEW OF FATAL CRASH DATA

The Fatality Analysis Reporting System (FARS) is a query-driven database where all vehicle crashes in the United States as recent as 2014 are provided for public access. Vehicle crash fatalities are able to be filtered by a number of different options depending on the thoroughness of crash reporting. The filtered options can then be univariate or cross-tabulated for comparing data. It is important to note that the traffic volume and roadway length are not provided in the FARS database and that full crash rates cannot be calculated or analyzed because the exposure factor cannot be assessed. It is also noteworthy that the FARS data only give information regarding light condition and do not consider visibility treatments associated with retroreflectivity.

These data were considered in the three areas of roadway departure, intersection, and pedestrian and bicycle safety. The data, however, are not consistent across the areas. These differences are summarized below. Additionally, other variables were considered in this analysis and are also listed below.

SAFETY DATA CONSIDERED

Roadway Departure

A crash is considered a roadway departure crash when a vehicle leaves the travel lane or lanes by either crossing the shoulder line or the center line of a roadway. It is important to note that the FARS database is not confident in the detailed reports of pedestrian and bicyclist data, including whether the pedestrian/bicyclist was on or adjacent to the roadway when struck, which would also inform roadway departure crashes.

Intersections

Intersections are areas of high conflict, and crashes at intersections can be attributed to a number of different causes. When considering pedestrians and bicyclists at intersections, similar to roadway departure crashes, the details for conflicts involving pedestrian and bicyclist crashes are not included in the FARS database.

Pedestrians/Bicyclists

There is a lack of data regarding conflicts with vehicles and pedestrian/bicyclist fatalities. The FARS database does have a disclaimer that inconsistencies were identified in the pedestrian and bicyclist data. Thus, while some of the data are used for this analysis and the absolute numbers of fatalities provided in the database are said to be accurate, further qualifiers such as motorist, pedestrian, and bicyclist position and maneuvers are not included.

Other Data Variables Considered

Light Condition

In an attempt to find gaps in the research surrounding lighting, the three light conditions made available in the FARS database were used for this research: daylight; dark, not lighted; and dark, lighted. The dark, not lighted and dark, lighted conditions both encompass nighttime driving scenarios; however, one includes artificial infrastructure lighting. Daylight is simply defined by when natural light is present and is not otherwise considered dawn or dusk. Dawn and dusk were not included in this research because it is believed that the reporting of these times of day are objective and apt to be misattributed.

Weather

Weather can impact several factors in a typical driving scenario, not limited to traction or visibility. The conditions predominantly considered were clear (as a baseline), rain, and fog/smog/smoke. Rain is an extremely common weather type and is encountered regularly by most drivers. Snow, sleet, and hail were not as focused in this effort due to the available crash statistics and the variance not accounted for. Snow can be on the roadway or be recently cleared and on the shoulder and still be considered a snowy condition. While snow, sleet, and hail do have an impact on lighting, it is believed to not be far from the effects of rain in general. Fog/smoke/smog are represented well in the FARS database, and these conditions have a very direct and noticeable impact on lighting.

Driver Age

Driver age is an important factor due to the levels of experience, cognitive factors, and visual ability. Younger drivers are perceived to be more risk taking and more inclined to speed, whereas older drivers are believed to have trouble navigating complex segments and intersections and react more slowly to weather or other traffic.

Speed

One of the variables believed to strongly impact all three focus areas is speeding. One-third of all fatalities are reported to be a result of speeding, so speed is seen as a significant threat to safety. Aside from lighting technology that can serve as delineators or overhead roadway smart lighting that can adapt to driver speed and perhaps encourage drivers to slow down, there are few applications in infrastructure design where lighting can serve to curb speeding behaviors. On the other hand, the use of retroreflective infrastructure such as markings, signing, and delineation has some potential to control speed. For instance, peripheral transverse markings have been shown to be a successful countermeasure to speed, particularly in advance of a horizontal curve.(31)

Rural and Urban

Not only do rural and urban roadways naturally distinguish themselves by the purposes they serve, the driver behavior on each may also be considered different. In general, rural roads are higher speed, are less populated, and consume longer stretches. Typically, urban roadways are lower speed, are more traveled, contain more pedestrians and bicyclists, abut varying types of intersections, and are more commonly lit by overhead roadway lighting.

ROADWAY DEPARTURE BREAKDOWNS

Roadway Departures by Rural and Urban by Weather

Clear conditions for 2014 account for nearly 7,000 fatalities on rural roadways and just over 4,500 for urban roadways. Shown in Figure 1, more crashes occur at night for both roadway types, with lighted areas consuming about half of all night crashes. Lighted areas are typically more complex areas or areas in which crashes are common or most likely. Due to this, results are somewhat skewed in their favor; however, data do not show that dark, unlighted areas may warrant lighting to curb the amount of crashes that take place. It is noteworthy that while there are some differences, most likely due to exposure (i.e., fewer rural roads have lighting) in general, the percentages of each of these lighting conditions are generally stable across all of the road types, and the percentages are also fairly evenly divided between the lighting conditions, even though there are typically much lower traffic volumes and exposure during the nighttime.

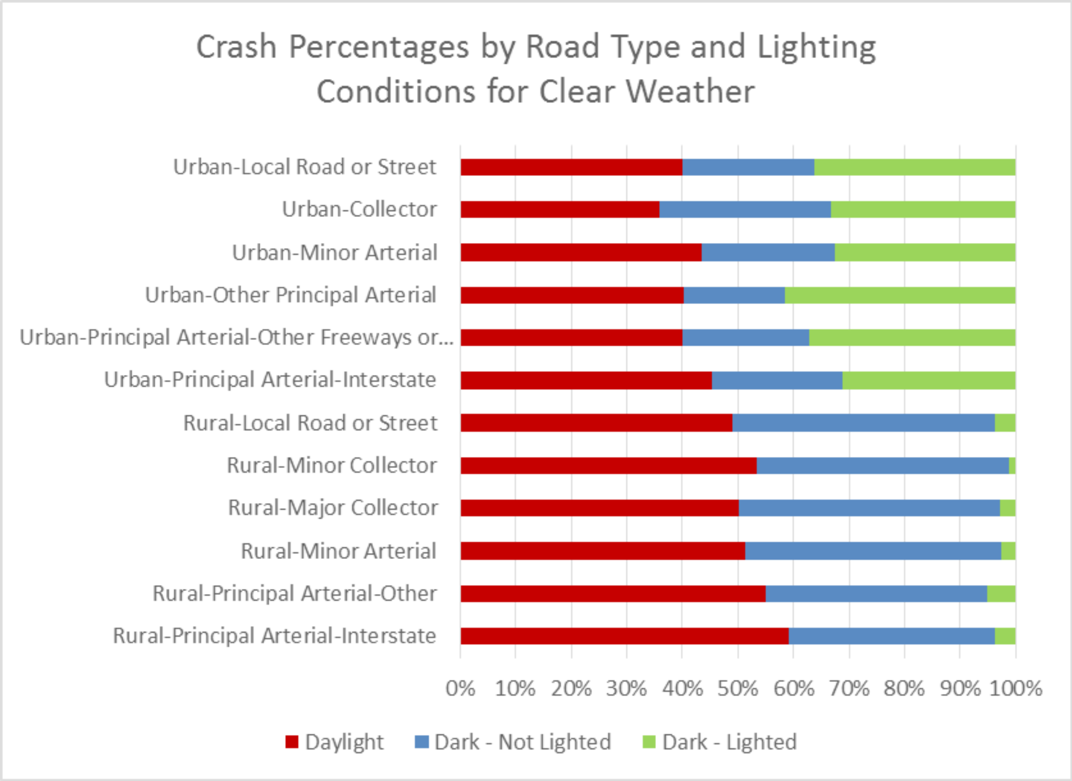

Figure 1. Crash percentages by road type and lighting conditions for clear weather. (FARS Database, 2014)

The rate of crashes in rain conditions is far less, with only 393 occurring on rural roadways and 270 on urban roadways (Figure 2). Despite the greater traffic on urban roadways, rural roadways account for more roadway departure fatalities for both clear and rainy conditions. This is likely due to the fact that less traffic allows drivers to increase their speed and higher speeds allow less opportunities for drivers to safely recover from a roadway departure, which tends to result in more severe crashes. Also, rural areas have much less access to timely emergency services, which increases the fatality rate. The other critical aspect is the change in the percentages for the dark, not lighted condition. While in clear conditions, the percentages were similar on many roadway types, the dark, not lighted condition has a higher percent contribution. This might indicate the importance of retroreflective performance and/or lighting in wet conditions in terms of roadway departure crashes.

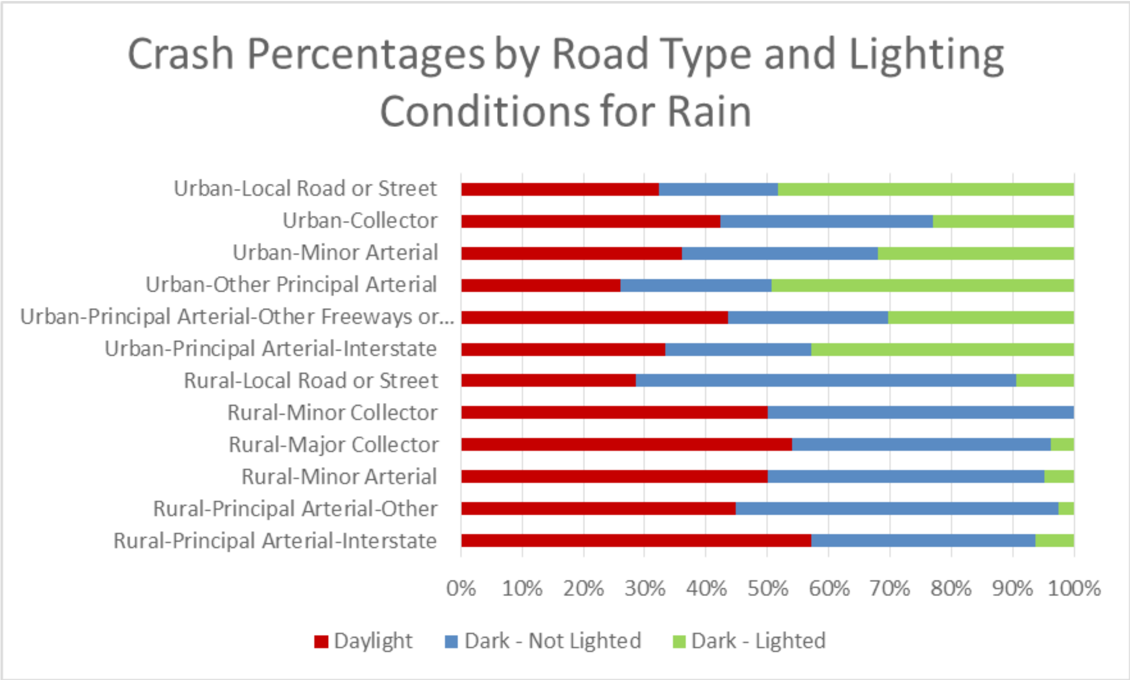

Figure 2. Crash percentages by road type and lighting conditions for rain. (FARS Database, 2014)

Weather Conditions and Roadway Departure

When conditions are clear or rainy, the rates of fatalities across lighting conditions are nearly identical. Figure 3 shows that larger differences exist during times of sleet, hail, snow, fog, and smoke. In general, sleet- or hail-related fatalities are very few, and only 13 total were reported in 2014 for rural and urban roadways combined. Snow-related fatalities occur more commonly in daylight or lit areas of urban roadways, again likely due to exposure. For rural areas, the link is more difficult to assess because snow presence/condition data are less available than they are for urban areas. Ideally, the snow presence/condition data would be more robust and include details on the difference between the presence of snow on a roadway and a scraped and salted roadway, which may not occur as often in some rural areas, and icy roadways as a result of all the above.

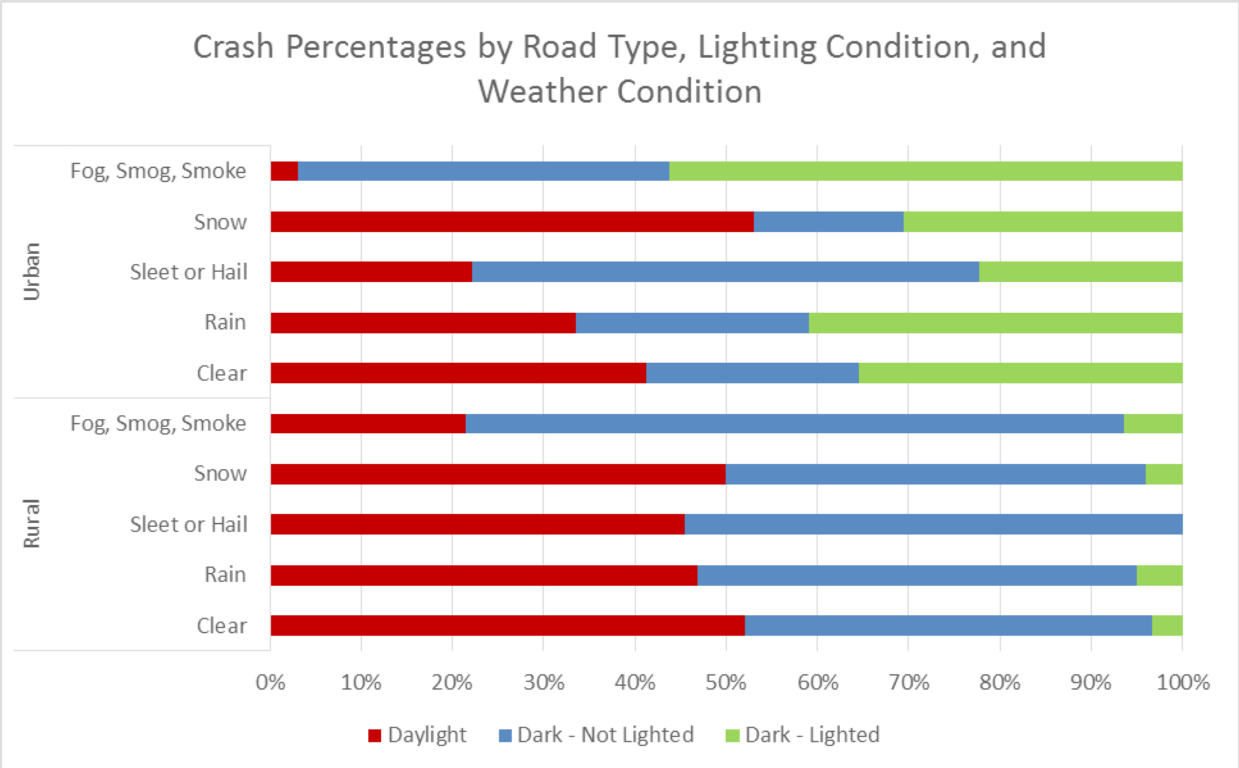

Figure 3. Crash percentages by road type, lighting condition, and weather condition. (FARS Database, 2014)

Age and Roadway Departure

Younger and middle-aged drivers perform similarly in clear and rainy conditions. Older drivers seem to have a higher daytime crash exposure than nighttime exposure. Again, older drivers tend to self-restrict their driving at night, so their exposure, particularly in the rain, is likely lower (Figure 4).

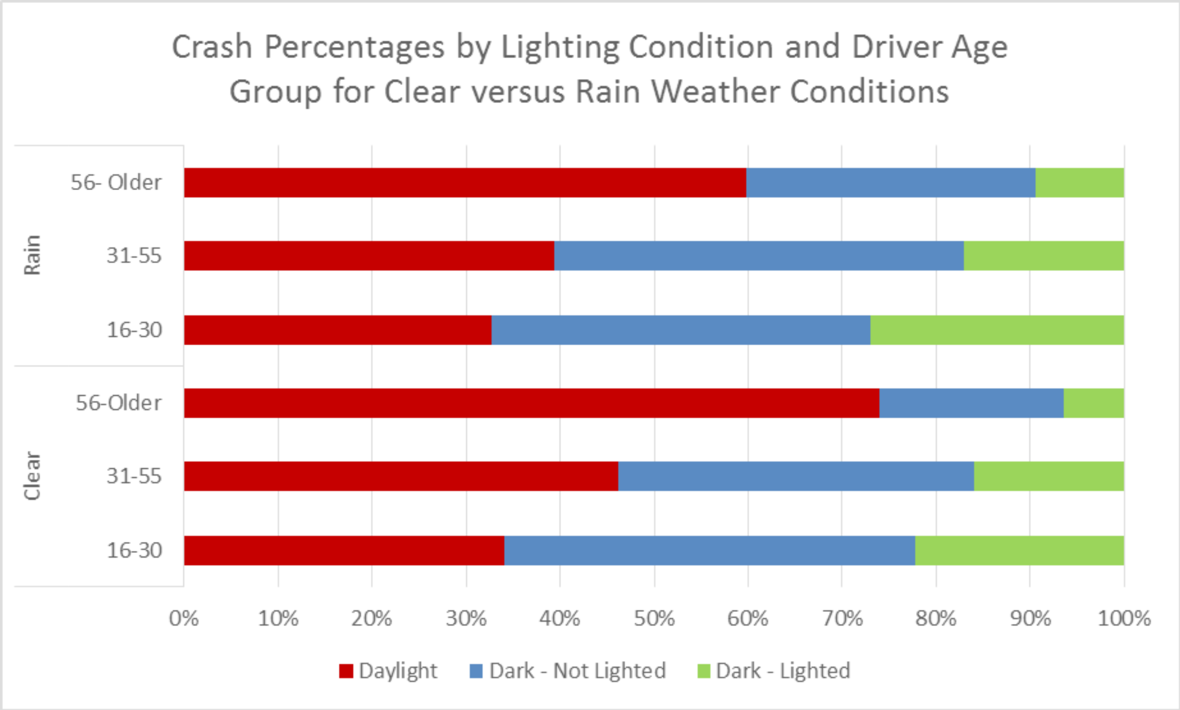

Figure 4. Crash percentages by lighting condition and age group for clear versus rain weather conditions. (FARS Database, 2014)

Roadway Departure as a Result of Speeding

Because roadway departures are often linked to speeding, it is no surprise that more speeding-related roadway departure fatalities occur at night due to the fact that drivers often out-drive their headlamps. In other words, headlamps span between 250 to 300 ft ahead of the car, and at higher speeds, the reaction time this span creates becomes smaller. The increased number of speed-related fatalities shown in Figure 5 for lighted areas is interesting because it is believed that there are many more unlighted roads and thus more opportunity for roadway departure crashes. However, as already mentioned, lighted roadways are often lighted because the proclivity for crashes is predicted to be higher in those locations.

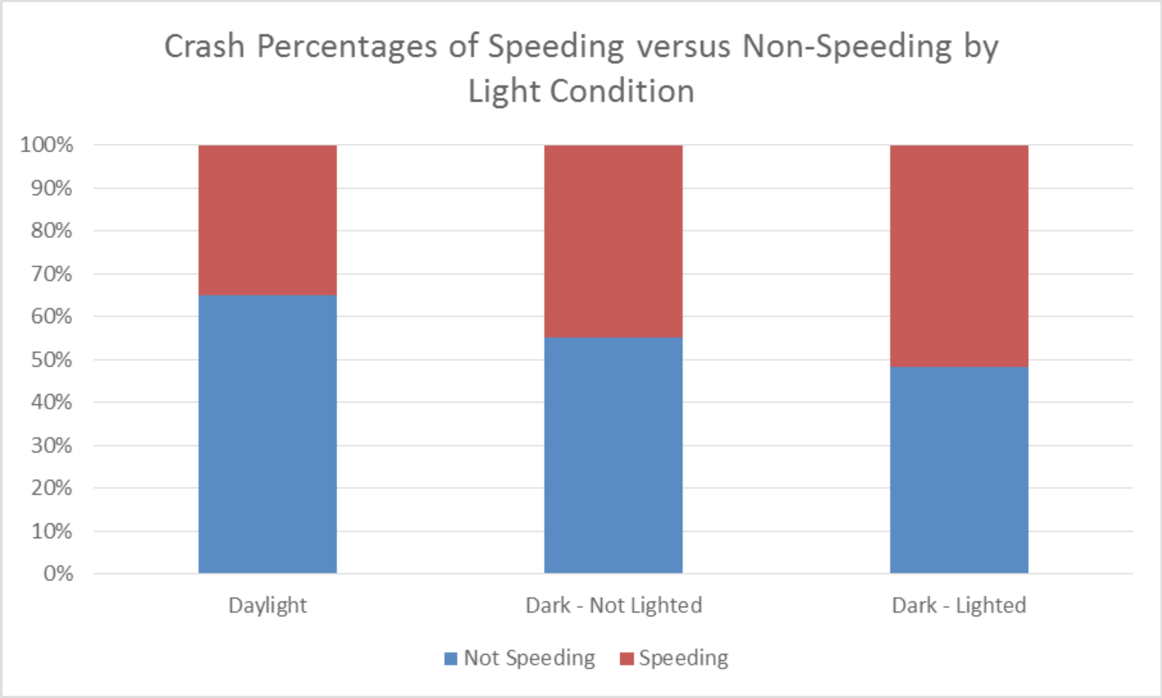

Figure 5. Crash percentages of speeding versus non-speeding by light condition. (FARS Database, 2014)

INTERSECTION BREAKDOWN

Intersection Fatalities by Light Conditions and Intersection Type

Figure 6 shows fatality crash totals for intersections. The percentages for intersections that are not four-way or T-intersections are perhaps too low for making statistical inferences, especially considering that roundabouts and five-point intersections are almost always lighted, so very few dark, not lighted fatalities will occur. The extent to which any of the intersections reflected in these data are lit is unknown. Despite some intersections being lighted already, there may be an opportunity to improve the lighting design. In many regards, the lighting of unique intersections, such as those with five or more points, may need to be considered case by case.

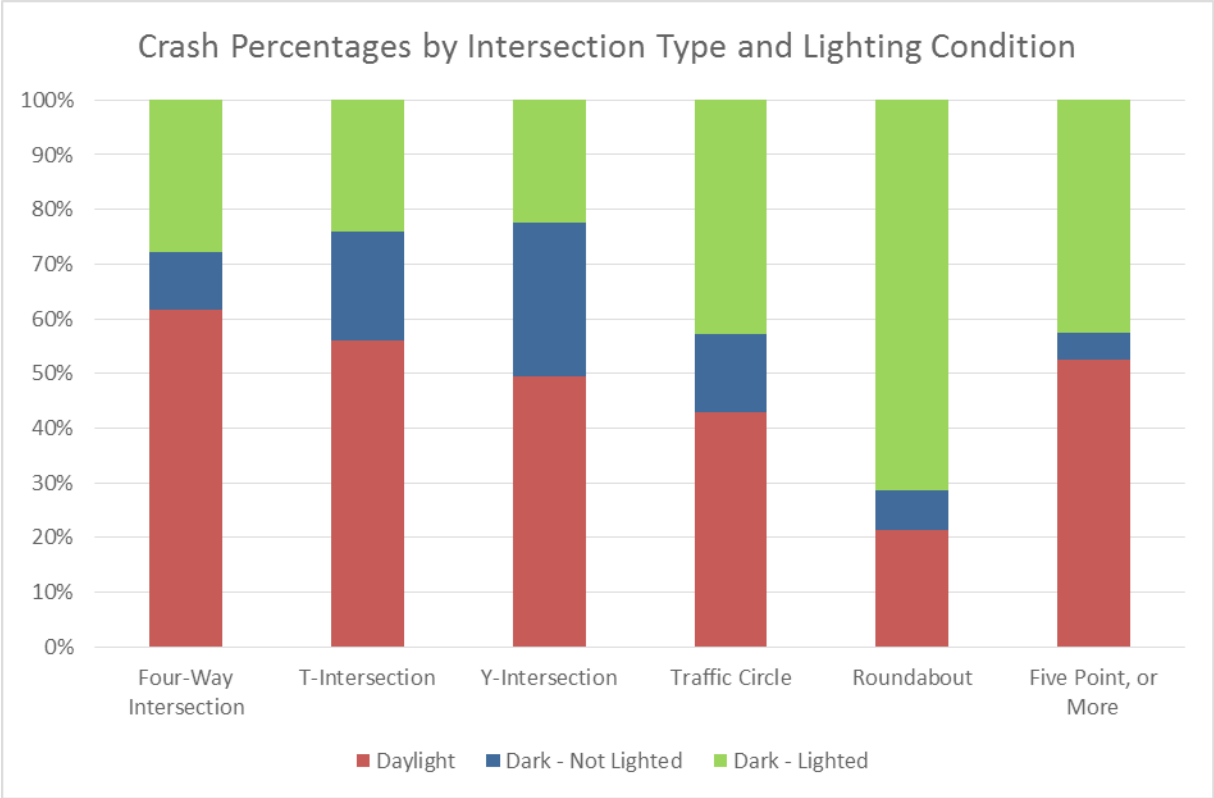

Figure 6. Crash percentages by intersection type and lighting condition. (FARS Database, 2014)

Fatalities at Four-Way Intersections by Age Group

Fatalities at four-way intersections are common among all age groups, with more older drivers being involved in fatal crashes during the daylight when they are likely more inclined to drive. Percentages in dark, unlit sections of road are consistent across all age groups, suggesting that unlit four-way intersections are less common and that age plays a small factor (Figure 7).

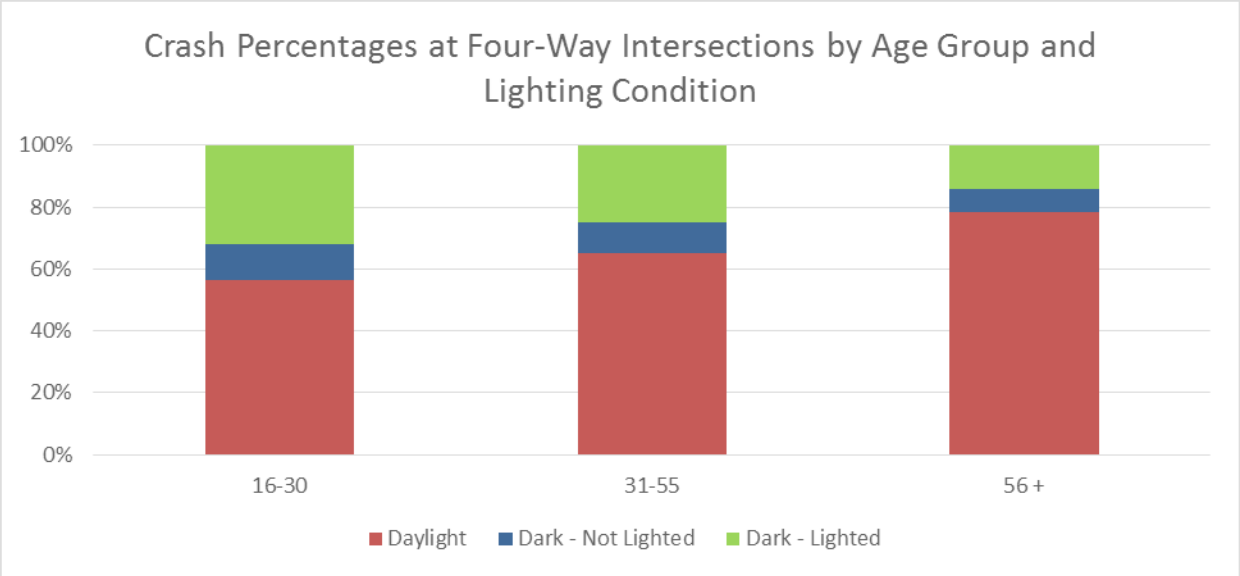

Figure 7. Crash percentages at four-way intersections by age group and lighting condition. (FARS Database, 2014)

Figure 8 and Table 1 demonstrate the differences in traffic control type by lighting condition. The influence of these data is largely dependent on design and exposure. If the number of pedestrians in an area warrants a pedestrian signal, then it is also likely going to be a lighted area. Areas without a pedestrian signal encounter fewer fatal crashes in general and also fewer at night. Intersections that are controlled only by stop signs or yield signs are not as typically lighted, resulting in a higher rate of dark and unlighted crashes. In general, the data indicate that dark but lighted intersections, which typically encounter more traffic and more pedestrians, may require a research effort to determine opportunities for improved safety.

It is important to note, in Table 1, several traffic control devices (flashing, warning, railroad, school, and unknown) and lighting conditions such as dusk and dawn are not included in these tallies.

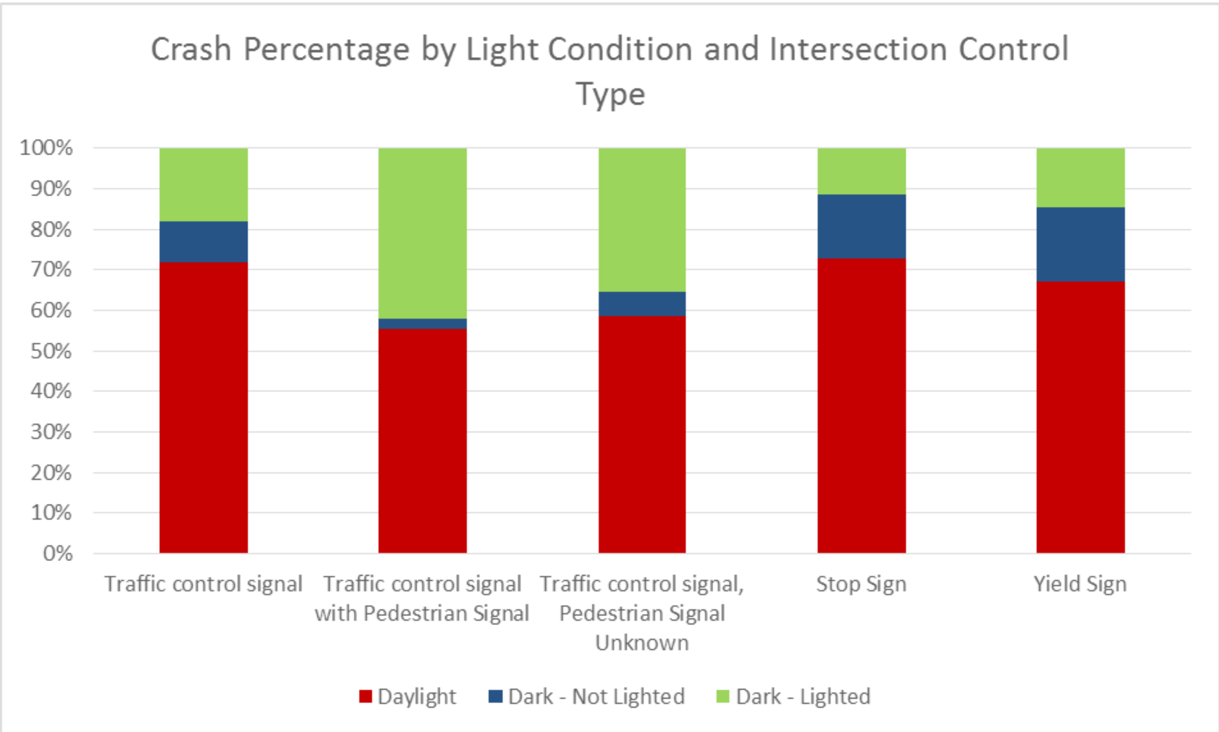

Figure 8. Crash percentage by lighting condition and intersection control type. (FARS Database, 2014)

Table 1. Total Fatal Crashes for Lighting Condition by Traffic Control Type.

Traffic Control Device	Daylight	Dark—Not Lighted	Dark—Lighted
Traffic control signal	275	39	70
Traffic control signal with pedestrian signal	446	20	344
Traffic control signal, pedestrian signal unknown	1,901	194	1,148
Stop sign	1,608	350	258
Yield sign	70	19	17
TOTAL	**4,300**	**622**	**1,837**

Fatalities by Intersection Type and Light Condition for Clear Conditions versus Rain

Figure 9 compares intersection type for weather conditions and shows an increase in the percentage of crashes at unlighted four-way intersections when rain is present. However, it is important to note that there are far fewer reported fatalities in rain conditions compared to clear conditions—5,002 fatalities compared to 372. The change in the percentage when lighting is added is interesting in that there appears to be a potential to reduce fatalities at intersections by adding lighting, in particular for T-intersections

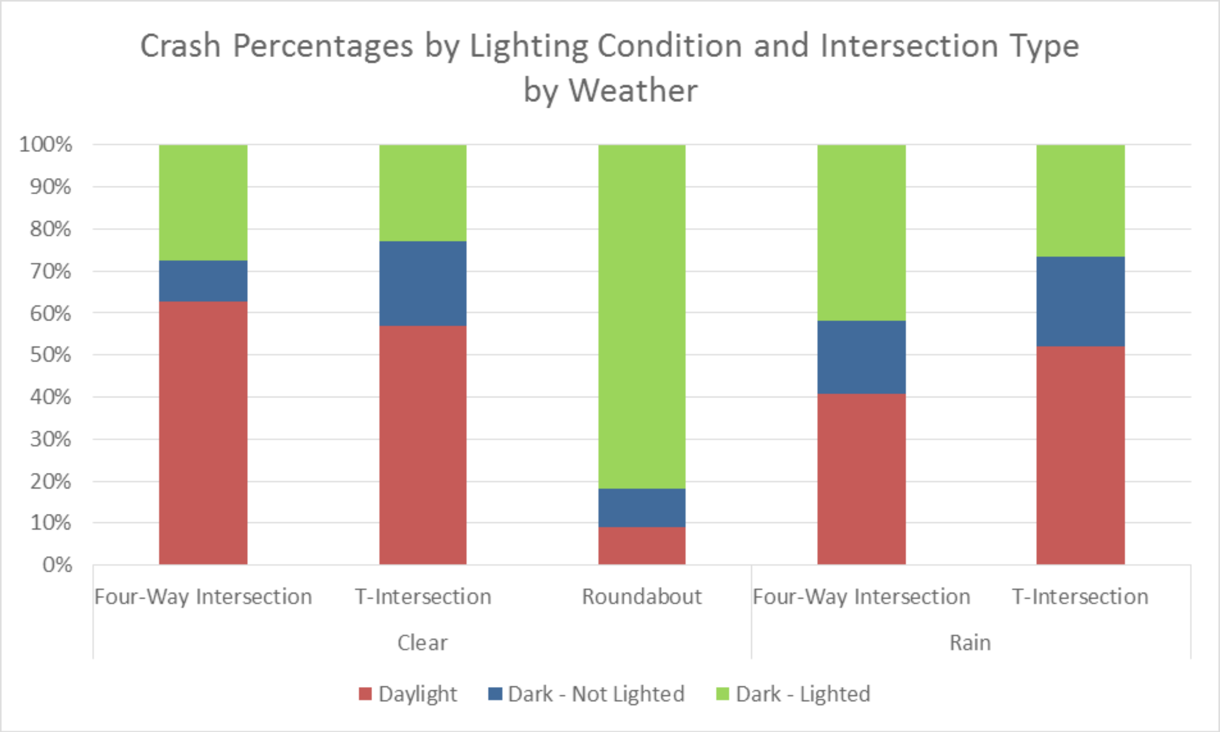

Figure 9. Crash percentages by lighting condition and intersection type by weather. (FARS Database, 2014)

PEDESTRIAN AND BICYCLIST SAFETY DATA

Pedestrian and Bicyclist Fatalities at Rural Intersection Types

Crash percentages (Figure 10) and total crashes (Figure 11) illustrate the major differences between main intersection types in rural zones. There are far fewer pedestrian- and bicyclist-related fatalities at intersections that are not either T-intersections or four-way intersections based solely on exposure since there is an overwhelmingly greater number of T- and four-way intersections. Interestingly, unlighted T-intersections are associated with more fatalities than other types for other lighting conditions, perhaps indicating a need for better understanding failure points at T-intersections and determining a need for lighting.

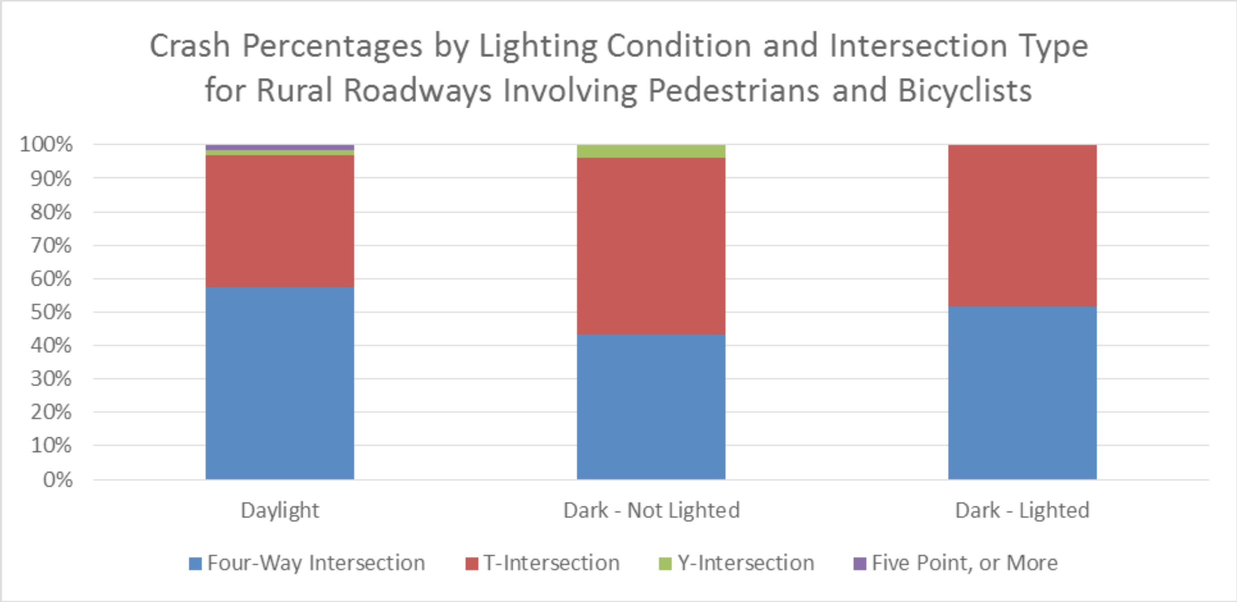

Figure 10. Crash percentages by lighting condition and intersection type for rural roadways involving pedestrians and bicyclists. (FARS Database, 2014)

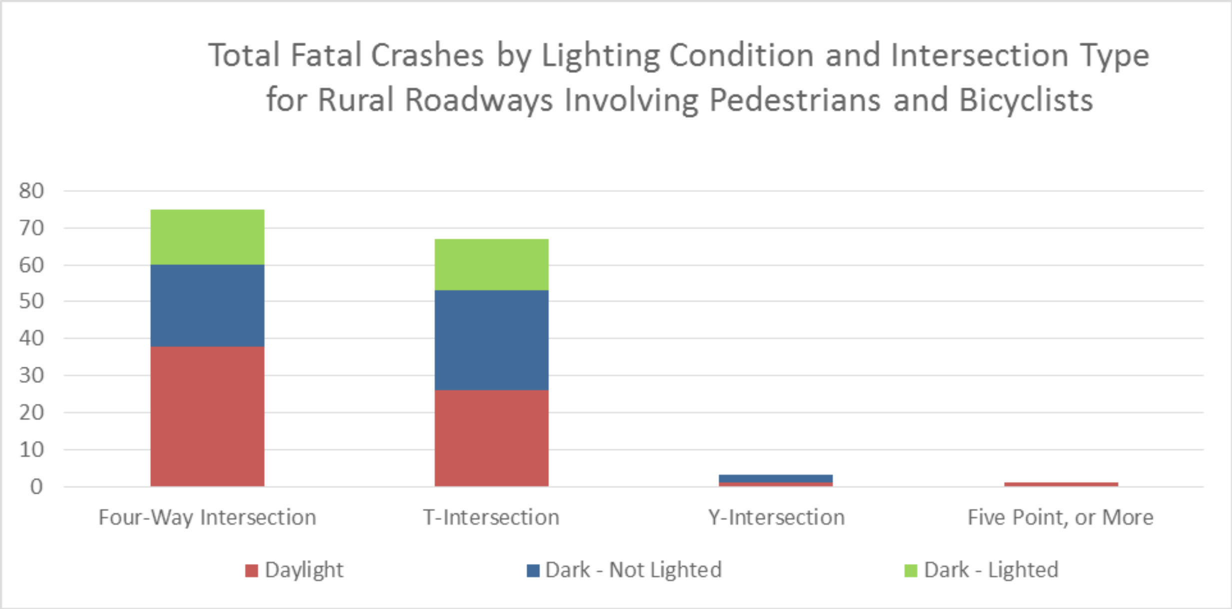

Figure 11. Total fatal crashes by lighting condition and intersection type for rural roadways involving pedestrians and bicyclists. (FARS Database, 2014)

Pedestrian and Bicyclist Fatalities at Urban Intersection Types

Crash percentages (Figure 12) and total crashes (Figure 13) illustrate the major differences between main intersection types in urban zones. The trends are similar to those of rural roadways; however, the sheer volume of incidents is much greater for urban areas, as is expected. Dark, lighted roadways encounter more fatal crashes involving pedestrians and bicyclists due to the common roadway design of having lighting placed in areas where pedestrian and bicycle traffic is typical.

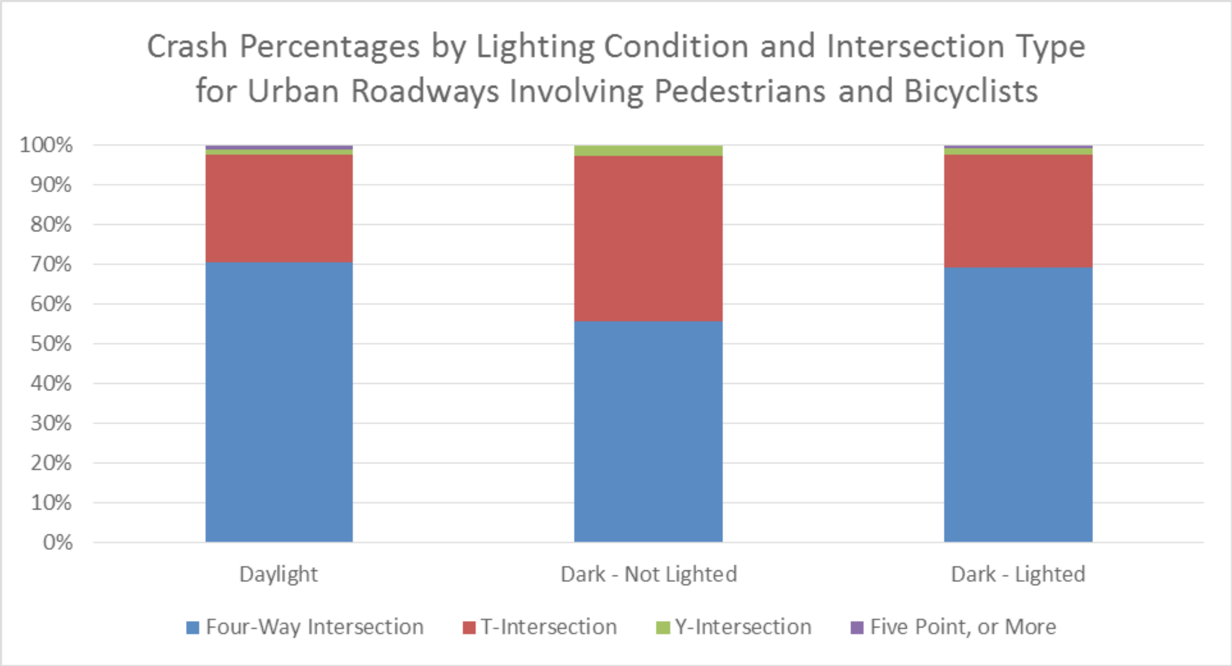

Figure 12. Crash percentages by lighting condition and intersection type for urban roadways involving pedestrians and bicyclists. (FARS Database, 2014)

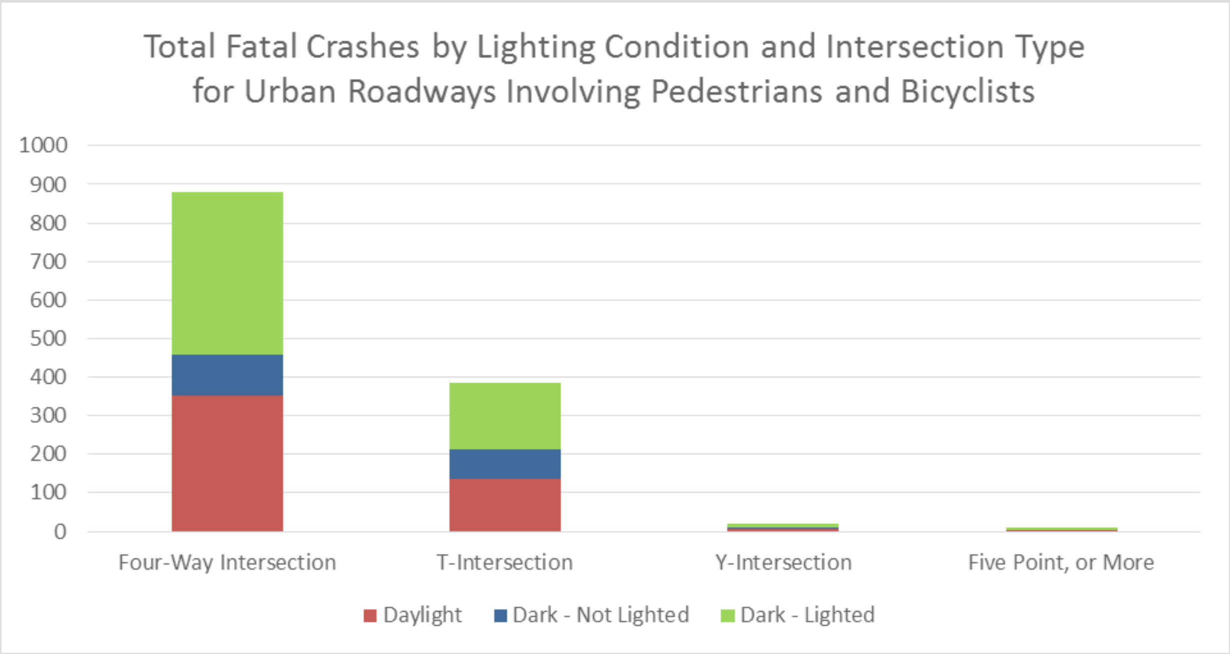

Figure 13. Total fatal crashes by lighting condition and intersection type for urban roadways involving pedestrians and bicyclists. (FARS Database, 2014)

SUMMARY OF FATALITY DATA REVIEW

While the FARS database provides a rich source of information for the potential causes and remedies for fatal crashes, the limitations in the data—in that the actual exposure cannot be calculated—confine the ability to perform a complete analysis of the impact of visibility treatments on fatalities.

There are some initial trends in terms of the impact of lighting that can be seen when considering the fatalities. In terms of roadway departures, there seems to be an impact of lighting in bad weather. Similarly, in terms of the intersections, there is the potential to reduce fatalities at T intersections with the addition of lighting. There may be many other trends in the data, but they are likely hidden by the crash exposure rate.

One of the primary findings in the data is that there is a significant need to perform a complete and proper analysis of visibility treatments in terms of safety that accounts for exposure, retroreflectivity, and all roadway geometry impacts.

4. BEST PRACTICES

In a review of current practices, some states and agencies emerged as leaders in the application of visibility treatments. A summary of the state practices for lighting is shown in Appendix B.

In terms of lighting, many states have moved significantly forward with the application of new lighting technology. Many states have developed a specification for solid state luminaires, including Virginia DOT, Illinois DOT, and Alaska DOT. These states have been sharing their results, and some similarity is being found in their specifications. This is an important step in the implementation of the new technology because LED luminaires are significantly different in their applicability to the roadway than are the traditional solutions.

From a city perspective, some municipalities are implementing adaptive lighting systems. These include the City of Cambridge, Massachusetts, and the City of San Jose, California. In both of these cities, lighting is dimmed based on the time of day. This practice has been implemented as both a cost-saving method and as an effort to reduce the negative impacts of lighting on the environment and roadway users.

Another implementation of a lighting control system is the use of the system to accurately provide a lighting level on the roadway regardless of the wattage and the power usage of the luminaire. Hawaii is using the same luminaire in all applications and then dimming to the appropriate lighting level. This approach significantly reduces inventory and maintenance costs while continuing to provide the recommended lighting levels.

Some cities, like the City of Los Angeles, are using the data-carrying capabilities of the lighting network to provide a backbone for connected-vehicle and smart-city applications.

Based on the assessment of the agencies, the best practices are (in order of technical complexity):

1. Development of a specification solid state lighting specific to the roadway types and needs of the lighting network.
2. Implementation of a control system where each luminaire is able to be managed from a central location.
3. Implementation of lighting only when and where it is needed through crash analysis and updated warrants.
4. Implementation of an adaptive lighting system based on the time of day.
5. Implementation of an adaptive lighting system based on road conditions, user needs, and connected vehicles.

While many agencies are working on some aspect of each of these approaches, no single agency has achieved the highest level of implementation.

5. CURRENT GAPS IN PRACTICE AND RESEARCH

As part of this study, researchers identified gaps in the current body of knowledge regarding the three areas of roadway departure, intersection, and pedestrian/bicycle safety. For each of these topics, an initial problem statement was developed and is presented in Appendix C.

ROADWAY DEPARTURE SAFETY

Placement of Roadway Lighting

Determining where lighting is most effective at reducing crashes could inform policy on roadway lighting design. Data made available in existing databases like SHRP2 can be a target of further research.

Geometric Considerations

Roadway departures occur on both tangents and curves. Determining the effectiveness of lighting a curve versus a tangent can be informative regarding how lighting can best be implemented. Current standards for curved roadways include instruction for pole placement to reduce the likelihood of a collision by an errant vehicle, but less research pertains to what areas of a curved roadway should be lighted to reduce departures.

Lighting and Inclement Weather

Adverse weather can reduce visibility of the roadway and pavement markings. The impact of lighting in adverse weather on many different road types and in combination with varying pavement markings and sign materials has yet to be fully explored. Policies rarely consider the diminished visibility caused by adverse weather conditions.

Determining When to Use Roadway Lighting

The use of roadway lighting is often determined by levels of annual average daily traffic in combination with areas of conflict, municipal regulations on lighting, economic viability, functional class, and zoning. Most traffic, however, occurs during the daytime. If roadway lighting is partially determined by traffic volumes, a count of nighttime traffic should be used as a decision threshold because it directly matches the traffic (vehicle miles traveled [VMT] for RwD, entering traffic for intersections, and pedestrians/bicyclists for that focus area) that would use the lighting. Another determining factor is public opinion on whether an area does or does not warrant lighting.

LED technology is slowly replacing HPS lighting conventionally used in most roadway lighting applications. LEDs can be controlled to output varying intensities and color, and achieve particular angles to satisfy ordinances. This adaptable aspect of an LED can foster more research in these specific areas that has not been possible with HPS and other light sources.

Vehicle Lighting

Headlamps are to have a minimum height of 22 inches, with a maximum of 54 inches. Taillamps are to be a minimum height of 15 inches, and no higher than 72 inches.[32] These measurements are to be made when there are no occupants or baggage in the vehicle. The additional weight would reduce the height of these lights. Guidelines for the design of vertical curvature and passing sections are based on stopping and passing sight distances that usually assume vehicle headlamps and taillamps are at a height of 24 inches.[7] With the allowable taillamp height lower than the assumption commonly used in design (and possibly even lower when the weight of passengers and baggage is accounted for), there are potential safety concerns related to stopping sight distances involving low vehicles on crest vertical curves.

It is understood that the characteristics of all vehicles cannot be accounted for in highway design, but there is a disconnect between the minimum specification for the heights of vehicle lamps and the values commonly used in design. Another issue related to headlamps and vertical curvature is the shadow zone that occurs beyond the crest of a vertical curve, where an object in the road may not be visible until it is within the direct line of an approaching vehicle's headlamps. The AASHTO Green Book suggests that with the assumed 24-inch height of headlamps, an object 16 inches above the roadway will be within the line of the headlamps at a distance equal to stopping sight distance.[7] This means drivers will typically see objects 16 inches above the pavement in time to stop. However, this may not be true for objects less than 16 inches high or if the headlamps are less than 24 inches high (which is currently permissible). Research that leads to coordination between the headlamp specifications and typical design assumptions is recommended.

The advent of LED headlamps has affected how drivers perceive and react to oncoming headlamps and glare. Research indicates that LED headlamp sources are better than halogen headlamps and comparable to high-intensity discharge headlamps in terms of photometric performance and visibility. The blue-white color produced by the headlamps does reportedly cause glare and discomfort to oncoming drivers.[33] Research into alternative LED colors and more precise beam patterns may mitigate the discomfort to other drivers and maintain photometric and visibility properties. Additionally, the colors produced by the different types of headlamps may have unique effects on sign visibility that are yet to be identified.

Vehicle headlamps are often overlooked when developing designs and policies for roadway lighting and signing. There are several positive safety effects of new headlamp technologies, such as adaptive headlamps that reduce glare for oncoming vehicles or turn in the direction of curves. However, these and other changes in headlamp illumination may have detrimental effects on visibility that should be considered in future research and policies. A new report by the Insurance Institute for Highway Safety (IIHS) demonstrates that most headlights need improvement.[34]

Standardized Police Reporting

The implementation of lighting is partially driven by crash data obtained from on-scene crash reporting. Currently, there are no known standards among law enforcement agencies for reporting the placement and contribution of lighting for crashes. An effort to collect data on how different agencies interpret and apply knowledge related to lighting for crashes could improve how crash data are reported and be a step toward standardizing the reporting process. Currently the Model Minimum Uniform Crash Criteria (MMUCC) includes a field *dark—lighted*.

Definition of Sight Distance

Sight distance is defined by AASHTO as the length of roadway visible to the driver. It can be categorized into horizontal and vertical sight distance: horizontal sight distance is limited by objects and the changing alignment in the horizontal plane, while vertical sight distance is limited by objects and the changing alignment in the vertical plane. Sight distance is generally not specified as being applicable to a certain time of day (daytime or nighttime). However, many of the assumptions used to calculate different sight distances (e.g., stopping sight distance, decision sight distance, passing sight distance) are based on values that may only be relevant for daytime conditions when daylight illuminates objects and the roadway environment.(7)

When discussing the topic of sight distance, the traditional design manuals have little mention of specific values or considerations for nighttime conditions. AASHTO guidelines for stopping sight distance (SSD), for example, are based on the provision of adequate sight distance at every location on a roadway such that drivers traveling at or near the design speed can see a stationary object in the road and stop before reaching it. The AASHTO assumptions for SSD use a driver eye height of 3.5 ft and an object height of 2 ft. (The 2-ft object height is one example where nighttime conditions are considered because most taillamps are 2 ft or higher from the ground. However, there is still a vulnerability from encounters with shorter objects or vehicles lower to the ground, as mentioned above.) There are no specifics to the shape, color, contrast, or reflection of the object, implying that this is a daytime design element. In general, decision sight distance uses the same basic models as SSD but with longer perception-reaction times, consequently neglecting the differences between day and night conditions.(7)

Pavement Marking Retroreflectivity

There is still some debate about the trade-off between pavement marking retroreflectivity levels and size of pavement markings (width). More research is needed to determine if wider longitudinal pavement markings (i.e., 6 inches) may provide more visibility to drivers and if that gain is enough to provide any relief to the proposed minimum retroreflectivity levels being pursued by FHWA. Also, there is a series of studies available in the last decade showing a consistently stronger link between pavement marking retroreflectivity and safety. However, there is not a general consensus on the relationship, and more work is needed to establish the link. Finally, since machine vision systems are becoming more common, there is a need to determine the pavement marking performance needs for machine drivers (compared to human drivers).

Research is also needed in the area of pavement markings specifically designed to maintain their retroreflective performance conditions under wet nighttime conditions. The crash data reviewed in this report indicate that roadway departure crashes under the category of the dark, not lighted condition were more prevalent in wet conditions compared to clear conditions. This finding seems to indicate the importance of retroreflective performance in wet conditions in terms of roadway departure crashes. However, more research is needed in this area to develop a better understanding of how increased wet nighttime retroreflectivity levels can mitigate roadway departure crashes.

Pavement Markings for Machine Vision

There has and continues to be a fast-paced advancement in vehicle technologies that provide driver assistance such as lane departure warning, lane keep assistance, and automated steering. The primary sensor used today for these systems is a camera mounted in the windshield. These systems are meant to keep vehicles on the road and in their lane. They rely on the ability to detect edge lines and lane lines. Research is currently underway to better understand the performance needs of pavement markings so that the machine vision systems can reliably perform their intended driver assist functions. NCHRP is sponsoring the research and the objective of the research is to develop information on the performance characteristics of pavement markings that affect the ability of machine vision systems to recognize them (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4004).

Traffic Sign Visibility

Recent research identifies conditions for which retroreflective traffic signs may be too bright.[35] While the MUTCD identifies minimum levels of maintained retroreflectivity, there are no guidelines specifying when the luminance from a sign causes glare that may be a safety hazard. The glare from signs reduces the distance at which drivers can see hazardous objects and also reduces response times.[36] The concern for glare from signs should extend to the use of digital signs as well. Digital signs can be loosely defined as LED-enhanced signs such as stop signs with flashing LEDs in the border, chevrons with flashing LEDs, or even full-color digital changeable message signs.

The MUTCD states that the brightness of changeable message signs should be adjusted under varying light conditions to maintain legibility, implying a concern that they need to be bright enough to be read during the daytime.[37] However, there is no mention of the issue that changeable message signs may be a source of glare at night. This concern should be especially noted for full-matrix LED signs capable of very high light output. While previous sign research emphasized the need for legibility, the improvements in sign materials and the increasing use of digital infrastructure open up the possibility that these signs are too bright for driver comfort and safety. Future research and applications should address these concerns.

Additionally, there is a need to identify stronger relationships between the retroreflectivity levels of traffic signs and roadway departure crashes. Research has shown some evidence that there appears to be a maximum level of retroreflectivity depending on specific conditions,[35] and FHWA has established minimum levels based on the needs of nighttime drivers in the MUTCD. However, there are no established correlations between retroreflectivity and crashes. In some ways, having recommended guidelines for appropriate sign sheeting selections based on the specific conditions (e.g., roadway, traffic, roadside) would be an alternative way to address this, but again, these would need to be developed.

Speed Limits

Most speed limits are set by legislative action or studies that determine the 85th percentile speed under free-flow conditions. When determined based on speed studies, most often the speed data are collected during the day, meaning that nighttime conditions are not accounted for in selecting speed limits. While separate speed limits are permitted at night, few agencies use nighttime speed limits, and there is no guidance provided in the MUTCD for establishing nighttime speed limits. In addition, there is the concern of over-driving headlamps at night. While no recent study has been completed on this topic, there is a growing concern that the new headlamp trends may be generating a need to take a fresh look at this somewhat controversial topic. On-going research may address this need (NCHRP 17-76, Guidance for Setting Speed Limits).

Horizontal Curve Design and Curve Advisory Speeds

The design of horizontal curves is based on comfortable lateral acceleration rates derived during daytime studies. At night, however, reduced visibility may affect a driver's threshold level of lateral acceleration where discomfort begins, thus affecting the comfortable curve advisory speed for the curve. While a separate advisory speed for night seems impractical, there may be implications related to safety if drivers are actually not comfortable adopting the advisory speed at night. In an exploratory analysis of unfamiliar driver data collected during both daytime and nighttime conditions, it was found that drivers on curves accept lower levels of lateral acceleration at night than during the day. However, contrasting the reduced lateral acceleration was a finding that driver speeds were higher at night (possibly from cutting curves with a wider path).(18) Further analysis of the implications of curve advisory speeds and nighttime driving could lead to improvements in how these advisory speeds are set and used.

INTERSECTION SAFETY

Lighting at Rural Intersections

Rural intersections vary in a number of ways, as do the policies and standards for lighting them. The factors involved in fatal crashes at many high-speed intersections in rural areas, whether signalized or not signalized, need to be explored to better inform policy for lighting.

Transient adaptation occurs when drivers travel to and from lit and unlit areas and may cause issues with vision for drivers as they pass through a lighted rural intersection. The general policy is to provide a tapering of lighting so that the transition between the two areas is gradual and comfortable. Exploring the limits of transient adaptation can better inform policies on rural intersection lighting as well as tunnel lighting.

As mentioned, another consideration for rural intersections are those of availability of electrical power, impact on flora and fauna as well as dark sky considerations. Reducing the light to a level that provides the safety benefits without over lighting is critical in these kinds of environments.

Using minimum lighting levels reduces the negative impacts of lighting, reduces consumption and provides the opportunity to investigate alternative power sources such as solar and wind generation. Determining this minimum level is another critical component of the required research.

Intersection Sight Distance and Gap Acceptance

A recent NCHRP project has identified the safety impacts of providing intersection sight distance (ISD), showing that fewer crashes occur as ISD increases.[38] Even though ISD is measured based on geometry, there may be issues related to nighttime visibility if the clear sight triangles needed for adequate ISD can be different during the night than during the day. Controls for ISD are based on principles of gap acceptance, which has been derived from daytime observations. A driver's gap acceptance is a function of perception-reaction time, the time (and distance) used to make an appropriate maneuver, the speed of the conflicting vehicles, and any buffer added for personal preference and safety. The duration of a gap that drivers select may vary with time of day. At night, this may be impacted more because visibility is limited and there is potential for misjudging the distance of a conflicting vehicle. It is possible that what may be an acceptable sight distance during the day may not be adequate at night. Future research may address how gap acceptance changes by time of day, whether there is a need to consider how nighttime gap acceptance may impact ISD and intersection safety, and whether or not intersection lighting would mitigate these effects.

Selecting Phasing for Left Turns

The second edition of the *Signal Timing Manual* (NCHRP Report 813) provides national guidance on the selection of left-turn phasing modes at signalized intersections. Practitioners select protected or permissive phasing based on criteria such as the number of left and through lanes, sight distance, turning volumes, speeds, and crash history.[39] There is no specific consideration for nighttime conditions. These guidelines can be improved by including special circumstances for nighttime conditions (for example, appropriate thresholds for nighttime crashes rather than total crashes only or turning volumes at night rather than peak-hour volumes). This is a classic example of where reviews of national policies is needed with a focus on nighttime considerations. Review teams would include a nighttime visibility expert along with a team of relevant subject matter experts. A review should also include more than just left phasing, for instance, right urn phasing, right turn on red, and protected/permission phasing.

Skewed Intersections: Visibility of Pedestrians or Bicycles at Night

Intersections with large skew angles are potential safety concerns at night for pedestrians and bicycles approaching the intersection from a conflicting direction. Because a vehicle's headlamps are directed forward, with only a small amount of illumination distributed away from the center, there may be conditions where drivers are unlikely to see pedestrians or bicycles from some directions, depending on the use of lighting. At night, the visual attention of drivers tends to be concentrated in a smaller area than during the day, meaning that drivers are additionally less likely to search for those approaching pedestrians and bicycles. This concern can be addressed by evaluating the illuminance patterns of headlamps and whether or not the light distributed horizontally at wide angles is enough for a driver to see pedestrians and bicycles.

Signal Warrants

Most of the warrants for determining whether a signal should be considered at an intersection focus on conditions experienced during the daytime. The heaviest traffic in most places tends to occur during morning and afternoon/evening peak hours, so it is reasonable that the listed warrants encourage the engineer to focus on those times of the day. However, special nighttime conditions may exist that warrant the use of a signal at an intersection. Examples may include reduced visibility or an unexpected peak in traffic due to a particular traffic generator. In fact, visibility appears to not be a concern in any signal warrant except indirectly as part of the crash warrant.

Alternative Interchanges and Intersections

Innovations in interchange and intersection design can promote large increases in efficiency, with some intersections (such as roundabouts) providing for the free flow of vehicles. Diverging diamond interchanges and displaced left-turn or continuous-flow intersections are recent concepts specifically designed to address conflicts with turning vehicles. The proper use of lighting and signage at these types of intersections is critical because they are very different from typical stop-controlled or signalized intersections. Pedestrian safety is also a critical component of determining the lighting and signage needs..

Traffic Signs

There is a need to establish recommendations for traffic sign retroreflectivity (materials) and possibly pavement markings. Depending on the type of environment and intersection control (rural versus urban, or stop sign versus signal), there could be justification for different performance levels. In fact, there are no national recommendations or guidelines that a practitioner can use to select the appropriate retroreflective product or performance level for a specific scenario. This is particularly needed for signing at intersections but it is also a general need that extends beyond intersections.

Automation and Controls

With the advent of solid state lighting, controlling where the lighting can be turned on and off as well as dimmed is becoming more important. This technology provides the opportunity to adjust lighting levels and to react to the presence of vehicles and pedestrians. The investigation of the possible options of this type of technology is general for all lighting in the roadway.

PEDESTRIAN AND BICYCLE SAFETY

Lighting for Pedestrians

Lighting is commonly designed for vehicles and not for pedestrians. Providing a standard of lighting that meets the criteria for both is a key interest. Lighting for pedestrians is believed to be more crucial in providing the greatest safety benefit at conflict points. Gap acceptances for pedestrians and the perception pedestrians have of how visible they are to drivers are research topics that have been explored in the past and can be re-explored with the advent of modern in-roadway lighting, crosswalk lighting, vehicle headlamps, and education.

Vertical illuminance is among the most important factors for determining the contrast and visibility for a crossing pedestrian. Methods for achieving the required vertical illuminance may need to be explored because current standards are often believed to be difficult to achieve. The amount of vertical illuminance required may vary depending on an array of variables including environmental lighting, intersection lighting, crosswalk size, and crosswalk geometry.

In-roadway lighting is becoming an important area of interest as more agencies adopt it as a method of promoting safety and reducing energy. In-roadway lighting at crosswalks is believed to be a benefit for drivers to visualize crosswalks ahead of time and for pedestrians to have a lit path. However, installations of in-roadway are difficult to maintain and can be very expensive. As a result, the effects of in-roadway lighting in combination with area signage, overhead lighting, and retroreflective markings need be explored along with a benefit and cost assessment to better inform policy.

Newer technology for modern roadway lighting has led to more precise output from luminaires. This results in less light spilling over to sidewalks since higher-quality optics provide adequate lighting for the roadway but not for pedestrians. Investigating the impact of newer technologies, such as the Nadir Dump and other luminaire types, may inform future roadway lighting design with sidewalks and crosswalks in mind.

Seasonal Fluctuations in Daylight Hours and Effects of Daylight Savings Time

The change in when daylight occurs because of the changing seasons and the adjustments that occur with the use of Daylight Savings Time (DST) mean that there are periods when road users may be accustomed to daylight but experience darkness. In some locations and during certain times of the year, peak traffic volumes may occur at night. With DST, the sudden change in whether or not a commute occurs during daylight has significant safety implications, especially on pedestrians and cyclists.[40] These road users are often poorly visible due to an absence of lighting. If agencies provide street lighting, it may be valuable to investigate how they address DST changes and gradual seasonal daylight changes, whether with automatic lighting or with timers. Consistency in when lighting is provided relative to ambient light is important, especially for these vulnerable road users.

Glare from Beacons, Signals, and Other Lights

Flashing beacons and lights used on signs at intersections, midblock crosswalks, and other locations have been shown to be effective at grabbing attention, but glare from these lights may have a detrimental effect on drivers' ability to see pedestrians and marked crosswalks, especially at night. Some text in the MUTCD instructs that automatic dimming for traffic signals should be used if a signal's indication is bright enough to cause glare.[37] There appear to be no specifications, however, for appropriate levels of illuminance for these lights at night. In addition to flashing beacons used for crosswalks, the concern regarding glare may be relevant for all sources of light, including all traffic signals (including PHBs), LEDs on signs, railroad gates, in-roadway lights, and lane use signals.

Assumptions for Pedestrian Walking Speed

The assumed pedestrian walking speed suggested in the MUTCD is conservatively set at 3.5 fps, with accommodation for slower walking speeds for special conditions.[37] It is likely that the research used to select the recommended pedestrian walking speed focused exclusively on daytime conditions, neglecting the behavior of pedestrians at night. Researchers in a recent study showed that the time of day may impact walking speeds, with pedestrians walking approximately 0.5 fps slower during the evening peak than during the morning peak.[41] That analysis, however, involved data collected only during those two time periods. Additionally, the data were collected in New York City (Manhattan), where the density of pedestrians tends to be high. Regardless, a different walking speed attributed to the time of day may justify examining the issue with more depth.

School Zones Marked with Word Markings

There are several instances in the MUTCD that specify that certain objects must have retroreflective properties.[37] There is currently no language specifying that the "SCHOOL" word marking informing drivers they are entering a school zone must be retroreflective. Although it is likely that the marking would be made of the same retroreflective material as the nearby line markings, there may be a question about whether the marking should be held to a standard of maintained retroreflectivity. If there are periods of the year during which school activities begin or end during dark or nighttime conditions, there may be justification to evaluate the brightness of the marking.

Bike Lanes

FHWA has approved the use of green pavements to delineate bike lanes. Generally, there is no nighttime visibility component to the green bike lanes (adding glass beads reduces the friction). There is a need to develop technologies and materials that can help provide nighttime visibility to bike lanes so that their paths are as easily identified during dark conditions as they are during daytime conditions.

OTHER AREAS WITH NIGHTTIME VISIBILITY CONCERNS

The following research concerns do not fit within the three target program areas, but the topics arose in the course of identifying gaps in current practices and research related to nighttime visibility. Several of these research areas are a result of budding and future technologies that promise ways to provide cheaper and more-efficient lighting through sensors and automation. The effect these technologies will have is unforeseen, and research into their impacts on safety is warranted.

Health Effects of Roadway Lighting

In a recent document, the American Medical Association (AMA) noted that the presence of the blue portion of the lighting spectrum in light sources has the potential to impact the health of humans living close to the light source.(42) AMA recommends that the light source be no greater than 3000K in color temperature. Studies have, however, shown that light sources with a 4100K color temperature perform at a higher level in terms of the visibility of objects in the roadway.(43) It is vital that these issues be considered.

Energy Consumption

Energy conservation has become a focus for many precincts and agencies. Removing lighting from infrastructure has become a popular method of conserving energy with some disregard to the impact of safety. Exploring methods of conserving energy in areas while maintaining safety should be a focus to inform policy and prevent uninformed decisions by infrastructure managers. Some known methods to efficient methods of lighting that allow for reduced energy consumption include the use of in-roadway lighting to highlight conflict points and prevent light trespass. Adaptive lighting technology is also a popular method of utilizing light only when it is necessary to do so.

The natural extension of this would be lighting on demand. LED lighting can be implemented with motion sensors or through connected-vehicle technologies to have lighting respond to the presence of a vehicle or pedestrian. Sample projects have been implemented in a controlled test road environment, but wider implementation will be developed in the future.

Automation

The anticipated adoption of connected and automated vehicles allows for innovative approaches to lighting. On one hand, vehicle automation may reduce the need to use lighting because so much of what the vehicles "see" will not be with light in the visible spectrum. On the other hand, there will still be other road users (such as pedestrians) that are just as deserving of safe and efficient transportation. The concept of smart cities with connected infrastructure opens up opportunities to apply lighting on demand and intelligently adapt to the users' needs.

Lighting Uniformity

Uniformity is regarded as a desired effect of roadway lighting, though some research disputes this claim. There is room to explore the limits of lighting uniformity and its interaction with in roadway lighting, retroreflectivity, pedestrian visibility, and lighting color. The day-to-night effect of uniformity is important since daylight is highly uniform and roadway lighting generally strives to replace daylight; however, differences in source location and mount height tend to affect the angle of intensity of lighting. This causes severe shadows. In addition to roadway lighting, uniformity in intersections where light sources from other vehicles and infrastructure exist should be investigated.

Bridges

The AASHTO Green Book calls into question the justification of cost for lighting rural bridges. Whether or not rural bridges attribute to a number of conflicts and collisions that can be rectified by the addition or subtraction of lighting or delineators should be explored.(7)

Interaction of Overhead Lighting

The effect roadway lighting has on fauna, foliage, and crops is an aspect of lighting that is rarely documented in policy. Exploring the factors that benefit or harm wildlife in regard to lighting can provide insight on better and safer implementations. Research on this topic can also seek to understand the effect of environmental lighting, which is currently based on consensus knowledge. Adaptive lighting takes environmental effects into account, but the extent has not been properly researched.

Curve Design Accounting for Nighttime Line of Sight

One of the controls for the design of horizontal curvature is the line of sight cutting across the inside of the curve, limited by an obstruction that is offset from the road. The equation for calculating whether or not there is sufficient sight distance for curves is based on an assumption that the obstruction is the only limiting factor and the object would otherwise be visible to the driver. At night, however, driver vision can be restricted to the pattern of light from headlamps, which is mostly concentrated in a direct line in front of the vehicle. driver at night may not be able to see an object in the road near the end of a curve since the headlamps are only directed straight ahead. The limited amount of headlamp illumination that is scattered horizontally needs to be considered to properly judge sight distance when designing horizontal curves. Potential research in this area should evaluate the distribution of light from headlamps and whether objects would be visible at the wide viewing angles that can occur with sharp curves.

REFERENCES

As stated previously, this report is a snapshot of some best management practices—currently under real-world deployment—within agencies around the nation; it is not intended to be a comprehensive guide to managing roadside trees and poles. There have been a number of other works written about tree and pole management strategies and additional research is being proposed within the industry. In addition to the *AASHTO Roadside Design Guide*, the two works described and cited below are recommended reading for additional information.

1. Hills, B.L. Vision, Visibility, and Perception in Driving. *Perception*, Vol. 9, 1980, pp. 183–216.
2. AASHTO. *Highway Safety Manual*. AASHTO, Washington, DC, 2010.
3. Allen, M.J., R.D. Hazlett, H.L. Tacker, and B.V. Graham. Actual Pedestrian Visibility and the Pedestrian's Estimate of His Own Visibility. *American Journal of Optometry & Archives*, Vol. 47, 1970.
4. Lutkevich, P., D. Mclean, and J. Cheung. *FHWA Lighting Handbook*. FHWA-SA-11-22. Federal Highway Administration, Washington, DC, 2012.
5. FHWA. Roadway Departure Safety. Available at http://safety.fhwa.dot.gov/roadway_dept/.
6. FHWA. FHWA Roadway Departure (RwD) Strategic Plan. Revised 2013. Available at http://safety.fhwa.dot.gov/roadway_dept/docs/rwd_strategic_plan_version2013.pdf.
7. AASHTO. *A Policy on Geometric Design of Highways and Streets* (Green Book). AASHTO, Washington, DC, 2004.
8. IESNA. *Roadway Lighting*. ANSI/IES RP-8-14. IESNA, New York, NY, 2014.
9. Carlson, P.J., E.S. Park, C. Andersen, B. Kuhn, A. Pike, J. Miles, R. Brydia, W. Ealding, and R.J. Porter. *Pavement Marking Demonstration Project: State of Alaska and State of Tennessee—Report to Congress*. FHWA-HRT-09-039. FHWA, Washington, DC, 2010.
10. Park, E.S., P.J. Carlson, R.J. Porter, and C.K. Anderson. Safety Effects of Wider Edge Lines on Rural, Two-Lane Highways. *Accident Analysis and Prevention*, Vol. 48, 2012, pp. 317–325.
11. Miles, J.D., P.J. Carlson, R. Eurek, J. Re, and E.S. Park. *Evaluation of Potential Benefits of Wider and Brighter Edge Line Pavement Markings*. FHWA/TX-10/0-5862-1. Texas Department of Transportation, Austin, TX, 2010.
12. Lyon, C., B. Persaud, and K. Eccles. *Safety Evaluation of Wet-Reflective Pavement Markings*. FHWA-HRT-15-065. FHWA, Washington, DC, 2015.
13. Donnell, E.T., and S. Sathyanarayanan. *Exploring the Statistical Association between Pavement Marking Retroreflectivity and Traffic Crash Frequency on Two- and Multilane Highways in North Carolina*. Pennsylvania State University, University Park, August 2007.
14. Smadi, O., N.R. Hawkins, R.R. Souleyrette, and D. Ormand. Analysis of Safety-Effectiveness of Pavement Marking Retroreflectivity. 2008 TRB Annual Meeting, Washington, DC, 2008.

15. Carlson, P.J., E.S. Park, and D.H. Kang. Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety. *Transportation Research Record*, No. 2337, Transportation Research Board, Washington, DC, 2013.
16. Avelar, R.E., and P.J. Carlson. Characterizing the Combined Association of Edge Line and Center Line Retroreflectivity to Nighttime Crashes on Michigan Two-Lane Rural Highways. *Transportation Research Record*, No. 2404, Transportation Research Board, Washington, DC, 2014.
17. Carlson, P.J., R.E. Avelar, E.S. Park, and D.H. Kang. Nighttime Safety and Pavement Marking Retroreflectivity on Two-Lane Highways: Revisited with North Carolina Data. Paper 15-5753, 2015 TRB Annual Meeting, 2015.
18. Carlson, P.J., B. Brimley, G. Hawkins, S. Himes, H. McGee., and F. Gross. *Traffic Control Device Guidelines for Curves*. Final Report, NCHRP Project 03-106, April 2015. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP03-106_FR.pdf.
19. Fitzpatrick, K., S. Chrysler, S. Sunkari, J. Cooper, B.J. Park, and L. Higgins. *Modern Traffic Control Devices to Improve Safety at Rural Intersections*. FHWA/TX-12/0-6462-1. Texas Department of Transportation, Austin, TX, 2011.
20. Sunkari, S.R. *Improvements to Rural Intersections to Improve Motorist Compliance.* FHWA/TX-14/9-1529-1. Texas Department of Transportation, Austin, TX, 2014.
21. Persaud, B., C. Lyon, K. Eccles, N. Lefler, and R. Amjadi. *Safety Evaluation of Increasing Retroreflectivity on STOP Signs*. FHWA-HRT-08-041. FHWA, Washington, DC, 2007.
22. Carlson, P.J., B. Brimley, J. Miles, S. Chrysler, R Gibbons, and T. Terry. *NCHRP Report 828: Guidelines for Nighttime Visibility of Overhead Signs*. Transportation Research Board, Washington, DC, 2016.
23. Edwards, C. *Lighting Levels for Isolated Intersections: Leading to Safety Improvements*. MnDOT 2015-05. Minnesota Department of Transportation, St. Paul, MN, 2015.
24. Obeidat, M.S., and M.J. Rys. Intersection Lighting Impacts on Nighttime Crashes Reduction and Safety Improvement. 2016 TRB Annual Meeting, Washington, DC, 2016.
25. Bhagavathula, R. *Effects of Intersection Lighting Design on Driver Visual Performance, Perceived Visibility, and Glare*. Dissertation, Virginia Polytechnic Institute, Blacksburg, VA, 2015.
26. National Highway Traffic Safety Administration. FARS Database Query Tool. Available at http://www-fars.nhtsa.dot.gov//QueryTool/QuerySection/SelectYear.aspx.
27. Findley, D., S. Searcy, K. Salamati, B. Schroeder, B. Williams, R. Bhagavathula, and L. Rodegerdts. *Accelerating Roundabout Implementation in the United States, Volume 7: Human Factor Assessment of Traffic Control Device Effectiveness*. FHWA-SA-15-075. FHWA, Washington, DC, 2015.
28. Fitzpatrick, K., R. Avelar, I. Potts, M. Brewer, J. Robertson, C. Fees, J. Hutton, L. Lucas, and K. Bauer. *Investigating Improvements to Pedestrian Crossings with an Emphasis on the Rectangular Rapid-Flashing Beacon*. FHWA-HRT-15-043. FHWA, Washington, DC, 2015.
29. Hunter, W.W., R. Srinivasan, and C.A. Martell. Evaluation of Rectangular Rapid Flash Beacon at Pinellas Trail Crossing in Saint Petersburg, Florida. *Transportation Research Record*, No. 2314, Transportation Research Board, Washington, DC, 2012, pp. 7–13.

30. Fitzpatrick, K., M.A. Brewer, and R. Avelar. *Driver Yielding at Traffic Control Signals, Pedestrian Hybrid Beacons, and Rectangular Rapid-Flashing Beacons in Texas*. Transportation Research Record, No. 2463, Transportation Research Board, Washington, DC, 2014, pp. 46–54.

31. Katz, B. *Peripheral Transverse Pavement Markings for Speed Control*. Dissertation, Virginia Polytechnic Institute, Blacksburg, VA, 2007.

32. Code of Federal Regulations (CFR) Title 49, Section 571.108. Federal Motor Vehicle Safety Standard 108. Available at https://www.gpo.gov/fdsys/pkg/CFR-2004-title49-vol5/xml/CFR-2004-title49-vol5-sec571-108.xml.

33. Kang, B., B. Yong, and K. Park. Performance Evaluations of LED Headlamps. *International Journal of Automotive Technology*, Vol. 11, No. 5, 2010, pp. 737–742.

34. Insurance Institute for Highway Safety Highway Loss Data Institute. In the Dark: New Ratings Show Most Headlights Need Improvement. Status Report, Vol. 51, No. 3, March 30, 2016. Available at http://www.iihs.org/iihs/sr/statusreport/article/51/3/1.

35. Carlson, P. Can Traffic Signs Be Too Bright on Low-Volume Roads? *Transportation Research Record, No. 2472, Transportation Research Board*, Washington, DC, 2015.

36. Oregon Department of Transportation (ODOT). *Stopping Sight Distance and Decision Sight Distance*. Discussion Paper No. 8A. ODOT, Salem, OR, 1997.

37. FHWA. *Manual on Uniform Traffic Control Devices*. FHWA, Washington, DC, 2009.

38. Himes, S., K. Eccles, K. Peach, C.M. Monsere, and T. Gates. Estimating the Safety Effects of Intersection Sight Distance at Unsignalized Intersections. 2016 TRB Annual Meeting, Washington, DC, 2016.

39. Urbanik, T. *NCHRP Report 813: Signal Timing Manual, Second Edition*. Transportation Research Board, Washington, DC, 2015.

40. Sullivan, J.M., and M.J. Flannagan. The Role of Ambient Light Levels in Fatal Crashes: Inferences from Daylight Saving Time Transitions. *Accident Analysis and Prevention*, Vol. 34, 2002, pp. 487–498.

41. Peters, D., L. Kim, R. Zaman, G. Haas, J. Cheng, and S. Ahmed. Pedestrian Crossing Behavior at Signalized Intersections in New York City. 2015 TRB Annual Meeting, Washington, DC, 2015.

42. American Medical Association. *Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting*. CSAPH Report 2-A-16. AMA, Chicago, IL, 2016.

43. North West Energy Alliance. *Seattle LED Adaptive Lighting Study*. North West Energy Alliance, Boulder, CO, 2014.

APPENDIX A. ROADWAY LIGHTING DETAILS

ASPECTS OF ROADWAY LIGHTING

As a tool for improving visibility, there are several effects agencies should consider when evaluating their policies related to lighting. Two principal concerns are glare and uniformity.

Glare

Glare is a haze within the eye that reduces visibility. When light is scattered in the eye, the phenomenon is referred to as veiling luminance. Veiling luminance can occur with bright oncoming headlamps, significantly reducing driver vision and leading to discomfort. Glare is either classified as discomfort glare or disability glare. Discomfort glare results in a sense of pain or annoyance. Disability glare inhibits vision.(1)

In addition to uniformity, AASHTO states that glare is also an indicator of quality. Uniformity and glare both depend on factors such as height and fixture type along with placement. Discomfort glare and impairment to drivers should be a priority of consideration. The comfort and security of pedestrians should also be considered when designing lighting for an intersection or crosswalk. Where only intersections are lighted, and not the approach to the intersection, the lighting should taper, with a gradual transition from dark to light.(2)

Uniformity

Uniformity is the ratio of the maximum measured light in an area (typically illuminance) to either the average or minimum measured light in an area. Uniformity of lighting is indicative of quality and should be considered along with illumination levels.(2) The AASHTO Green Book states that lighting should be both continuous and energy saving, which may appear to be at odds.(2)

Signage policies included in the MUTCD for lighting include the notion of uniformity, which must be maintained without a decrease in visibility, legibility, or driver comprehension during either day or night conditions.(3)

LIGHTING REQUIREMENTS

In general, the MUTCD offers specific and often technical guides for lighting. For example, most regulatory, warning, and guide signs must be retroreflective or illuminated to show the same shape and similar color by both day and night. Sign illumination requirements cannot be met using lighting exterior to the sign, like highway lighting or that of a nearby business.(3)

LED-Enhanced Signs

LEDs are a relatively new technology employed with signs. LEDs cannot be used in the background area of the sign, and even the size of the LEDs is prescribed by the MUTCD. According to the guide, LEDs should not have a diameter greater than ¼ inch. For LED color, the MUTCD prohibits colors outside of white or red to indicate stop or yield. Regulatory signs other than stop or yield must use white only; guide signs must also use white only. Warning signs and school area signs must use white or yellow. Temporary traffic control must use white, yellow, or orange. The MUTCD indicates that LED units for flashing devices (that enhance conspicuity) should flash simultaneously at more than 50 and less than 60 times per minute.(3)

Changeable Message Signs

Changeable message signs (CMSs) have been utilized increasingly on public roadways. The MUTCD instructs that on roadways with speed limits of 55 mi/h and greater, the sign should be visible from at least a half mile under both day and night conditions. The message on the sign should be legible from a minimum of 600 ft for nighttime and 800 ft for daytime conditions. If neither of those distance recommendations can be met, the MUTCD suggests using fewer words on the sign or incorporating familiar symbols. CMSs should automatically adjust their brightness under varying light conditions to maintain legibility, while the luminance should meet certain criteria for day and night conditions. Luminance contrast specifically should measure between 8 and 12 for all conditions. Contrasts on CMSs should always be positive.(3)

LIGHTING SELECTION

The FHWA Lighting Handbook offers a bulleted list of considerations when designing for lighting and selecting light. These considerations include photometric performance, durability, aesthetics, maintenance requirements, and operation costs. Specific luminaire requirements include ingress protection rating, lens material, housing, internal electrical components, and backlight, up-light, and glare (BUG) ratings.(1)

Luminaire Classification System

The Luminaire Classification System (LCS) was developed to help define luminaire distribution and efficiency. The LCS allows for the evaluation and comparison of outdoor luminaires. The primary areas for LCS are forward-light, backlight, and up-light zones. Each zone is then broken down further into solid angles within the area. The sum of percentages of lamp lumens within the three primary areas is equal to the photopic luminaire efficiency. This allows designers to find the best fit for their application.(1,4)

BUG Rating System

The BUG rating system existed prior to the LCS and is similar to it. Each category (backlight, up-light, and glare) consists of areas that surround the luminaire. Each region has an upper limit that must be met to obtain the rating. All criteria must be met for a luminaire to receive a B, U, or G rating.(1)

LIGHTING DESIGN

This section highlights general policy concerning light design in terms of height, placement, and utilization.

Layouts and Spacing

Lighting pole layouts typically follow one of four formats: one-sided lighting, opposite lighting, staggered lighting, and median lighting. In a one-sided layout, all of the luminaires are on one side of the road. In an opposite lighting layout, the lighting is on direct opposite sides of the roadway. The staggered layout is like the opposite layout except the luminaires are offset from each other and do not directly face each other. Median lighting requires a divided roadway where the luminaires are placed in a single row along the median.(1)

High Mast

In addition to typical luminaire pole spacing, the FHWA Lighting Handbook also details spacing designs for high mast poles that are typically found at freeway interchanges. These designs are more intricate and involve the consideration of a number of factors, including the height, number of luminaires for each pole, optics and orientation, wattage, source, and photometrics.(1)

High mast installations are generally regarded as being more visually comfortable. The height of the light source keeps it out of the typical viewing angle of drivers, but the amount of light provides illumination around a large corridor. Because more luminaires are attached to a single pole, there are fewer poles in the area, thus reducing the probability of one being struck in a roadway departure.(4)

Adaptive Lighting

Adaptive lighting was born from the idea of reducing power consumption by controlling light levels in off-peak hours. It is believed that a significant amount of power can be saved by varying the levels of lighting when traffic volumes change,(1) resulting in an energy savings of up to 50 percent. Light levels are originally established by applying criteria based on the road type, conflict levels, pedestrian levels, and traffic volume. The current design practice is to design based on the highest pedestrian conflict level for an area and to establish minimum lighting levels based around that. Once that minimum is established, lighting systems provide that level of lighting throughout all hours of darkness. While traffic levels and pedestrian levels taper at later hours, lights have traditionally provided the same output.(1)

It is not recommended to reduce lighting levels or implement adaptive lighting near signalized intersections, midblock crosswalks, roundabouts, rail crossings, or the canopy area of toll plazas. (1,4) Before designing for adaptive lighting, it is recommended that the Illuminating Engineering Society of North America's (IESNA's) RP-8 be reviewed.(1) The recommendations of the RP-8-14 suggest adjusting the fluctuation of adaptive lighting based on the existing classifications for pedestrian conflict. A major roadway with high pedestrian conflict would require 1.2 cd/m¬2, but when pedestrian numbers drop in later hours to a low classification, the lighting can be allowed to reduce to 0.6 cd/m2.(4)

COMMON PRACTICES FOR LIGHTING ROADWAYS

Street and Freeway Lighting

The AASHTO Green Book provides some separate policies on lighting streets, highways, and freeways in both urban and rural areas. The functional classification of the roadway typically factors into the decision to light it. Other factors include pedestrian and cyclist presence; night-to-day crash ratios; geometry of the roadway; and number of lanes, curves, and intersections.[2]

Streets and roadways often have roadside infrastructure not pertinent to the roadway, such as power poles. Even light poles that are necessary for hoisting the luminaires that light the roadway must be carefully placed to minimize a potential hazard.[1,2] For the varying street classifications in the RP-8-14 roadway lighting guide, specifications for average luminance and uniformity as well as maximum uniformity and glare are detailed. Further specifications exist for each classification by the level of pedestrian conflict—either high, medium, or low. In general, the lower the classification of street, the less average luminance and uniformity prescribed.[4]

Freeways do not contain pedestrians or roadside entrances, so many conflict points typically found on streets and roadways are not found along freeways. However, freeways have higher speed limits and merging lanes. The RP-8-14 details the lighting design criteria for roadways. There are different specifications for average luminance, average uniformity ratio, maximum uniformity ratio, and glare depending on roadway class.[4]

Interchange Lighting

Fixed-source lighting is essential at interchanges so that drivers can clearly discern the roadway ahead, the possible paths to be followed, and all other vehicles in enough time to make correct decisions. The AASHTO Green Book states that an unlit interchange decreases its usefulness because cars would inherently slow down as drivers approach with less certainty. It is important that retroreflective devices are also used so that drivers can make out grade separators such as curbs, piers, and abutments. In general, lighting becomes more useful as traffic volume increases.[2]

Arterials

Lighting on arterials is assumed to reduce sudden braking and swerving. The policy mentions that older drivers specifically benefit from well-lit arterials, which perhaps welcomes the idea of lighting based on area demographics. An excerpt from the AASHTO Green Book claims, "A safely designed, adequate lighting system is more important to optimum operation of an urban arterial than for any other type of city street."[2]

Other Lighted Infrastructure Types

Miscellaneous roadway segments such as railroad crossings, tunnels, toll plazas, overpasses and underpasses, and bridges have less mention in the AASHTO guidance.

For railroad crossings, the AASHTO guidance mentions the use of floodlighting or highway lighting, with little other documentation[2]; however, RP-8-14 recommends lighting the conflict area 30 m before and after the crossing as well as providing auxiliary lighting to highlight the sides of the passing train cars.[4]

Railroad-highway grade crossings consist of either passive or active preemptive warnings for drivers. Passive signals include signing and pavement markings, whereas active signals include flashing beacons, gates, and bells. There is no quantitative information about the crash effects of illumination at railroad crossings.(5)

The AASHTO guidance brings to question the justification of cost for lighting rural bridges.(2)

Toll plazas have four distinct areas according to IESNA: approach/departure zones, queuing areas, toll collection islands, and infield.(4) There are also two recognized types of toll plaza types: in-line and off-line. In-line plazas require all vehicles to stop or slow down and pay a toll before continuing. Off-line plazas only require vehicles to stop and pay when they want to enter or exit a road. The lighting principles for each are similar, though the key difference is that the in-line plaza does not contain any ramps leading to or away from it. The RP-8-14 details specifics in terms of illumination for each of the four zones and two types of toll plazas, including luminaire placement, glare requirements, illumination level, and controls.

For underpasses and overpasses, the consideration for day and nighttime needs must be assessed. Nighttime underpass lighting should follow the same requirements as roadway lighting for that section. Daytime lighting must follow requirements suggested by American National Standards Institute (ANSI) RP-22-11, which provides recommendations on tunnel lighting.(4)

Tunnel lighting is dependent on grade and length and how much natural light can enter the portal. Lighting expenses are typically greater near portals since special consideration must be given so that drivers do not endure optical shock from traveling between natural and artificial lighting. The finish to the walls must also be given special consideration so that the surfaces increase reflectivity to enhance brightness and uniformity. Road design should avoid the need for guide signs inside tunnels.

Road Geometry

Steep grades and curves cause a visual problem for drivers and often require more lighting. The steeper the grade or sharper the curve is, the closer the luminaires should be spaced. Careful orientation of luminaires in these scenarios is required to maximize uniformity.(4)

Intersection Lighting

Intersections often have a concentration of pedestrians and roadside interference. Fixed-source lighting in these areas tends to reduce crashes. Rural intersections require more justification in terms of traffic volume, planned geometrics, and peak-time congestion.(2,3) For the benefit of non-local highway users, the lighting of a rural intersection is desirable to aid the driver in ascertaining sign messages during non-daylight hours.

In general, the warrant for lighting an intersection must provide evidence of excessive delay, congestion, unfavorable approach conditions, or surrounding conditions that cause driver confusion.(3) The FHWA Lighting Handbook details a point scale developed by the Transportation Association of Canada that assists engineers and planners in deciding if an intersection warrants lighting and how much to provide. The scale uses a point system to decide whether to fully light, partially light, only light certain areas, or not use any lighting at the intersection. There are other warranting systems in existence, many of which simply rely on traffic volume as a determinant.(1)

Rural at-grade intersections are lit depending on the layout and traffic volumes. Intersections without channelization, or multi-roads and turning lanes, are often left unlighted. However, broad-scale, multi-road intersections are often lighted in rural areas. Sharper curves, limited ability of headlamps for wide turning radii, and presence of pedestrians often justify fixed lighting. The fixed lighting can also serve as an indication for drivers to adjust their speed on approach.(2)

IESNA details six types of intersections based on the convergence of three different road types: major, collector, and local. In general, the functional classification of the intersections ranked busiest to least busy in terms of traffic and pedestrian conflict are lit accordingly, with more light being required for major-to-major intersections and less lighting being required for local-to-local intersections. The need for uniformity also lessens with lower functional classifications.(4)

Roundabouts

The two main purposes for lighting roundabouts are the same as those for lighting an intersection: provide visibility from afar for users of the roundabout and provide visibility in key conflict areas to improve navigation. In general, the illumination should be designed to create a break in the continuous path of the roadway and emphasize the circular aspect of the roundabout.(4, 6)

Like intersections, the overall illumination of the roundabout should be approximately equal to the sum of the illumination levels of intersecting roadways. If continuous roadway lighting leading up to the roundabout is not present, transition lighting should be provided for the driver to taper in and out of the lighted section of the roundabout. In general, adequate illumination needs to be provided on the approach, at all conflict areas where traffic is entering the stream of cars in the roundabout, and at all places where cars break away to exit the roundabout.(6)

Illumination of a roundabout is beneficial when one or more approaches are illuminated and heavy traffic including pedestrians and cyclists is anticipated. Unlike intersections, it is encouraged that all roundabouts, independent of traffic volume, be illuminated.(6)

Crosswalks and Pedestrians

There are three classifications for pedestrian conflict, each dependent upon the type of abutting land use. High conflict areas expect pedestrians to be on sidewalks or crossings during hours of darkness. Areas near theaters and stadiums are examples where pedestrian conflict can be high. Where pedestrians are expected to be fewer at night but are still a factor during the day are considered medium conflict areas. Areas and blocks adjacent to office buildings, industrial parks, and libraries fit the description. Low areas have few pedestrians during night or day and may be in residential areas or rural zones.(4)

Crosswalks are often collocated at intersections but may be considered more dangerous at midblock locations. At an intersection crosswalk, it is important to light the crosswalk to stand out from the intersection in the background. Midblock crosswalks do not always have surrounding light sources, so lights may need to be placed specifically at certain points in the midblock in order to provide sufficient illumination to the crosswalk and pedestrians.(7)

An FHWA publication regarding the design for crosswalk lighting concluded that a vertical illuminance level of 20 lx measured at 5 ft from the road service allowed drivers to detect pedestrians more easily at midblock crossings. A high level of vertical illuminance such as this may be required for crosswalks when there is a possibility of continuous glare from opposing vehicles, the crosswalk is located in an area of high ambient light levels, or the crosswalk is located in a lighted intersection.(7)

Lighting designed specifically for pedestrians is often lower to the ground. A pole height of 3 to 6 m (10 to 25 ft) is more common for pedestrian-heavy zones than are typical roadway lighting systems, which are mounted often twice that high.(4)

In addition to lighting, other safety measures include automated pedestrian detectors that allow for adjusting the countdown timer on a crosswalk to the speed and volume of pedestrians crossing. This implementation appears to reduce pedestrian-vehicle conflicts as well as reduce the number of pedestrians who choose to cross during the "Don't Walk" phase.(5)

REFERENCES

1. Lutkevich, P., D. Mclean, and J. Cheung. *FHWA Lighting Handbook*. FHWA-SA-11-22. Federal Highway Administration, Washington, DC, 2012.
2. AASHTO. *A Policy on Geometric Design of Highways and Streets* (Green Book). AASHTO, Washington, DC, 2004.
3. FHWA. *Manual on Uniform Traffic Control Devices*. FHWA, Washington, DC, 2009.
4. IESNA. *Roadway Lighting*. ANSI/IES RP-8-14. IESNA, New York, NY, 2014.
5. AASHTO. *Highway Safety Manual*. AASHTO, Washington, DC, 2010.
6. Rodegerdts, L., et al. *NCHRP Report 672: Roundabouts: An Informational Guide—Second Edition*. Transportation Research Board, Washington, DC, 2010.
7. Gibbons, R., C. Edwards, and B. Williams. *FHWA Informational Report on Lighting Design for Midblock Crosswalks*. FHWA, Washington, DC, 2008.

APPENDIX B. STATE PRACTICES

Below is a table of referenced sources on the standards and policies for each state. The information here consists of what was made available on the Internet through sources such as the MUTCD and state DOT websites. Hyperlinks to relevant sources are provided.

Table 2. Referenced Sources for Standards and Policies for Each State.

Source	MUTCD	State-Supplemented MUTCD	State MUTCD	RP-8	FHWA *Lighting Handbook*	*Highway Safety Manual*	AASHTO Green Book	AASHTO Roadway Lighting Design Guide
Alabama		X					X	X
Alaska		X						
Arizona		X						
Arkansas	X							
California			X					
Colorado		X		X				
Connecticut	X							
Delaware			X				X	X
Florida	X							X
Georgia	X			X	X	X		X
Hawaii	X						X	
Idaho		X						
Illinois		X		X	X		X	X
Indiana			X	X	X		X	X
Iowa		X		X	X			
Kansas	X							
Kentucky	X						X	X
Louisiana	X						X	
Maine	X						X	
Maryland			X	X			X	
Massachusetts		X		X				
Michigan		X					X	
Minnesota			X		X			X
Mississippi	X				X			X
Missouri			X				X	
Montana	X			X	X		X	X
Nebraska		X					X	
Nevada		X		X			X	

Source	MUTCD	State-Supplemented MUTCD	State MUTCD	RP-8	FHWA *Lighting Handbook*	*Highway Safety Manual*	AASHTO Green Book	AASHTO Roadway Lighting Design Guide
New Hampshire	X			X			X	X
New Jersey	X			X	X		X	
New Mexico	X						X	
New York		X			X		X	X
North Carolina		X					X	
North Dakota		X						X
Ohio			X	X			X	
Oklahoma		X						
Oregon		X		X			X	X
Pennsylvania		X					X	X
Rhode Island	X						X	
South Carolina		X					X	X
South Dakota	X						X	
Tennessee	X			X	X		X	X
Texas			X	X			X	X
Utah			X					X
Vermont	X			X		X	X	X
Virginia		X		X	X			X
Washington		X		X	X	X	X	
West Virginia		X						
Wisconsin		X		X				X
Wyoming	X						X	

In addition to the resources used by the states as listed above, the following states include citations to these additional references:

- Illinois:
  - National Electrical Code, National Fire Protection Association.
  - National Electrical Safety Code, American National Standards Institute/Institute of Electrical and Electronics Engineers.
  - Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, AASHTO.
  - Structural Supports for Highway Signs, Luminaires, and Traffic Signals, NCHRP Report No. 411, TRB (TRB).
  - Standard Specifications for Road and Bridge Construction, Illinois DOT.
  - Supplemental Specifications and Recurring Special Provisions, Illinois DOT.
  - BDE Special Provisions, Illinois DOT.
  - Highway Standards, Illinois DOT.

- Warrants for Highway Lighting, NCHRP Report No. 152, TRB.
- Partial Lighting of Interchanges, NCHRP Report No. 256, TRB.
- American National Standard Practice for Tunnel Lighting, ANSI/IESNA RP-22, ANSI/IESNA.
- Recommended Practice for Roadway Sign Lighting, IESNA RP-19, IESNA.
- Design Guide for Roundabout Lighting, IESNA DG-19, IESNA.
- Luminaire Classification System for Outdoor Luminaires, IESNA TM-15, IESNA.
- US Coast Guard Bridge Administration Manual COMDTINST M16590.5C, Bridge Lighting and Other Signals.
- CFR Title 33, Part 118.
- Federal Aviation Administration Advisory Circular AC 70/74602J, Proposed Construction or Alteration of Objects That May Affect the Navigable Airspace.
- The Lighting Handbook, Illuminating Engineering Society.

• Tennessee:

- 2006 Lighting Software Directory, IESNA Computer Committee.
- Highway Lighting, Chapter 56, Illinois DOT.
- Highway Lighting Systems, Section 11, New Jersey DOT (NJDOT).
- Nashville Downtown Streetscape Elements Design Guidelines, Metropolitan Development and Housing Agency.
- National Electrical Code, National Electrical Code Committee of ANSI, sponsored by the National Fire Protection Association (NFPA).
- National Electrical Safety Code, American National Standards Institute/Institute of Electrical and Electronics Engineers.
- Partial Lighting of Interchanges, NCHRP Report No. 256, TRB.
- Roadside Design Guide, AASHTO.
- Roadway and Structure Lighting Specifications, Section 714, Tennessee DOT.
- Roadway Lighting Handbook, U.S. Department of Transportation, FHWA, Offices of Research and Development, Office of Traffic Operations.
- Rules and Regulations for Accommodating Utilities within Highway Rights-of-Way, Chapter 1680-06-01, Tennessee DOT.
- Standard English Drawings, Tennessee DOT.
- Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, AASHTO.
- Street Light Design Manual, Nashville Electric Service.
- Structural Supports for Highway Signs, Luminaires, and Traffic Signals, NCHRP Report No. 411, TRB.
- Warrants for Highway Lighting, NCHRP Report No. 152, TRB.
- Traffic Engineering Design Manual 2006, Section V, Chapter 2—Engineering.

- Virginia:
  - IESNA Recommended Practices for Tunnel Lighting, IESNA PR-22 (the most current edition of this document is RP-22-11).
  - IESNA Recommended Practices for Sign Lighting, IESNA PR-19.
  - The National Electric Code (NEC), NFPA. (Latest adopted NFPA 70/NEC by Virginia DOT).
- Oregon:
  - FHWA Rules and Guidelines.
  - CFR Title 23, Sub-Chapter G.
  - Federal Aviation Administration's "Obstruction Marking and Lighting" advisory circular.
  - Local agency agreements, League of Oregon Cities and Association of Oregon Counties "Guidelines and Working Agreements for Local Government Programs" (pp. 32–33).
  - Local Officials Advisory Committee (local design standards).
- Indiana:
  - NCHRP Report No. 152, Warrants for Highway Lighting, TRB (not used on an Indiana DOT [INDOT] project).
  - NCHRP Report No. 256, Partial Lighting of Interchanges, TRB (not used on an INDOT project).
  - Chapter 49, "Roadside Safety," Indiana Design Manual, INDOT.
  - INDOT Standard Drawings, INDOT.
  - INDOT Standard Specifications, INDOT.
  - National Electrical Code.
  - National Electric Safety Code.
- Delaware:
  - Delaware State Code, Title 7, Chapter 71A.
  - Functional Classification Maps, Delaware DOT.
  - Road Design Manual, Delaware DOT.
  - Standard Construction Details, Delaware DOT.
  - Lighting for Parking Facilities (RP-20-98), IESNA.
- Iowa:
  - Roadway Lighting Design Manual, Minnesota DOT, 2003.
  - IES Lighting Handbook, 9th Edition, IESNA.
  - Iowa Administrative Codes, 2011.
- Montana:
  - Recommended Practice for Tunnel Lighting, IESNA.
  - Recommended Lighting for Walkways and Class 1 Bikeways, IESNA.
  - Standard Specifications of Structural Supports for Highway Signs, Luminaires and Traffic Signals, AASHTO.

- Standard Specifications for Road and Bridge Construction, Montana Department of Transportation (MDT).
- MDT Detailed Drawing, MDT.
- MDT Electrical Detailed Drawing, MDT.
- Chapter 6, Roadside Safety, MDT Traffic Engineering Manual.
- Chapter 14, Roadside Safety, MDT Road Design Manual.
- Chapter 8, Project Development Process, MDT Traffic Engineering Manual.
- Chapter 9, Project Coordination, MDT Traffic Engineering Manual.
- Chapter 10, Plan Preparation, MDT Traffic Engineering Manual.
- ALADAN—A GE Lighting Application Design and Analysis Computer Program, General Electric Lighting Systems.
- Lighting Design Guide for Use with ALADAN, General Electric Lighting Systems.
- Warrants for Highway Lighting, NCHRP Report No. 152, TRB.
- Partial Lighting of Interchanges, NCHRP Report No. 256, TRB.
- A Guide to Standardized Highway Lighting Pole Hardware, AASHTO.
- National, state, and local electrical codes.

- Nevada:
  - Standard Plans for Road and Bridge Construction, Nevada DOT, 2010.
  - NEC, NFPA, 2011.
  - Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, AASHTO, 2002 and Interims.
  - Photometric Measurement of Roadway Lighting Installations—LM-50-99, IESNA.
  - Design Guide for Roadway Lighting Maintenance—DG-4-03, IESNA.
  - Addressing Obtrusive Light in Conjunction with Roadway Lighting—TM-10-00, IESNA.
  - Accessible Rights of Way: A Design Guide, U.S. Access Board.
- New Hampshire:
  - Manual on Uniform Traffic Control Devices, FHWA, 2007.
  - Minnesota Manual on Uniform Traffic Control Devices, Minnesota DOT, December 2001.
  - Roadway Lighting Design Manual, Minnesota DOT, 2006.
  - Indiana Manual on Traffic Control Devices, Indiana DOT, 2008.
  - Specifier Bulletin for Dark Sky Applications—Volume 2: Issue 1, International Dark Sky Association, 2009.
  - Holophane Product Catalogue, September 2001.
  - Highway Design Manual, New Hampshire DOT, 2007.
- New Jersey:
  - Standard Specifications for Road and Bridge Construction, NJDOT.

- Supplemental Specifications, NJDOT.
- Special Provisions, NJDOT.
- Standard Electrical Details, NJDOT.
- Electrical Material Specifications, NJDOT.
- NFPA NEC.
- Sample Plans, NJDOT.
- CADD Manual, NJDOT.

- New York:
  - Policy on Highway Lighting, Traffic Engineering and Safety Division, New York State Department of Transportation (NYSDOT), 1979.
  - Roadway Lighting Handbook, Addendum to Chapter 6, U.S. Department of Transportation, FHWA, September 1983.
  - American National Standard Practice for Roadway Lighting, IESNA, July 1983.
  - Americans With Disabilities Act Accessibility Guidelines for Buildings and Facilities (ADAAG), Landscape Architecture Bureau, NYSDOT, December 1993.
  - Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, AASHTO, 1994.
  - American National Standard Practice for Tunnel Lighting, IESNA, 1987.
  - Guide for the Design of Park-and-Ride Facilities, AASHTO, 1992.
  - Geometric Design Policy for Bridges, Structures Design and Construction Division, NYSDOT, 1993.
  - Recommended Practice for Roadway Sign Lighting, IESNA, 1983.
- Pennsylvania:
  - Publication 408, Specifications, and associated changes, Pennsylvania DOT.
  - Current Publication 72M, Roadway Construction Standards, Highway Lighting Drawings, RC-80M, RC-81M, RC-82M, RC-83M and RC-84M.
  - Current Publication 219M, Standards for Bridge Construction, BC-721M and BC-722M.
  - Publication 10, Design Manual, Part 1, Transportation Program Development and Project Delivery Process.
  - Publication 10C, Design Manual, Part 1C, Transportation Engineering Procedures.
  - Publication 10X, Design Manual, Part 1X, Appendices to Design Manuals 1, 1A, 1B, and 1C.
  - Publication 14M, Design Manual, Part 3, Plans Presentation.
  - Publication 15M, Design Manual, Part 4, Structures.
- Texas:
  - Standard Specifications for Construction of Highways, Streets, and Bridges, Texas Department of Transportation (TxDOT).
  - Traffic Operations Standard Plans, TxDOT.

- Texas Manual on Uniform Traffic Control Devices, TxDOT.
- Other TxDOT manuals.
- National Electrical Code Handbook, NFPA.
- Lighting Handbook: Reference and Application (HB-9-00), IESNA.
- Recommended Practices for Tunnel Lighting (RP-22-96), IESNA.
- Nomenclature and Definitions for Illuminating Engineering (RP-16-96), IESNA.
- Other IESNA publications.

- Vermont:
  - RP-22 Standard Practice for Tunnel Lighting, ANSI/IES.
  - DG-19 Design Guide for Roundabout Lighting, IES.
  - RSDG-3 Roadside Design Guide, AASHTO.
  - A Policy on Geometric Design of Highways and Streets, AASHTO.

APPENDIX C. RESEARCH PROBLEM STATEMENTS

ROADWAY DEPARTURE SAFETY

Placement of Roadway Lighting and Geometric Considerations

The placement of roadway lighting is typically left to city planners. Planners establish a need for lighting based on crash data and existing criteria, but the exact placement of lighting is often determined by spacing or convenience. Determining where lighting is most effective at reducing crashes could inform policy on roadway lighting design. This research would differ from most previous research, which focuses on lighting output or the visibility provided by the light output, by focusing on physical placement of luminaires in conventional circumstances such as areas with geometric considerations.

Statement of Urgency

Roadway departures occur on both tangents and curves. Determining the effectiveness of lighting a curve versus a tangent can be informative regarding how lighting can best be implemented. Current standards for curved roadways include instruction for pole placement to reduce the likelihood of a collision by an errant vehicle, but less research pertains to what areas of a curved roadway should be lighted to reduce departures.

Project Objective

The outcome of this research would include a report detailing any statistical differences found in the physical placement of luminaires in areas such as intersections, horizontal and vertical curves, and merge points. The data may be acquired from literature and case study research, the SHRP2 database, or an experimental driving study that incorporates alternative lighting placement as a variable.

Relationship to Existing Body of Knowledge

Data made available by existing databases like SHRP2 can be a target of further research. In addition, mapped data of lighting output combined with crash data can inform best practices. Results of this research can serve to validate existing practices or to provide information on better means of placing luminaires, specifically in areas where roadway departures are more problematic.

Anticipated Work Tasks

An effort to gather information on current policies and trends on lighting placement should be conducted and analyzed. This would determine conventional methods as well as newer techniques that can be leveraged in an experiment.

The design of this research should incorporate a variety of geometric instances of vertical and horizontal curves with the ability to manipulate lighting placement on the roadway. In general, the results of the study would determine if there is a difference in speed adjustment and lane keeping among the variations. It may also be beneficial to track eye movements of drivers in these scenarios to better understand where drivers fixate and gaze to and from while driving in lighting curves.

Lighting and Inclement Weather

Adverse weather can reduce visibility of the roadway and pavement markings. The impact of lighting in adverse weather on many different road types and in combination with varying pavement markings and sign materials has yet to be fully explored. Policies rarely consider the diminished visibility caused by adverse weather conditions.

Statement of Urgency

Improving driving in inclement weather, specifically at night when vision is already diminished, is key to improving overall safety and driver confidence in these conditions. As it stands, there is very little research regarding the interaction of lighting and inclement weather, such as rain, snow, sleet, and hail. Lighting may have the ability to improve lane keeping in these conditions and prevent roadway departure crashes from occurring.

Project Objective

The outcome of this research would be a report of experimental analysis of varying lighting techniques employed in an experiment with the consideration of varying weather effects such as rain, sleet, snow, hail, and fog. The resulting findings should provide guidelines and recommendations for lighting in these conditions in terms of roadway visibility.

Relationship to Existing Body of Knowledge

Lighting has been researched thoroughly in clear night conditions. Typically, inclement weather visibility focuses on the visibility of pavement markings as they relate to retroreflection and headlamps or the use of actively lighted delineators. Roadway lighting and its effects with inclement weather activity has been understudied.

Anticipated Work Tasks

The research tasks associated with this effort must focus on evaluating the impact of varying weather conditions in combination with conventional roadway lighting on visibility. This would inform standards and policy regarding lighting during periods of inclement weather. An improved lighting policy focused on inclement weather may cause drivers to meet appropriate speeds sooner, anticipate events more quickly, and avoid roadway departure crashes more often.

Determining When to Use Roadway Lighting

The use of roadway lighting is often determined by levels of annual average daily traffic in combination with areas of conflict, municipal regulations on lighting, economic viability, functional class, and zoning. Most traffic, however, occurs during the daytime. If roadway lighting is partially determined by traffic volumes, a count of nighttime traffic should be used as a decision threshold because it directly matches the traffic (VMT for RwD, entering traffic for intersections, and pedestrians/bicyclists for that focus area) that would use the lighting. Another determining factor is public opinion on whether an area does or does not warrant lighting.

Statement of Urgency

LED technology is slowly replacing HPS lighting conventionally used in most roadway lighting applications. LEDs can be controlled to output varying intensities and color, and achieve particular angles to satisfy ordinances. This adaptable aspect of an LED can foster more research in these specific areas that has not been possible with HPS and other light sources. As LEDs become the preferred and adopted lighting technology, research should begin focusing on LED capabilities in terms of energy consumption and cost savings.

Project Objective

The outcome of this research can inform many municipalities about a method of reducing costs and conserving energy while maintaining their current level of safety. In addition, this research may find a need for more LED lighting with controlled output in areas where roadway departure is most common.

Relationship to Existing Body of Knowledge

Adaptive lighting is a trending topic in research. Moving forward, the topic would benefit from a better understanding of when lighting is most and least important for safety. In addition, techniques for managing the lighting in adaptive areas, such as dimming by certain amounts over time or sensing the presence of vehicles and traffic, are topics that can be expanded on.

Anticipated Work Tasks

A research effort should determine any viable opportunities to reduce lighting at night in locations where traffic and pedestrian activity is significantly reduced. Traffic behavior in areas will differ depending on several factors including location, time zone, and proximity to residential and commercial areas. Observing a variety of locations that have the opportunity to decrease lighting output would form guidelines for when to reduce lighting and the rate at which the lighting should be reduced in order to maintain current levels of safety and safety perception.

Vehicle Lighting Height and Considerations

Headlamps are to have a minimum height of 22 inches, with a maximum of 54 inches. Taillamps are to be a minimum height of 15 inches, and no higher than 72 inches.[1] These measurements are to be made when there are no occupants or baggage in the vehicle. The additional weight would reduce the height of these lights. Guidelines for the design of vertical curvature and passing sections are based on stopping and passing sight distances that usually assume vehicle headlamps and taillamps are at a height of 24 inches.[2] With the allowable taillamp height lower than the assumption commonly used in design (and possibly even lower when the weight of passengers and baggage is accounted for), there are potential safety concerns related to stopping sight distances involving low vehicles on crest vertical curves.

Statement of Urgency

It is understood that the characteristics of all vehicles cannot be accounted for in highway design, but there is a disconnect between the minimum specification for the heights of vehicle lamps and the values commonly used in design. Another issue related to headlamps and vertical curvature is the shadow zone that occurs beyond the crest of a vertical curve, where an object in the road may not be visible until it is within the direct line of an approaching vehicle's headlamps. The AASHTO Green Book suggests that with the assumed 24-inch height of headlamps, an object 16 inches above the roadway will be within the line of the headlamps at a distance equal to stopping sight distance.(2) This means drivers will typically see objects 16 inches above the pavement in time to stop. However, this may not be true for objects less than 16 inches high or if the headlamps are less than 24 inches high (which is currently permissible). Research that leads to coordination between the headlamp specifications and typical design assumptions is recommended.

Project Objective

Results from this project would inform auto manufacturers and policy makers about how vehicle headlamp height differences impact the visibility of roadway objects at night. Better visibility due to headlamps and less glare caused by them may reduce roadway departure crashes.

Relationship to Existing Body of Knowledge

There is plenty of literature surrounding the height of headlamps and visibility, but very little information exists on how they can be improved in regard to highway design. It is believed that the current guides, such as the AASHTO Green Book, could be updated to current trends in headlamp technology.

Anticipated Work Tasks

Research on this problem would require a variety of vehicle heights and headlamp types to be tested against standard visibility measures. In addition to examining how headlamp height has an effect on forward visibility, it is also important to determine the impact of glare produced by different sized vehicles. Human subjects must test the ability of the vehicle headlamps to promote visibility but reduce offensive glare from an oncoming source.

LED Vehicle Headlamp Considerations

The advent of LED headlamps has affected how drivers perceive and react to oncoming headlamps and glare. Research indicates that LED headlamp sources are better than halogen headlamps and comparable to high-intensity discharge headlamps in terms of photometric performance and visibility. The blue-white color produced by the headlamps does reportedly cause glare and discomfort to oncoming drivers.(3) Research into alternative LED colors and more precise beam patterns may mitigate the discomfort to other drivers and maintain photometric and visibility properties. Additionally, the colors produced by the different types of headlamps may have unique effects on sign visibility that are yet to be identified.

Statement of Urgency

Vehicle headlamps are often overlooked when developing designs and policies for roadway lighting and signing. There are several positive safety effects of new headlamp technologies, such as adaptive headlamps that reduce glare for oncoming vehicles or turn in the direction of curves. However, these and other changes in headlamp illumination may have detrimental effects on visibility that should be considered in future research and policies. A new report by IIHS demonstrates that most headlights need improvement.(4)

Project Objective

The outcome of this type of research would inform auto manufacturers about the glare and perception of vehicle headlamps. Improvements in these areas could result in a reduction of roadway departure crashes.

Relationship to Existing Body of Knowledge

Research related to this topic has been conducted in the past; however, headlamp technology is constantly changing. In addition, a complete survey of existing LED headlamps and their effects on drivers in terms of depth perception, visibility, glare, and preference has not been conducted.

Anticipated Work Tasks

To determine the improvement needs of headlamps, a strong literature review of the current state of headlamps must be completed. The amount of glare produced by newer technologies should be assessed and compared to conventional headlamp technology. In addition, the visibility produced by varying headlamp technologies should be tested and compared using human subjects in a controlled environment.

Standardized Police Reporting

The implementation of lighting is partially driven by crash data obtained from on-scene crash reporting. Currently, there are no known standards among law enforcement agencies for reporting the placement and contribution of lighting for crashes. An effort to collect data on how different agencies interpret and apply knowledge related to lighting for crashes could improve how crash data are reported and be a step toward standardizing the reporting process.

Statement of Urgency

Much of what is determined as a need to be researched or improved stems from fatal crash reporting provided by on-scene law enforcement when a crash has occurred. The methods for reporting a crash and the details surrounding it differ agency to agency, state to state. There are no standard definitions or guidelines to establish criteria for law enforcement when submitting a report.

Project Objective

The objective of this research would be to determine the differences in reporting fatal crashes among many different agencies and levels. In addition, a guideline or recommendation for revising fatal crash reporting methods and systems should be made.

Relationship to Existing Body of Knowledge

There are currently no existing widespread efforts to standardize police reporting techniques.

Anticipated Work Tasks

A research effort should involve reviewing as many crash reporting methods as can be made available. This effort may not result in forming a universal crash reporting system but would inform researchers and practitioners on some of the differences that may affect the crash data. A next step would be to attempt to establish a common guide to be used across agencies.

Definition of Sight Distance

Sight distance is defined by AASHTO as the length of roadway visible to the driver. It can be categorized into horizontal and vertical sight distance: horizontal sight distance is limited by objects and the changing alignment in the horizontal plane, while vertical sight distance is limited by objects and the changing alignment in the vertical plane. Sight distance is generally not specified as being applicable to a certain time of day (daytime or nighttime). However, many of the assumptions used to calculate different sight distances (e.g., stopping sight distance, decision sight distance, passing sight distance) are based on values that may only be relevant for daytime conditions when daylight illuminates objects and the roadway environment.(2)

Statement of Urgency

When discussing the topic of sight distance, the traditional design manuals have little mention of specific values or considerations for nighttime conditions. AASHTO guidelines for SSD, for example, are based on the provision of adequate sight distance at every location on a roadway such that drivers traveling at or near the design speed can see a stationary object in the road and stop before reaching it. The AASHTO assumptions for SSD use a driver eye height of 3.5 ft and an object height of 2 ft. (The 2-ft object height is one example where nighttime conditions are considered because most taillamps are 2 ft or higher from the ground. However, there is still a vulnerability from encounters with shorter objects or vehicles lower to the ground, as mentioned above.) There are no specifics to the shape, color, contrast, or reflection of the object, implying that this is a daytime design element. In general, decision sight distance uses the same basic models as SSD but with longer perception-reaction times, consequently neglecting the differences between day and night conditions.(2)

Project Objective

The outcome of this work would directly influence policy on speed limits in areas that are unlighted or have increased crash risks due to geometry or wildlife presence. Improvement in these areas can reduce roadway departure crashes that are a result of excessive speeding, dodging wildlife, or failure to adjust to a curve.

Relationship to Existing Body of Knowledge

Results from this effort would influence guides such as AASHTO's Green Book and IESNA's RP-8 to include night-specific design criteria for roadways.

Anticipated Work Tasks

A research effort on this topic must incorporate closed-course testing of sight distance at different times of day including twilight and night with headlamps.

Pavement Marking Width and Retroreflectivity

There is still some debate about the trade-off between pavement marking retroreflectivity levels and size of pavement markings (width). More research is needed to determine if wider longitudinal pavement markings (i.e., 6 inches) may provide more visibility to drivers and if that gain is enough to provide any relief to the proposed minimum retroreflectivity levels being pursued by FHWA. Also, there is a series of studies available in the last decade showing a consistently stronger link between pavement marking retroreflectivity and safety. However, there is not a general consensus on the relationship, and more work is needed to establish the link. Finally, since machine vision systems are becoming more common, there is a need to determine the pavement marking performance needs for machine drivers (compared to human drivers).

Research is also needed in the area of pavement markings specifically designed to maintain their retroreflective performance conditions under wet nighttime conditions. The crash data reviewed in this report indicate that roadway departure crashes under the category of the dark, not lighted condition were more prevalent in wet conditions compared to clear conditions. This finding seems to indicate the importance of retroreflective performance in wet conditions in terms of roadway departure crashes. However, more research is needed in this area to develop a better understanding of how increased wet nighttime retroreflectivity levels can mitigate roadway departure crashes.

Statement of Urgency

To better understand how improvements to pavement markings, whether by width or maintenance schedules, can reduce the likelihood of roadway departures, research in this area is the necessary first step.

Project Objective

Results of this effort would inform policy on pavement marking design and placement as well as improve safety and perhaps reduce the rate of roadway departure crashes.

Relationship to Existing Body of Knowledge

Regarding nighttime continuous roadway delineation, agencies have two factors within their control: pavement marking width and pavement marking brightness. There is not a good understanding of how these two interact and/or how an emphasis on either one provides more benefit. Both have been studied independently, but this work would be focused on developing a better understanding of how they interact.

Anticipated Work Tasks

Weather simulation and a test track with a means for applying a variety of pavement markings for testing are essential to this research. A human subjects test for visibility of pavement markings of varying width, materials, and weather conditions is recommended.

LED Sign Brightness

Recent research identifies conditions for which retroreflective traffic signs may be too bright.[5] While the MUTCD identifies minimum levels of maintained retroreflectivity, there are no guidelines specifying when the luminance from a sign causes glare that may be a safety hazard. The glare from signs reduces the distance at which drivers can see hazardous objects and also reduces response times.[6] The concern for glare from signs should extend to the use of digital signs as well. Digital signs can be loosely defined as LED-enhanced signs such as stop signs with flashing LEDs in the border, chevrons with flashing LEDs, or even full-color digital changeable message signs.

Statement of Urgency

The MUTCD states that the brightness of changeable message signs should be adjusted under varying light conditions to maintain legibility, implying a concern that they need to be bright enough to be read during the daytime.[7] However, there is no mention of the issue that changeable message signs may be a source of glare at night. This concern should be especially noted for full-matrix LED signs capable of very high light output. While previous sign research emphasized the need for legibility, the improvements in sign materials and the increasing use of digital infrastructure open up the possibility that these signs are too bright for driver comfort and safety. Future research and applications should address these concerns.

Project Objective

The outcome of this research would inform policy for changeable message signs in guides such as the MUTCD.

Relationship to Existing Body of Knowledge

The MUTCD is the primary guide for sign implementation. Currently, there are no standards or guides in relation to LED signs or their brightness as there are for retroreflective signs. This is true despite the increasing number of LED sign installations on highways.

Anticipated Work Tasks

Research on this problem should incorporate an LED sign capable of very high light output and have human subjects rate the glare for different messages at different levels of brightness. In addition, visibility tests should be conducted using human subjects in the vicinity of the message boards to ensure the signs are not inhibiting drivers from attending to potential roadway hazards.

Retroreflectivity Levels of Traffic Signs

There is a need to identify stronger relationships between the retroreflectivity levels of traffic signs and roadway departure crashes. Research has shown some evidence that there appears to be a maximum level of retroreflectivity depending on specific conditions,[8] and FHWA has established minimum levels based on the needs of nighttime drivers in the MUTCD. However, there are no established correlations between retroreflectivity and crashes. In some ways, having recommended guidelines for appropriate sign sheeting selections based on the specific conditions (e.g., roadway, traffic, roadside) would be an alternative way to address this, but again, these would need to be developed.

Statement of Urgency

Nighttime fatality rates are approximately three times higher than daytime fatality rates. While various factors are involved, sign visibility is one factor that can be designed, specified, and maintained so that it is not a contributor to the increased fatality rate at night. Developing the data needed to support the appropriate safety-derived levels of retroreflectivity would be useful information that agencies can use to select the appropriate materials and maintain their signs to the appropriate retroreflectivity levels (the current retroreflectivity levels are based on legibility needs).

Projective Objective

The aim of this research would be to develop correlations between sign brightness (retroreflectivity) and nighttime crash rates. This should include roadway departure crashes as well as intersection crashes.

Relationship to Existing Body of Knowledge

Safety-derived retroreflectivity recommendations have been researched and partly developed for pavement markings. This work would be similar in nature but focused on traffic signs.

Anticipated Work Tasks

The research that would be beneficial here is to develop a database of signs and their retroreflectivity levels (measured or carefully estimated) along roadways where the geometric characteristics, as well as the traffic levels and mix, are known. This information would be combined with multiple years of nighttime crash information so that the appropriate statistical analyses could be performed to determine how sign retroreflectivity levels impact nighttime crashes. An alternative to tracking or modeling sign retroreflectivity would be to identify agencies that have upgraded their signing. Knowing when signs were upgraded would allow agencies to theoretically obtain before and after crash data (preferably at least 3 years of both before and after data) to analyze the impacts of the new signs. The specific areas where this research may pay off is horizontal curves, which are overrepresented in RwD crashes.

Speed Limits at Night

Most speed limits are set by legislative action or studies that determine the 85th percentile speed under free-flow conditions. When determined based on speed studies, most often the speed data are collected during the day, meaning that nighttime conditions are not accounted for in selecting speed limits.

Statement of Urgency

While separate speed limits are permitted at night, few agencies use nighttime speed limits, and there is no guidance provided in the MUTCD for establishing nighttime speed limits. In addition, there is the concern of over-driving headlamps at night. While no recent study has been completed on this topic, there is a growing concern that the new headlamp trends may be generating a need to take a fresh look at this somewhat controversial topic.

Project Objective

The findings of this research should be used to determine the necessary conditions for implementing a night-specific speed limit to a roadway. This may be completed by human-subject research based on visibility as well as a survey of areas that currently employ night-specific speed limits.

Relationship to Existing Body of Knowledge

This research can add to the headlamp research opportunities previously mentioned with a focus on speed limits and areas where speed limits may need to be altered at night versus day to prevent roadway departures.

Anticipated Work Tasks

A survey of current trends in roadway design and speed limits should be followed by a human-subject test to determine, in combination with sight distance and headlamps, if speed limits should be reduced in certain situations. The reduction of speed limits in some areas where roadway departures are most common may mitigate crashes.

Horizontal Curve Design and Curve Advisory Speeds

The design of horizontal curves is based on comfortable lateral acceleration rates derived during daytime studies. At night, however, reduced visibility may affect a driver's threshold level of lateral acceleration where discomfort begins, thus affecting the comfortable curve advisory speed for the curve. While a separate advisory speed for night seems impractical, there may be implications related to safety if drivers are actually not comfortable adopting the advisory speed at night.

Statement of Urgency

Further analysis of the implications of curve advisory speeds and nighttime driving could lead to improvements in how these advisory speeds are set and used. There is currently very little consideration of curve advisory speeds for nighttime visibility. Sight distance at night and especially around curves where headlamps are not angled to illuminate is greatly diminished. Progress on this topic can result in fewer roadway departure crashes due to speeding in curves.

Project Objective

Increased knowledge about curves with higher rates of roadway departure crashes would allow policy makers to establish criteria for advisory speeds. Results of this effort should provide recommendations for implementing advisory speed systems based on curve design.

Relationship to Existing Body of Knowledge

In an exploratory analysis of unfamiliar driver data collected during both daytime and nighttime conditions, it was found that drivers on curves accept lower levels of lateral acceleration at night than during the day. However, contrasting the reduced lateral acceleration was a finding that driver speeds were higher at night (possibly from cutting curves with a wider path).[9]

Anticipated Work Tasks

A survey of policies around curve design and horizontal curve speed limits should first be conducted. It is perhaps not practical to test multiple curves and speeds with human subjects, but a survey of areas with increased crash data may suggest some trends in design. The survey should incorporate lighting, pavement marking design, material, width, roadway design speed and advisory speed, location, and guardrail presence.

INTERSECTION SAFETY

Lighting at Rural Intersections

Rural intersections vary in a number of ways, as do the policies and standards for lighting them. The factors involved in fatal crashes at many high-speed intersections in rural areas, whether signalized or not signalized, need to be explored to better inform policy for lighting.

Transient adaptation occurs when drivers travel to and from lit and unlit areas and may cause issues with vision for drivers as they pass through a lighted rural intersection. The general policy is to provide a tapering of lighting so that the transition between the two areas is gradual and comfortable.

Statement of Urgency

Due to the high rate of crashes associated with rural intersections at night, lighted and non-lighted, findings from this effort can increase understanding of potential causational factors associated with crashes. A focus on transient adaptation, its effects, and methods of limiting this effect at rural intersections would benefit intersection design and safety.

Project Objective

This project should explore the limits of transient adaptation and general safety concerns of rural intersections. The results of the project should progress policy to include lighting techniques and standards to improve safety at rural intersections.

Relationship to Existing Body of Knowledge

Existing research has explored the best methods to lighting intersections in terms of visibility inside the box where points of conflict mostly occur. This research should build on that existing research as well as determine visibility issues, if any, that exist around the intersection due to the lighting.

Anticipated Work Tasks

To explore the limits of transient adaptation, human subjects should perform visibility tasks in various intersection lighting setups. A survey of conventional lighting methods in addition to alternative methods should be explored in this way.

Intersection Sight Distance and Gap Acceptance

A recent NCHRP project has identified the safety impacts of providing ISD, showing that fewer crashes occur as ISD increases.[10] Even though ISD is measured based on geometry, there may be issues related to nighttime visibility if the clear sight triangles needed for adequate ISD can be different during the night than during the day. Controls for ISD are based on principles of gap acceptance, which has been derived from daytime observations. A driver's gap acceptance is a function of perception-reaction time, the time (and distance) used to make an appropriate maneuver, the speed of the conflicting vehicles, and any buffer added for personal preference and safety.

Statement of Urgency

The duration of a gap that drivers select may vary with time of day. At night, this may be impacted more because visibility is limited and there is potential for misjudging the distance of a conflicting vehicle. It is possible that what may be an acceptable sight distance during the day may not be adequate at night. Future research may address how gap acceptance changes by time of day, whether there is a need to consider how nighttime gap acceptance may impact ISD and intersection safety, and whether or not intersection lighting would mitigate these effects.

Project Objective

Research to support this issue would be focused on how daytime versus nighttime drivers judge the speed and distance of approaching vehicles in terms of gap acceptance. If nighttime gap acceptance differs from daytime gap acceptance, then changes to policies to accommodate the difference may lower certain types of intersection-related crashes.

Relationship to Existing Body of Knowledge

There is limited research on this topic. The research that is available is focused on gap acceptance (day versus night) at two-way stop-controlled intersections and shows a statistically significant difference in gap acceptance capabilities for older drivers (they need significantly larger gaps during nighttime conditions).[11]

Anticipated Work Tasks

The research might start with simulator work, but definitive research would involve actual studies of gap acceptance under similar conditions except time of day. These could be observation studies under the correct scenarios and/or closed-course studies.

Selecting Phasing for Left Turns

The second edition of the Signal Timing Manual (NCHRP Report 813) provides national guidance on the selection of left-turn phasing modes at signalized intersections. Practitioners are to select protected or permissive phasing based on criteria such as the number of left and through lanes, sight distance, turning volumes, speeds, and crash history.[12]

Statement of Urgency

There is no specific consideration for nighttime conditions. These guidelines can be improved by including special circumstances for nighttime conditions (for example, appropriate thresholds for nighttime crashes rather than total crashes only or turning volumes at night rather than peak-hour volumes). This is a classic example of where a nighttime review of national policies is needed, including nighttime visibility, especially with a collaborative team of relevant subject matter experts.

Project Objective

The application of the results would be applied to the current guidelines for converting permissive left turns to protected left turns. The results from this research could reduce left-turn crashes at night under permissive control conditions.

Relationship to Existing Body of Knowledge

The current recommendations do not specifically address nighttime gap acceptance, but crashes of this type are common during nighttime conditions.

Anticipated Work Tasks

The research for this would be similar to the day versus night gap acceptance research described above.

Skewed Intersections: Visibility of Pedestrians or Bicycles at Night

Intersections with large skew angles are potential safety concerns at night for pedestrians and bicycles approaching the intersection from a conflicting direction. Because a vehicle's headlamps are directed forward, with only a small amount of illumination distributed away from the center, there may be conditions where drivers are unlikely to see pedestrians or bicycles from some directions, depending on the use of lighting.

Statement of Urgency

At night, the visual attention of drivers tends to be concentrated in a smaller area than during the day, meaning that drivers are additionally less likely to search for those approaching pedestrians and bicycles. This concern can be addressed by evaluating the illuminance patterns of headlamps and whether or not the light distributed horizontally at wide angles is enough for a driver to see pedestrians and bicycles.

Project Objective

The objectives of this research would be to determine the extent of off-axis pedestrian lighting that exists from conventional headlamps and determine those limits, as well as to compare the capabilities of those headlamps to angles produced by skewed intersections and determine safety implications at those intersections. The results of this effort would support pedestrian safety and visibility and inform municipalities of when additional visibility aids such as lighting need to be implemented in skewed intersections.

Relationship to Existing Body of Knowledge

Research on this topic would progress existing research related to headlamp and pedestrian safety. Curve-adapted headlamp technologies need to be researched to better understand how they address existing corner cases. In addition, alternative intersection angles are understudied in terms of pedestrian safety.

Anticipated Work Tasks

This research would include an assessment of how much light conventional and contemporary headlamps provide for pedestrian detection off-axis of the vehicle direction. Mapping the beam pattern onto nonconventional intersection designs (such as skewed intersections and roundabouts) would be a unique way to compare current sight distance and visibility assessment techniques with relevant data. This technique would also be a useful way to optimize the location of intersection lighting, with respect to pedestrian visibility at an intersection of interest.

Free-Flow Interchanges and Intersections

Innovations in interchange and intersection design can promote large increases in efficiency, with some intersections (such as roundabouts) providing for the free flow of vehicles. Diverging diamond interchanges and displaced left-turn or continuous-flow intersections are recent concepts specifically designed to address conflicts with turning vehicles. The proper use of lighting and signage at these types of intersections is critical because they are very different from typical stop-controlled or signalized intersections.

Statement of Urgency

There may be visibility issues at night that are not obvious during the day, especially for roundabouts, where drivers are not expecting to stop unless they see another vehicle. This makes pedestrians even more vulnerable at roundabouts and other free-flow intersections where speeds are typically higher than traditional intersections. Lighting and signage in these spaces need to be designed and implemented to ensure pedestrian safety.

Project Objective

The primary objective would be to identify critical points in free-flow interchanges and intersections and evaluate the effect of lighting and signage at those points.

Relationship to Existing Body of Knowledge

This research would expand on existing research centered on roundabout and free-flow interchange gaze behavior. Many of the current observations are based on daytime research, and evaluating nighttime driving may point to different critical aspects. A better understanding of nighttime driver behavior would inform the proper implementation of signage and lighting in free-flow type intersections.

Anticipated Work Tasks

This research would include an assessment of how much light conventional and contemporary headlamps provide for pedestrian detection off-axis of the vehicle direction. Mapping the beam pattern onto nonconventional intersection designs (such as skewed intersections and roundabouts) would be a unique way to compare current sight distance and visibility assessment techniques with relevant data. This technique would also be a useful way to optimize the location of intersection lighting, with respect to pedestrian visibility at an intersection of interest.

Traffic Signs

There is a need to establish recommendations for traffic sign retroreflectivity (materials) and possibly pavement markings. Depending on the type of environment and intersection control (rural versus urban, or stop sign versus signal), there could be justification for different performance levels. In fact, there are no national recommendations or guidelines that a practitioner can use to select the best retroreflective product or performance level for a specific scenario. This is a general need that extends beyond intersections.

The MUTCD contains requirements for minimum levels of traffic sign retroreflectivity.(7) These requirements are based on research conditions that represent dark rural highways. As shown in the recent NCHRP Report 828, nighttime sign brightness must increase to offset increasing levels of background visual complexity.(13) Intersections generally have more background complexity than a random section of highway, particularly urban signalized intersections.

Statement of Urgency

There is a need to evaluate shoulder-mounted sign visibility in areas with more visual complexity than a dark rural highway. Increased retroreflectivity levels for these types of intersections would make the signs more visible and may lead to fewer nighttime intersection-related crashes.

Project Objective

The primary focus of this effort would be to create recommendations for retroreflective materials based on the evaluations of performance levels in specific scenarios such as rural, urban, stop-controlled, or signalized intersections.

Relationship to Existing Body of Knowledge

NCHRP Report 828 provides the most relevant demonstration that this research is needed. In NCHRP Report 828, overhead sign performance levels were developed based on the background complexity.(13) Similar work would be needed for ground-mounted signs in different environmental conditions.

Anticipated Work Tasks

This work could be similar to the work that was performed for NCHRP Report 828, which included closed-course legibility studies as well as open-road recognition studies.(13)

Roadway Lighting Automation and Controls

With the advent of solid state lighting, controlling where the lighting can be turned on and off as well as dimmed is becoming more important. This technology provides the opportunity to adjust lighting levels and to react to the presence of vehicles and pedestrians.

Statement of Urgency

As more agencies adopt solid state lighting, the need to establish guides for automation and controls grows. A survey of current trends and capabilities of the technology is important for developing policies.

Project Objective

Results of this effort would provide municipalities and policy makers with information for deciding to use an automated lighting system. Automated lighting has impacts on energy consumption and can produce an economic benefit.

Relationship to Existing Body of Knowledge

There has been recent research utilizing programmable solid state lighting, but these studies have been isolated. A full-scope evaluation of the systems should include a wide variety of road types and consider multiple regions.

Associated Work Tasks

Research would require a survey of the solid state lighting control systems currently available. Experiments should focus on reliability, network reach, and usability of controls. In addition, research should take into account any limitations the systems have in terms of interference or delay.

PEDESTRIAN AND BICYCLE SAFETY

Lighting for Pedestrians

Lighting is commonly designed for vehicles and not for pedestrians. Providing a standard of lighting that meets the criteria for both is a key interest. Lighting for pedestrians is believed to be more crucial in providing the greatest safety benefit at conflict points. Gap acceptances for pedestrians and the perception pedestrians have of how visible they are to drivers are research topics that have been explored in the past and can be re-explored with the advent of modern in-roadway lighting, crosswalk lighting, vehicle headlamps, and education.

Vertical illuminance is among the most important factors for determining the contrast and visibility for a crossing pedestrian. Methods for achieving the required vertical illuminance may need to be explored because current standards are often believed to be difficult to achieve. The amount of vertical illuminance required may vary depending on an array of variables including environmental lighting, intersection lighting, crosswalk size, and crosswalk geometry.

In-roadway lighting is becoming an important area of interest as more agencies adopt it as a method of promoting safety and reducing energy. In-roadway lighting at crosswalks is believed to be a benefit for drivers to visualize crosswalks ahead of time and for pedestrians to have a lit path. The effects of in-roadway lighting in combination with area signage, overhead lighting, and retroreflective markings need be explored to better inform policy.

Statement of Urgency

Newer technology for modern roadway lighting has led to more precise output from luminaires. This results in less light spilling over to sidewalks since higher-quality optics provide adequate lighting for the roadway but not for pedestrians. Investigating the impact of newer technologies, such as the Nadir Dump and other luminaire types, may inform future roadway lighting design with sidewalks and crosswalks in mind.

Project Objective

The purpose of this project would be to develop a cost-efficient plan for lighting pedestrians that promotes safety. The results of this project would inform policy on lighting crosswalks and other critical pedestrian conflict points.

Relationship to Existing Body of Knowledge

Pedestrian visibility has been evaluated in a number of ways. The primary focus is typically either the use of roadway lighting to spill light onto pedestrian walkways or crosswalk-specific lighting. This research would build onto that existing body of knowledge by considering alternative methods.

Associated Work Tasks

First, a survey of all available pedestrian- and crosswalk-related technologies must be considered. Then, an experimental design that involves human subjects detecting the presence of pedestrians under varying lighting technologies could determine the best methods for lighting pedestrians. The environments of sidewalks and crosswalks can vary in ambient lighting, which may impact visibility and thus should also be explored.

Seasonal Fluctuations in Daylight Hours and Effects of Daylight Savings Time

The change in when daylight occurs because of the changing seasons and the adjustments that occur with the use of Daylight Savings Time mean that there are periods when road users may be accustomed to daylight but experience darkness. In some locations and during certain times of the year, peak traffic volumes may occur at night. With DST, the sudden change in whether or not a commute occurs during daylight has significant safety implications, especially on pedestrians and cyclists.(14) These road users are often poorly visible due to an absence of lighting.

Statement of Urgency

If agencies provide street lighting, it may be valuable to investigate how they address DST changes and gradual seasonal daylight changes, whether with automatic lighting or with timers. Consistency in when lighting is provided relative to ambient light is important, especially for these vulnerable road users.

Project Objective

Results of this survey would serve as a step toward forming guidelines that may improve lighting for pedestrians in some areas.

Relationship to Existing Body of Knowledge

DST-related issues are an understudied aspect of roadway lighting and visibility. There is a link between DST and pedestrian-related crashes. This research would explore that link and attempt to establish recommendations regarding pedestrian safety at those times.

Anticipated Work Tasks

A survey of municipality ordinances on lighting, specifically during periods of DST, as well as pedestrian-related crash rates in these locations would serve as data for this project. It is important that many municipalities in varying regions be considered so that the many nuances in DST are reviewed.

Glare from Beacons, Signals, and Other Lights

Flashing beacons and lights used on signs at intersections, midblock crosswalks, and other locations have been shown to be effective at grabbing attention, but glare from these lights may have a detrimental effect on drivers' ability to see pedestrians and marked crosswalks, especially at night. Some text in the MUTCD instructs that automatic dimming for traffic signals should be used if a signal's indication is bright enough to cause glare.[7]

Statement of Urgency

There appear to be no specifications, however, for appropriate levels of illuminance for these lights at night. In addition to flashing beacons used for crosswalks, the concern regarding glare may be relevant for all sources of light, including all traffic signals (including PHBs), LEDs on signs, railroad gates, in-roadway lights, and lane use signals.

Project Objective

Results from this effort would inform policy makers on how bright beacons and lights at intersections and crosswalks can be while maintaining the level of visibility and safety for pedestrians and other road users.

Relationship to Existing Body of Knowledge

In 2008, NCHRP Report 624: Guidelines for Selection and Application of Warning Lights on Roadway Operations Equipment presented guidelines for selection and application of warning lights to improve the conspicuity and recognizability of roadway operations equipment used for construction, maintenance, utility work, and other similar activities.[15] Since NCHRP Report 624 was completed, significant technology changes and pressure from increased speeds, traffic volumes, and distracted drivers have occurred, necessitating additional guidelines.

Associated Work Tasks

Research on this topic should involve access to an intersection with the ability to manipulate lighting types and levels. A human subjects test involving the visibility of pedestrians at crosswalks and intersections while exposed to a variation of lighting technologies must be conducted.

Assumptions for Pedestrian Walking Speed

The assumed pedestrian walking speed suggested in the MUTCD is conservatively set at 3.5 fps, with accommodation for slower walking speeds for special conditions.(7)

Statement of Urgency

It is likely that the research used to select the recommended pedestrian walking speed focused exclusively on daytime conditions, neglecting the behavior of pedestrians at night.

Project Objective

The objective of this research would be to determine if there are different nighttime walking speeds and then make appropriate adjustments in the signal phasing plans. The results may lead to fewer nighttime intersection-related crashes.

Relationships to Existing Body of Knowledge

Researchers in a recent study showed that the time of day may impact walking speeds, with pedestrians walking approximately 0.5 fps slower during the evening peak than during the morning peak.(16) That analysis, however, involved data collected only during those two time periods. Additionally, the data were collected in New York City (Manhattan), where the density of pedestrians tends to be high. Regardless, a different walking speed attributed to the time of day may justify examining the issue with more depth.

Associated Work Tasks

This research would be aimed at collecting nighttime pedestrian walking speeds and comparing the results to the existing literature, which includes mostly, if not only, daytime pedestrian walking speeds.

School Zones Marked with Word Markings

There are several instances in the MUTCD that specify that certain objects must have retroreflective properties.[7] There is currently no language specifying that the "SCHOOL" word marking informing drivers they are entering a school zone must be retroreflective. Although it is likely that the marking would be made of the same retroreflective material as the nearby line markings, there may be a question about whether the marking should be held to a standard of maintained retroreflectivity.

Statement of Urgency

If there are periods of the year during which school activities begin or end during dark or nighttime conditions, there may be justification to evaluate the brightness of the marking.

Project Objective

The research objectives would be to determine if there is an overlooked need to implement retroreflective markings in school zones and provide recommendations on how to determine those needs. Results of this project would influence policy makers and reduce the number of fatal crashes at school zones.

Relationship to Existing Body of Knowledge

Part 7 of the MUTCD includes standards for marking school zones.(7) The standards are based on consensus voting of agencies across the United States. However, they could be enhanced with research results to help agencies better understand how to make modifications to increase visibility and safety.

Associated Work Tasks

This research could involve surveys of nighttime drivers who drove through areas with and without retroreflective school markings. If they have a better recall of the retroreflective markings, then there would be some merit to requiring them to be retroreflective.

Bike Lanes

FHWA has approved the use of green pavements to delineate bike lanes. Generally, there is no nighttime visibility component to the green bike lanes (adding glass beads reduces the friction). Markings are retroreflective because of glass or ceramic spheres. While this adds an element of nighttime visibility to the markings, it can also create slippery markings, especially when wet. Bike lanes need to be carefully designed to avoid slippery conditions because of the need to balance a bike (two wheels versus four wheels). Therefore, the bike lanes do not include retroreflective properties, which reduces their visibility at night.

Statement of Urgency

There is a need to develop technologies and materials that can help provide nighttime visibility to bike lanes so that their paths are as easily identified during dark conditions as they are during daytime conditions.

Project Objective

The objective of this research would be to develop a material that provides daytime color of bikes lanes during nighttime conditions, while maintaining a high degree of friction. The outcome of this research would support bicycle safety and reduce crashes between motorists and bicyclists.

Relationship to Existing Body of Knowledge

Studies to date have demonstrated that bike lanes generally improve biker safety. None of the existing studies have had the opportunity to examine bike lanes that provide a highly visible path to the nighttime bikers.

Associated Work Tasks

Observational studies before and after the treatment of visible bike lane materials would be needed.

OTHER AREAS WITH NIGHTTIME VISIBILITY CONCERNS

The following research concerns do not fit within the three target program areas, but the topics arose in the course of identifying gaps in current practices and research related to nighttime visibility. Several of these research areas are a result of budding and future technologies that promise ways to provide cheaper and more-efficient lighting through sensors and automation. The effect these technologies will have is unforeseen, and research into their impacts on safety is warranted.

Health Effects of Roadway Lighting

In a recent document, AMA noted that the presence of the blue portion of the lighting spectrum in light sources has the potential to impact the health of humans living close to the light source.(17) AMA recommends that the light source be no greater than 3000K in color temperature. Studies have, however, shown that light sources with a 4100K color temperature perform at a higher level in terms of the visibility of objects in the roadway.(18) It is vital that these issues be considered.

Statement of Urgency

There is a disagreement between visibility researchers and health researchers on which light should be used for nighttime driving. A better understanding and consensus on this topic is vital for maintaining road safety and user health.

Project Objective

The purpose of this project would be to gain insight on how lighting, particularly that associated with driving, affects health. Insight on this topic can ensure that driver visibility and human health are maintained.

Relationship to Existing Body of Knowledge

There are several reports and research efforts that discuss this issue. Most of these are discussed in the AMA report.(17) However, these research efforts are limited in the dosage level of the light source. This means that the research was performed at much higher levels of light than typically experienced by a driver. As such, the applicability of the results and the assessment of the overall impact can be limited. The full impact of this effect is unknown, and this research would serve to fill this gap in the knowledge.

Associated Work Tasks

This research effort should begin with an extensive literature review about the effect of lighting on health, specifically in terms of the light spectrum. In addition, a survey of the multiple ways humans are exposed to different spectrums of light, not just in a roadway setting, is crucial to the observation.

Energy Consumption

Energy conservation has become a focus for many precincts and agencies. Removing lighting from infrastructure has become a popular method of conserving energy with some disregard to the impact of safety. Exploring methods of conserving energy in areas while maintaining safety should be a focus to inform policy and prevent uninformed decisions by infrastructure managers. Some known methods to efficient methods of lighting that allow for reduced energy consumption include the use of in-roadway lighting to highlight conflict points and prevent light trespass. Adaptive lighting technology is also a popular method of utilizing light only when it is necessary to do so.

The natural extension of this would be lighting on demand. LED lighting can be implemented with motion sensors or through connected-vehicle technologies to have lighting respond to the presence of a vehicle or pedestrian. Sample projects have been implemented in a controlled test road environment, but wider implementation will be developed in the future.

Statement of Urgency

As mentioned previously, due to the increased focus of energy conservation, roadway and infrastructure lighting is being removed with little regard for safety. Alternatives to lighting that may alleviate economic concerns and improve energy efficiency exist. These alternatives need to be thoroughly explored for wider implementation to take place.

Project Objective

The project should determine the safety aspects of adaptive and on-demand lighting. The adoption rate and economic justifications for installation and maintenance also need to be considered. The implications of this research could have huge impacts on municipal budgets and local economies as well as reduce the overall energy consumption.

Relationship to Existing Body of Knowledge

The technological aspects of adaptive lighting and on-demand lighting have been researched, as have some safety components of on-demand systems. This research would focus on energy conservation and economic benefits as a means of providing a more detailed breakdown of costs and savings to interested agencies.

Associated Work Tasks

Wider implementation would warrant testing on-demand lighting and reduced lighting technologies in a number of naturalistic locations. Doing so would create observable data on the behavior and safety of the lighting.

Vehicle Automation

The anticipated adoption of connected and automated vehicles allows for innovative approaches to lighting. On the one hand, vehicle automation may reduce the need to use lighting because so much of what the vehicles "see" will not be with light in the visible spectrum. On the other hand, there will still be other road users (such as pedestrians) that are just as deserving of safe and efficient transportation. The concept of smart cities with connected infrastructure opens up opportunities to apply lighting on demand and intelligently adapt to the users' needs.

Statement of Urgency

Vehicle automation is on the horizon, and very little consideration has been given to existing infrastructure in the wake of this movement.

Project Objective

Using a smart city or network of automated vehicles and infrastructure, this project would identify weak points and areas of consideration in terms of vehicle and user safety (e.g., pedestrians). The results of this research would lay the foundation for safety guidelines in relation to automation.

Relationship to Existing Body of Knowledge

There have been very few opportunities for a rigorous smart city or simulation thereof to be conducted due to the limitations of most research facilities. These opportunities are becoming more plentiful, and research on this topic would keep safety ahead of the curve.

Associated Work Tasks

Research would require a smart-city simulation with vehicle and infrastructure communication in place. Testing would involve an evaluation of the technology's capabilities as well as human interaction with it.

Lighting Uniformity

Uniformity is regarded as a desired effect of roadway lighting, though some research disputes this claim. There is room to explore the limits of lighting uniformity and its interaction with in roadway lighting, retroreflectivity, pedestrian visibility, and lighting color.

Statement of Urgency

The day-to-night effect of uniformity is important since daylight is highly uniform and roadway lighting generally strives to replace daylight; however, differences in source location and mount height tend to affect the angle of intensity of lighting. This causes severe shadows. In addition to roadway lighting, uniformity in intersections where light sources from other vehicles and infrastructure exist should be investigated.

Project Objective

The primary objective of this effort would be to compare visibility in a uniform driving environment versus a nonuniform environment. Results of this study could directly impact roadway design practices.

Relationship to Existing Body of Knowledge

Uniformity typically falls under the school of thought that more lighting at night is typically better for visibility; however, some recent studies have found that uniform lighting on a roadway can decrease contrast in some instances.

Associated Work Tasks

A research effort would require comparing small-target visibility, a metric commonly used in roadway visibility tests, of uniform and nonuniform roadways. A facility equipped with adjustable roadway lighting and the ability to perform visibility evaluations from inside a vehicle is preferred. The results of this study may influence lighting policy and affect the amount of lighting used on a roadway, which impacts the economy, energy consumption, and safety.

Lighting on Rural Bridges

The AASHTO Green Book calls into question the justification of cost for lighting rural bridges. Whether or not rural bridges attribute to a number of conflicts and collisions that can be rectified by the addition or subtraction of lighting or delineators should be explored.(2)

Statement of Urgency

Lighting on rural bridges has been removed in some areas for cost savings; however, very little regard has been given to the safety implications of those removals. Bridges, particularly the variety of ones in rural areas, are unique and may provide visibility limitations and lack cues drivers need for safety.

Project Objective

The focus of this effort would be to determine the impact of lighting on rural bridges and establish when removal of lighting is permissible in regard to safety. The outcome of this research would inform policy makers and municipalities about the importance of lighting for rural bridges prior to a decision to remove the lighting.

Relationship to Existing Body of Knowledge

In general, providing light in rural areas improves visibility and safety; however, very little research has been conducted in regard to lighting on specifically rural bridges.

Associated Work Tasks

A survey of bridges and their crash rates should be conducted. In addition, innovative lighting solutions to rural bridges that may be less costly to implement and maintain should be investigated.

Interaction of Overhead Lighting with Fauna, Foliage, and Crops

The effect roadway lighting has on fauna, foliage, and crops is an aspect of lighting that is rarely documented in policy. Exploring the factors that benefit or harm wildlife in regard to lighting can provide insight on better and safer implementations. Research on this topic can also seek to understand the effect of environmental lighting, which is currently based on consensus knowledge. Adaptive lighting takes environmental effects into account, but the extent has not been properly researched.

Statement of Urgency

As the lighting inventory evolves rapidly from traditional sources to solid state LED sources, these issues of impact on the environment need to be considered in much greater detail. Taking action now to identify the issues would reduce issues later that may require a redesign or further retrofit of the system. As an example, there has long been an impact on the growth patterns of soybeans based on proximity to roadway lighting. As agencies convert to solid state sources, the change in the spectrum and selection of the light source may impact this soybean-to-light relationship. As a result, the selection of the light source today is critical to minimizing the future impact of the lighting system.

Project Objective

The objective of this research would be to analyze the interaction of lighting on the growth and behavior of fauna, foliage, and crops. The secondary mission of this research would be to develop alternatives that would be less impactful than the conventional lighting systems used. The results of this research would serve to inform specification on light trespass and lighting design in the roadway.

Relationship to Existing Body of Knowledge

This is a growing body of knowledge. Existing studies have shown impacts on turtle migration, bird flight paths, soybean maturity, and other growth. However, the development of the application factors for the lighting impacts and the mitigation techniques are required to fully mitigate these issues.

Associated Work Tasks

Research in this area would involve assessing the plant growth and studying the animal migratory patterns and vehicle-animal crashes in areas with roadway lighting. A variety of plant species and animal types should be considered since the spectral receptivity of the plants and animals can vary from human responses. A variety of lighting levels would also be required to determine the threshold of impact of the lighting.

Curve Design Accounting for Nighttime Line of Sight

One of the controls for the design of horizontal curvature is the line of sight cutting across the inside of the curve, limited by an obstruction that is offset from the road. The equation for calculating whether or not there is sufficient sight distance for curves is based on an assumption that the obstruction is the only limiting factor and the object would otherwise be visible to the driver. At night, however, driver vision can be restricted to the pattern of light from headlamps, which is mostly concentrated in a direct line in front of the vehicle.

Statement of Urgency

A driver at night may not be able to see an object in the road near the end of a curve since the headlamps are only directed straight ahead. The limited amount of headlamp illumination that is scattered horizontally needs to be considered to properly judge sight distance when designing horizontal curves.

Project Objective

The purpose of this research would be to evaluate headlamps and their limitations in curves. Results of this research would better inform policy on curve design and headlamp design. Solutions for protecting cyclists and other road users in areas such as this are also dependent on this research.

Relationship to Existing Body of Knowledge

The IIHS is currently testing curve-adapted headlamp technology with two specific radii (500 ft and 800 ft). Readings are taken 10 inches from the ground for visibility and 3 ft 7 inches from the ground for glare.[19] While this testing provides some initial information, additional research is needed to understand the gaps in this technology and how it affects driver behavior.

Associated Work Tasks

Potential research in this area should evaluate the distribution of light from headlamps and whether objects would be visible at the wide viewing angles that can occur with sharp curves. This research would be similar to that of skewed intersections. In addition to evaluating the capabilities of headlamps, the research would also benefit from better understanding the gaze patterns of drivers in curves at night. Eye-tracking data can provide feedback for where in curves drivers fixate, whether at the farthest depth their headlamps reach or at some point in the curve.

REFERENCES

1. Code of Federal Regulations (CFR) Title 49, Section 571.108. Federal Motor Vehicle Safety Standard 108. Available at https://www.gpo.gov/fdsys/pkg/CFR-2004-title49-vol5/xml/CFR-2004-title49-vol5-sec571-108.xml.
2. AASHTO. *A Policy on Geometric Design of Highways and Streets* (Green Book). AASHTO, Washington, DC, 2004.
3. Kang, B., B. Yong, and K. Park. Performance Evaluations of LED Headlamps. *International Journal of Automotive Technology*, Vol. 11, No. 5, 2010, pp. 737–742.
4. Insurance Institute for Highway Safety Highway Loss Data Institute. In the Dark: New Ratings Show Most Headlights Need Improvement. *Status Report*, Vol. 51, No. 3, March 30, 2016. Available at http://www.iihs.org/iihs/sr/statusreport/article/51/3/1.
5. Carlson, P. Can Traffic Signs Be Too Bright on Low-Volume Roads? *Transportation Research Record*, No. 2472, Transportation Research Board, Washington, DC, 2015.
6. Oregon Department of Transportation (ODOT). *Stopping Sight Distance and Decision Sight Distance*. Discussion Paper No. 8A. ODOT, Salem, OR, 1997.
7. FHWA. *Manual on Uniform Traffic Control Devices*. FHWA, Washington, DC, 2009.
8. Carlson, P. Can Traffic Signs Be Too Bright on Low-Volume Roads? *Transportation Research Record*, No. 2472, Transportation Research Board, Washington, DC, 2015.
9. Carlson, P.J., B. Brimley, G. Hawkins, S. Himes, H. McGee., and F. Gross. *Traffic Control Device Guidelines for Curves*. Final Report, NCHRP Project 03-106, April 2015. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP03-106_FR.pdf.
10. Himes, S., K. Eccles, K. Peach, C.M. Monsere, and T. Gates. Estimating the Safety Effects of Intersection Sight Distance at Unsignalized Intersections. 2016 TRB Annual Meeting, Washington, DC, 2016.
11. Dissanayake, S., J.J. Lu, and P. Yi. Driver Age Differences in Day and Night Gap Acceptance Capabilities. *IATSS Research*, Vol. 26, No. 1, 2002, pp. 71–79.
12. Urbanik, T. *NCHRP Report 813: Signal Timing Manual, Second Edition*. Transportation Research Board, Washington, DC, 2015.
13. Carlson, P.J., B. Brimley, J. Miles, S. Chrysler, R Gibbons, and T. Terry. *NCHRP Report 828: Guidelines for Nighttime Visibility of Overhead Signs*. Transportation Research Board, Washington, DC, 2016.
14. Sullivan, J.M., and M.J. Flannagan. The Role of Ambient Light Levels in Fatal Crashes: Inferences from Daylight Saving Time Transitions. *Accident Analysis and Prevention*, Vol. 34, 2002, pp. 487–498.
15. Gibbons, R.B., S.E. Lee, B. Williams, and C.C. Miller. *NCHRP Report 624: Guidelines for Selection and Application of Warning Lights on Roadway Operations Equipment*. Transportation Research Board, Washington, DC, 2008.

16. Peters, D., L. Kim, R. Zaman, G. Haas, J. Cheng, and S. Ahmed. Pedestrian Crossing Behavior at Signalized Intersections in New York City. 2015 TRB Annual Meeting, Washington, DC, 2015.

17. American Medical Association. *Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting*. CSAPH Report 2-A-16. AMA, Chicago, IL, 2016.

18. North West Energy Alliance. *Seattle LED Adaptive Lighting Study*. North West Energy Alliance, Boulder, CO, 2014.

19. Insurance Institute for Highway Safety Highway Loss Data Institute. Headlight Evaluation: About Our Tests. Available at http://www.iihs.org/iihs/ratings/ratings-info/headlight-evaluation.

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