Design Criteria for Adaptive Roadway Lighting

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Turner-Fairbank Highway Research Center
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FOREWORD

The Federal Highway Administration's Office of Safety Research and Development focuses on conducting research that promotes a safe driving environment while offering practical considerations to address the needs of practitioners. Roadway lighting offers significant safety benefits but also represents a substantial share of the operating budgets of agencies tasked with maintaining the lighting infrastructure. Therefore, there is a need to optimize the safety implications and budgetary considerations.

This report describes an in-depth effort to assess the impact of roadway lighting on the overall safety performance of roadways. To accomplish this goal, the research team collected thousands of miles of real-world roadway lighting data and compared the varying lighting levels, roadway characteristics, and traffic volumes with crash history information. This comparison required extensive data manipulation and the use of geospatial linkages to pull the data together in a useable form. A robust statistical analysis of the underlying relationships among these data revealed the effects and limits of lighting on the overall roadway safety performance.

The results of this report were used to develop a proposed set of adaptive lighting criteria to assist jurisdictions in making sound safety-based decisions when considering adaptive lighting approaches. In addition, this is the most robust analysis of real-world lighting data conducted to date and is intended to serve as the foundation for future roadway lighting analyses.

Monique R. Evans
Director, Office of Safety
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16. Abstract

This report provides the background and analysis used to develop criteria for the implementation of an adaptive lighting system for roadway lighting. Based on the analysis of crashes and lighting performance, a series of criteria and the associated design levels have been developed to provide an approach for light level selection and the adjustability of the light level based on the needs of the driving environment. The data, the analysis, and the developed methodology are all considered in the document.

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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 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°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

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

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LIST OF ABBREVIATIONS

AADT	Annualized average daily traffic
ADT	Average daily traffic
ANSI	American National Standards Institute
CIE	Commission Internationale de l'Eclairage
FHWA	Federal Highway Administration
GIS	Geographic information system
GPS	Global Positioning System
HFC	Horizontal foot candles
HSIS	Highway Safety Information System
IES	Illuminating Engineering Society of North America
LCL	Lower confidence limit
LOS	Level of Service
LZ	Lighting Zone
NOAA	National Oceanic and Atmospheric Administration
NTDCRR	Night-to-day crash rate ratio
RLMMS	Roadway Lighting Mobile Measurement System
UCL	Upper confidence limit
UR	Uniformity Ratio
VTTI	Virginia Tech Transportation Institute

INTRODUCTION

With the development of new lighting technology and a push to reduce the overall energy and environmental impact of lighting, adaptive lighting has become a new trend in the roadway industry. Adaptive lighting is a design methodology in which the light output of a system is adjusted as traffic conditions change. More specifically, roadway lighting illumination levels are adjusted based on the needs of the roadway's users. The level of lighting can be reduced or dimmed when traffic on highways, sidewalks, or both is reduced. Dimming the lighting level while maintaining the lighting configuration will not affect the uniformity of the lighting or an object's contrast; however, contrast thresholds will increase, resulting in longer detection times. In addition, luminaires installed in new lighting designs often exceed the requirements of the lighting design. Over time, the system will meet or exceed the design level even as the lamps age and dirt accumulates on lenses. Adjusting the output of luminaires so the system meets the design level throughout the service life of the lamps can also save on energy costs and eliminate periods of over-lighting. This form of lighting control is not specifically considered adaptive lighting, but an adaptive lighting system provides this option.

The objectives and methodology of this project have been developed to update *Reduced Lighting on Freeways During Periods of Low Traffic Density* (Publication No. FHWA-RD-86-018), and to develop application guidelines that address the following issues:(1)

- Optimal times and conditions for reducing lighting.
- Appropriate lighting levels for various roads and road features.
- Appropriate approaches for reducing lighting.
- Energy savings and reduction in greenhouse gases that may result from reducing lighting.
- Potential legal issues related to reducing lighting, including the development of such issues since the release of the original report.

The resulting design methodology is based on existing Commission Internationale de l'Eclairage (CIE) roadway lighting criteria and provides a process to determine whether adaptive lighting is appropriate for a given roadway.

BACKGROUND

More than 50 percent of all fatal crashes occur at night, even though nighttime volumes are approximately 25 percent of all traffic. The resulting fatality rate for drivers is three times higher at night.(2,3,4) In general, the introduction of roadway lighting has been found to be a crash countermeasure on highways.

In 1989, Box completed a study comparing the crash rates on a predetermined route (approximately 1.7 mi (2.8 km)) before and after lighting units were installed.(5) The route contained five lanes, with a two-way left turn in the center lane. Several night/day evaluations were conducted to determine the number of crashes occurring at intersections with lighting versus those without lighting. Also of particular interest was the number of crashes occurring in the midblock section. Initial research showed that a total of 146 daytime and 72 nighttime intersection crashes (33 percent of crashes) occurred before the lighting installations were made. A total of 112 daytime and 44 nighttime midblock crashes (28 percent) were also noted. Following the installation of lighting units, 210 daytime and 72 nighttime intersection crashes (26 percent) were reported, and 145 daytime and 31 nighttime midblock crashes (18 percent) were reported. (These numbers include an annualized average daily traffic (AADT) increase of 33 percent between 1984 and 1987.) The ratio of night crashes to day crashes dropped following the lighting installation.

Another study completed by Box examined the relationship between illumination level and freeway crashes.(6) Data were collected on 203 mi (326.7 km) of selected roadways. The selection of the roadways was based on minimum requirements set by the research team: 1) traffic volume data collected for a full year, 2) minimum section length of 1 mi (1.6 km), 3) 1 to 3 years of crash data, and 4) unlit portions of roadway as well as lit portions with complete maintenance and installation records for luminaires. The ratio of night-to-day crashes for lighted and unlighted roadways was 1.43 and 2.37, respectively. Box reported that installing lights on freeways could potentially reduce nighttime crashes by an average of 40 percent and overall crashes by 18 percent. In addition, roadway sections with the lowest illumination range (0.3 to 0.6 horizontal foot candles (HFC)), compared with higher illumination levels (0.8 to 1.1 HFC and 1.3 to 1.5 HFC), had the lowest night-to-day crash ratios. However, Box performed a limited statistical analysis. Figure 1 shows the study's results. Using these results, an analysis of variance statistical test was performed with illuminance as a main effect. The statistical results show that there is no relationship between the number of crashes and the measured illuminance level ($F = 0.54$, $p = 0.663$). These results indicate that there is limited applicability of the results from this investigation.

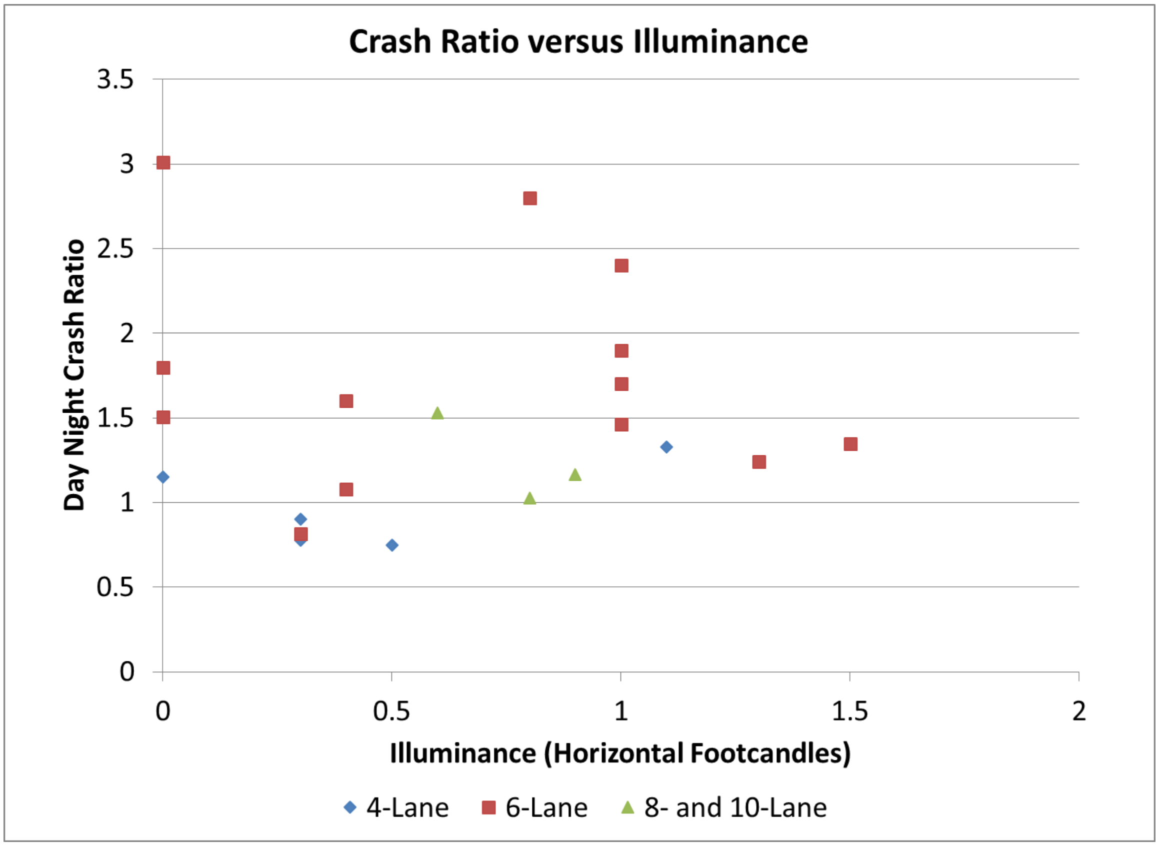


Figure 1. Graph. Crash ratio versus illuminance (horizontal foot-candles) from Box, 1971.(5)

Removal and reduction of roadway lighting have also been studied. In a study by Hilton in which every third luminaire was turned off, the lighting system still maintained the minimum design illumination (according to roadway standards) despite a 22-percent reduction in illumination. (Note that this reduction of 22 percent from shutting off 33 percent of the luminaires is not expected in terms of the delivered light on the roadway; however, new lamps were installed at the same time.)(7) In fact, most roadway lighting systems provide more illumination than the design requires. This is because roadway lighting systems are intended to meet the design levels at the end of the lamp service life. Turning off every third luminaire, on a system with new lamps, was partially compensated for by this initial light level. After 2 years, illumination had fallen to 32 percent of the initial value and barely met the 3:1 maximum suggested for uniformity for freeways. (Uniformity Ratio (UR) is the ratio of the average lighting level on the roadway to the minimum lighting level on the road.) Hilton does not provide crash data for the road segment during this evaluation, so it is not known whether the reduction in light level resulted in more crashes. Hilton’s findings suggest that standards should consider the impact of depreciation of light over time. Initial light output could be reduced when sources are producing higher light levels than required for the lighting design. As the sources age, the light output can be increased to continue to meet design levels. This would conserve energy over the service life of the lamps. Hilton recommended that illumination levels should be reduced on initialization by one-third for no more than 6 months after activation.(7)

Richards's 1979 case study on Texas highways highlighted the economic consequences of reducing roadway lighting during a time of energy conservation in the early 1970s.(8) A segment of road approximately 7 mi (11.2 km) long on Interstate 35 was chosen for the lighting reduction. Richards found that despite reducing the yearly cost of energy by nearly $25,000, the State estimated an increase in crash costs of $17,000 per year. Richards studied crash rates and costs for 2 years before and 2 years after lighting removal. In the 2 years after lighting removal, Richards cites an increase not only in crash rates but also in crash severity as the rate of fatal crashes increased.(8) The crash increase led to a crash cost total of $33,880, which exceeded the estimates developed by the State prior to the project.

In 2001, Oregon chose to reduce power consumption by State agencies by 10 percent in response to a perceived energy shortage in the Pacific Northwest. The Oregon Department of Transportation (ODOT) saw the opportunity to conserve energy by selectively reducing illumination on interstate highways within the State. Traffic engineers selected what they perceived to be the safest stretches of highway—based on geometry, crash history, and pedestrian activity—for lighting reduction.(9)

The reduction locations fit into three categories, as listed by Monsere et al.: 1) interchanges where lighting was reduced from full to partial lighting design, 2) interchanges where lighting was reduced from a partial plus design to a partial design, and 3) highway sections where mainline lineal lighting was reduced or removed.(9) In all, lighting systems at 47 total interchanges and just over 6 mi (9.7 km) of highway were modified. The researchers completed a before-and-after study on the safety effects of these changes. The study includes 9 years of before and 4 years of after data.(9)

When the lighting design was reduced from full to partial, nighttime crashes increased less than 4 percent. When adjusted from full lineal lighting to all or some luminaires turned off, crashes increased nearly 30 percent, and fatal and injury crashes increased nearly 40 percent. When lighting was reduced from partial plus to partial design, crashes decreased by 35 percent; however, Monsere et al. explain that this comparison was the least robust because the sample size was much smaller, and the result should not be interpreted as a definitive safety benefit.(8) Also, the roadways chosen for reductions in lighting designs were selected based on a history of safety, which may have biased the results.(9)

ADAPTIVE LIGHTING

Control systems are becoming more prevalent for roadway lighting. These systems allow the output of each luminaire to be controlled to avoid over-lighting, which Boyce et al. proposed could initially exceed lighting requirements by as much as 40 percent for newly installed luminaires.(10) (The amount of over-lighting depends on the light source and how much its output declines over time.) These control systems consist of a home base controller and individual modules in each luminaire, which allow for separate and direct control of each luminaire. Development of these types of lighting control systems enables adaptive roadway lighting. Adaptive lighting considers the possible energy conservation when lighting is reduced during non-peak traffic hours. During hours when pedestrian and motor traffic decreases, lighting can, in theory, be reduced without resulting in an increase in crashes or crash severity.

There are various degrees of adaptive lighting. The level of lighting can be reduced or dimmed when traffic on highways, sidewalks, or both is reduced. Reducing the light level will not affect the uniformity of the lighting or an object's contrast; however, the contrast threshold will increase, resulting in a longer detection time. FHWA-RD-86-018, developed in 1985, lists five different methods for reducing lighting to conserve energy.(1) One is to eliminate all lighting after midnight or during other designated periods of reduced pedestrian and motor traffic. Two partial lighting methods involve extinguishing every other luminaire or extinguishing all luminaires on just one side of the roadway. A fourth method is to install two luminaires per light pole and extinguishing one light per pole. The final method, and the one frequently discussed, uses special dimming technology that will reduce the lighting by a predetermined percentage. All five of these methods may be implemented after midnight or another appropriate, designated time. These dimming methods depend on the available technology and the ability to control the lighting system remotely. In addition to adapting light levels based on motor vehicle and pedestrian traffic, luminaire output can be controlled so that the system does not exceed the design levels by adjusting the light output level to respond to lamp aging and dirt depreciation.(11)

Lighting can be turned off completely if a considerable decrease in traffic rate is expected. However, despite the increased energy savings, this method is not recommended by the CIE.

The lighting can also be adaptive by detecting an increase in roadway users or a need for more lighting and controlling itself accordingly, provided that the technology is available to do so.

For cost efficiency, it is thought that methods involving turning lights completely off, turning off lights on one side, or turning off every other light are the most efficient. These methods reduce energy usage and costs and are more practical for implementation. However, these methods present legal issues associated with whether the resulting lighting meets accepted design criteria after the lighting is reduced and whether changes to the design criteria might affect safety of roadway users.(1)

Methods that involve dimming the lights do not conserve as much energy as light-extinguishing methods. However, light-dimming methods are considered neutral regarding their impacts on safety because the resulting light levels meet appropriate design criteria that are believed to meet the requirements of road users under the specified traffic conditions. These methods are considered more prudent because the amount of light is more likely to meet Illuminating Engineering Society of North America (IES) and American National Standards Institute (ANSI) Recommended Practice for Roadway Lighting (ANSI/IES RP-8-00) recommendations.(4)

In 1985, the Federal Highway Administration (FHWA) evaluated detection performance for drivers detecting a small target under different reduced lighting conditions.(3) The target was a 6- by 6-inch (152.4- by 152.4-mm) square with a smooth, non-reflective surface. The best condition for observing targets from farthest away was full (continuous), unaltered lighting, which had a mean observation distance of 287.9 ft (87.8 m). The mean detection distance for lighting dimmed to 75-percent power was 232.6 ft (70.9 m). When the power was reduced to 50 percent, the mean distance was 223.8 ft (68.2 m). When every other luminaire was extinguished, the distance dropped to 204.8 ft (62.4 m). When only one side of a roadway previously lit on both sides was lit, the mean detection distance dropped to 163.4 ft (49.8 m), a detection distance similar to that when no lighting at all was operational (163.2 ft (49.7 m)).

These results indicate that maintaining a proper lighting design, with consistent URs, results in improved target detection distances, which strongly suggests improved safety as compared to extinguishing selected luminaires.(3)

The cost-benefit analysis observed by the 1985 FHWA study revealed a contrasting result.(1) In terms of annual energy savings per mile, eliminating all roadway lighting was the most conservative and annually saved $1,877 per mi. Extinguishing half of the lights, whether all on one side or every other luminaire, saved approximately $938 per mi. Fixed or variable power dimming up to 50 percent also saved approximately $938 per mi. These results, coupled with the detection results, tend to suggest that reducing the power of the luminaires (dimming) while maintaining uniformity might be the best solution for conserving energy without negatively affecting driver or pedestrian safety.

CURRENT STANDARDS FOR ADAPTIVE LIGHTING

The current approach to adaptive lighting is supported by two guidance documents: ANSI/IES RP-8-00 and CIE Document Number 115 (CIE 115).(11)

The IES method specifies roadway lighting by road type and the potential for pedestrian conflict. The lighting requirements, as of the date of this publication, are shown in table 1. This method adjusts the lighting levels based on changes in the pedestrian conflict level, rather than by reclassifying the roadway.

Table 1. IES recommended maintained luminance values for roadways.(4)

Road and Area Classification					
Road	**Pedestrian Conflict Area**	**Average Luminance L_{avg} (cd/m^2)**	**Luminance Uniformity Ratio L_{avg}/L_{min}**	**Luminance Uniformity Ratio L_{avg}/L_{max}**	**Veiling Luminance Ratio (maximum) L_v to L_{avg}**
Freeway Class A	No Conflict	0.6	3.5	6.0	0.3
Freeway Class B	No Conflict	0.4	3.5	6.0	0.3
Expressway	High	1.0	3.0	5.0	0.3
	Medium	0.8	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Major	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Collector	High	0.8	3.0	5.0	0.4
	Medium	0.6	3.5	6.0	0.4
	Low	0.4	4.0	8.0	0.4
Local	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

The CIE method for adapting roadway lighting is much more flexible: roadways are classified as *M* for motorway, *C* for conflict areas, and *P* for roadway with pedestrians.

Using the CIE method to standardize how lighting may be adapted, we must first investigate how non-adaptive lighting levels are derived. Data from the CIE (table 2) detail the parameters for selecting M-class lighting. Values are defined for each parameter option (e.g., very high speed > 65 mi/h (105 km/h)), each parameter value is then given a weighting value (V_W), and the sum of those weighting values (V_{WS}) is used in the following equation:

$$\text{Number of lighting class } M = 6 - \mathrm{V_{WS}}$$

Figure 2. Equation. Number of lighting class M.

Table 2. CIE parameters for selecting M lighting class.(11)

Parameter	**Options**	**Weighting Value $\mathbf{V_W}$**
Speed	Very High High Moderate	1 0.5 0
Traffic volume	Very High High Moderate Low Very Low	1 0.5 0 -0.5 -1
Traffic composition	Mixed with High Percentage of Nonmotorized Mixed Motorized	2 1 0
Separation of carriageways (median)	No Yes	1 0
Intersection density	High Moderate	1 0
Parked vehicles	Present Not Present	0.5 0
Ambient luminance	High Moderate Low	1 0 -1
Visual guidance/Traffic control	Poor Moderate or Good	0.5 0
Sum of weighting values ($\mathbf{V_{WS}}$):		

Table 3 details lighting classes M1 through M6, which cover various roadway conditions and road surface luminance levels. A lighting class is chosen based on summing the weighting values, subtracting from six, and applying the resulting value as the M class. If the resulting number is not a whole number, then the next lowest whole number is used. As an example, if $V_{WS} = 4.5$, the lighting class is M1. ($6 - 4.5 = 1.5$, which is reduced to M1.) If the resulting number is negative, the lighting class is M1.

Table 3. Lighting classes for motorized traffic.(11)

Lighting Class	Road Surface				Threshold Increment	Surround Ratio
	Dry			Wet		
	L_{av} in cd*m^{-2}	U_u	U_t	U_o	f_{TI} in %	R_S
M1	2.0	0.40	0.70	0.15	10	0.5
M2	1.5	0.40	0.70	0.15	10	0.5
M3	1.0	0.40	0.60	0.15	15	0.5
M4	0.75	0.40	0.60	0.15	15	0.5
M5	0.50	0.35	0.40	0.15	15	0.5
M6	0.30	0.35	0.40	0.15	20	0.5

In an adaptive lighting implementation, lighting classes change depending on the change in parameters. If traffic volume, intersection density, or ambient luminance fluctuates nightly or even hourly, an adaptive control system can monitor the changes and illuminate accordingly.

It is important to note that other parameters and lighting classes exist; the ones presented here are examples of how lighting classes can be adaptive. CIE 115 contains more classes and specific parameters that pertain to those classes.(11)

SUMMARY

Previous efforts that investigated the potential for adaptive lighting show that there is a benefit to having the lighting available for both the driver and other road users, but there is the potential to reduce lighting based on established criteria. The next phase of the current effort is to consider the development of specific design criteria for the development of guidelines for adaptive lighting. These design criteria will include both the previous design criteria and methodologies.

CHAPTER 1. DATA COLLECTION APPROACH

The development of design criteria requires establishing a link between the lighting level and roadway safety. This relationship will establish the possibility of defining the design criteria as well as determining the important parameters that may affect the lighting design level. To establish these criteria, a significant amount of data was obtained from participating States and through field measurements. A significant amount of data was also gathered from the Highway Safety Information System (HSIS), which contains linked crash and roadway data for State-maintained roadways in participating States.

STATE DATA

Data collected from the States included crash data, lighting design, traffic data, and roadway data. Each of these data categories was loaded into a geographic information system (GIS) data system to geographically relate all the data measures. Because of inconsistencies in data format and variables from multiple data sources, separate data structures were maintained for each data type and each State. A geocoded system relates and compares the collected data.

Based on geographic coverage as well as availability of crash and lighting pole location data, seven States were selected for in situ data collection. Participating States in the study were California, Delaware, Minnesota, North Carolina, Vermont, Virginia, and Washington.

The sources for each State are shown in table 4.

Table 4. Primary State-level data sources.

State	CA	DE	NC	MN	VA	VT	WA
GIS Road Network	Caltrans	DelDOT	NCDOT	MnDOT	VDOT	VTrans	WSDOT/ HSIS
Lighting Performance Data	VTTI	VTTI	VTTI	VTTI	VTTI	VTTI	VTTI
Lighting Design Data	Caltrans	DelDOT	NCDOT	MnDOT	VDOT	VTrans	WSDOT; City of Seattle
Crash Data	HSIS	DelDOT	HSIS	HSIS	VDOT	VTrans	WSDOT/ HSIS
Roadway Data	HSIS	DelDOT	HSIS	HSIS	VDOT	VTrans	WSDOT/ HSIS
Traffic Data	Caltrans	DelDOT	NCDOT	MnDOT	VDOT	VTrans	WSDOT

Caltrans = California Department of Transportation
DelDOT = Delaware Department of Transportation
MnDOT = Minnesota Department of Transportation
NCDOT = North Carolina Department of Transportation
VDOT = Virginia Department of Transportation
VTrans = Vermont Agency of Transportation
VTTI = Virginia Tech Transportation Institute
WSDOT = Washington State Department of Transportation

LIGHTING PERFORMANCE DATA

The lighting performance data were collected in the field and convey detailed information on the performance of the lighting systems at the time of collection. This study represents the first national-level effort to collect such data, which are a major contribution of this research.

Lighting performance was measured in situ using a mobile data collection system developed by the research team. The Roadway Lighting Mobile Measurement System (RLMMS), developed by the Virginia Tech Transportation Institute (VTTI), has the ability to collect data regarding horizontal illuminance, roadway luminance, glare from oncoming traffic and other external light sources, and Global Positioning System (GPS) position. The system also has input buttons to flag special features in the data stream.

The RLMMS contains four waterproof illuminance detectors. Each detector is positioned on the end (facing upward) of each of four arms of an apparatus (also known as the “Spider”), which is mounted on the roof of a vehicle. Positioned in the center of the four arms is a GPS receiver. The GPS’s Universal Serial Bus cable and the detector leads are routed into the vehicle via a rear window data collection box. A fifth illuminance detector is mounted on the windshield, facing forward, to measure vertical illuminance on the windshield. This value is a surrogate for oncoming glare.

The illuminance measurements are coupled with luminance and color cameras that take snapshots of the roadway. The cameras are connected to their own stand-alone computer for housing the images, which can also be viewed on a single laptop screen along with the other data being collected in the vehicle by using a Controller Area Network reader. Validation of the cameras included rigorous calibration and tuning. Further details of the analyses of the camera's output are also detailed in Meyer et al.(12) The system layout is shown in figure 3. The GPS unit and the illuminance meter network are placed on the roof of the vehicle on an aluminum framework, which is attached using suction cups. The color camera, the luminance camera, and the vertical illuminance meter are attached on the inside of the windshield with suction cups.(13) The data from the RLMMS have been found to be both repeatable and reproducible through standard repeatability and reproducibility techniques.(12)

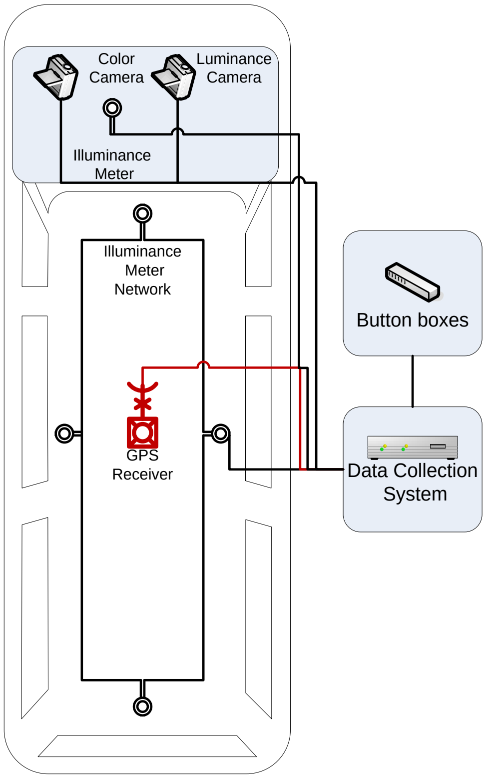
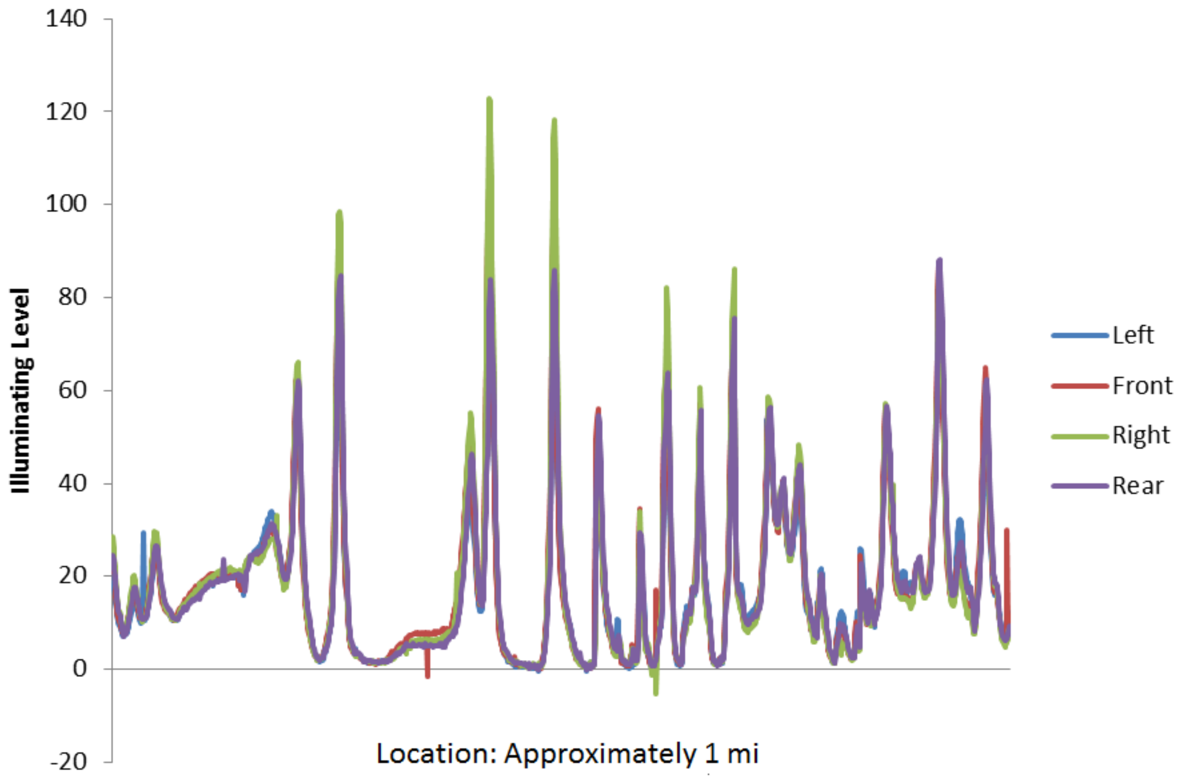


Figure 3. Diagram. Roadway Lighting Mobile Monitoring System (RLMMS).(1)

Members of the project team drove on the routes selected and collected lighting data at a frequency of 20 Hertz (Hz) and at a video capture rate of 3.75 frames per second (fps). The data collection vehicle adhered to the posted speed limit and followed the direction of roadway signage. Because of the significant number of miles over which the lighting performance data were collected, multiples files were generated.

The acquired data were integrated with ARC-GIS™ software with the capability of converting the roadway lighting data gathered and forming a visual database.

As shown in Figure 4, the measured lighting level is captured along the roadways by the four detectors (left, front, right, and rear). Because the angle and length of the line of sight between each detector and each luminaire are different, there are differences in the detector readings. As a result, detectors were processed separately in the data reduction. Note the data have been smoothed using a moving window algorithm to mitigate the fluctuation in lighting caused by locations of lighting poles.



1 mi = 1.6 km

Figure 4. Graph. Field-collected lighting data (1-mi segment).

Another issue in field data collection is that the location of the lighting pole varies from segment to segment, for example on the left or right side. To minimize the resulting discrepancy in lighting measurement and to increase the accuracy of the measurements, data were collected in the outermost and innermost lanes for roadways consisting of at least two lanes in each direction. The only time these lanes were not used was for construction or cases in which emergency vehicles were parked on the shoulder.

DATA ANALYSIS

The data analysis focused on the relationship between lighting level and crash risk during nighttime. Specific emphasis was on whether roadway and traffic characteristics affect this relationship. The analysis was conducted using the in situ lighting data collection and historical data, including traffic and crash information.

The nighttime crash risk can be measured by several metrics. Simple crash rate for a road segment, as measured by number of crashes per million vehicle mi traveled, is shown in the equation in figure 5.

$$\text{crash rate} = \frac{\#\text{ of crashes}}{\text{traffic volume} \times \text{segment length}}$$

Figure 5. Equation. Crash rate for States with traffic volume information.

The nighttime crash risk can be affected by many factors other than lighting, for example geometric design features and traffic control. The daytime crash rate at the same road segment was used as a control for these potential confounding factors. For each road segment, the night-to-day crash rate ratio (NTDCRR) was calculated as shown in the equation in figure 6. The NTDCRR reflects the relative magnitude of nighttime crash risk compared with daytime crash risk. Because daytime and nighttime crashes shared the same road design features and traffic control features, the rate ratio directly reflects the factors that only differ by day and night, with visibility level being the primary one. Therefore, the NTDCRR indicates the impact of lighting and light levels while controlling for the impact of the roadway design, traffic concerns, and other factors associated with road segment characteristics. As such, the NTDCRR was considered the primary metric to evaluate the effects of roadway lighting.

$$\text{Night - to - day crash rate ratio} = \frac{\text{crash rate of night}}{\text{crash rate of day}}$$

Figure 6. Equation. Night-to-day crash rate ratio for States with day/night traffic volume information.

The calculation of night-to-day crash rate ratios requires night and day traffic volumes. In this study, we used continuous hourly traffic count stations in close proximity to the study road segments and average daily traffic (ADT) on the study road segments to estimate hourly traffic. The National Oceanic and Atmospheric Administration (NOAA) sunrise and sunset times were used to classify the natural lighting into day, night, and twilight conditions. Twilight was defined as 30 minutes before sunrise and 30 minutes after sunset. The nighttime traffic volume was estimated based on the time of nighttime and hourly traffic volume.

The data availability varies by State. As listed in table 5, not all States provided hourly traffic count station data and thus no night and day traffic volume information. For States without day/night traffic volume information (i.e., Delaware, North Carolina, and California), the night-to-day crash ratio as shown in the equation in figure 7 can be used.

$$\text{Night} - \text{to} - \text{Day crash ratio} = \frac{\#\text{ of crashes at night}}{\#\text{ of crashes during the day}}$$

Figure 7. Equation. Night-to-day crash ratio for States without day/night traffic volume information.

The night-to-day crash ratio does not factor in the differences in day and night traffic volumes. To make the comparison among road segments meaningful, the underlying assumption is that night-to-day traffic volume ratio should be similar across road segments. Therefore, the results in the following analysis were based on the four States with night/day traffic volume (i.e., Washington, Minnesota, Virginia, and Vermont).

Table 5. Day and night traffic volume indication per State.

State	Has night/day traffic volume	ADT
Washington	Yes	Yes
Delaware	No	Yes
Minnesota	Yes	Yes
Virginia	Yes	Yes
North Carolina	No	Yes
Vermont	Yes	Yes
California	No	Yes

The analysis is based on road segments. All major data sources, including crash, traffic volume, road characteristics, and lighting data, were integrated based on spatial relationship, the processing of which was only feasible in a GIS environment. In a GIS base map, roads are represented by a series of arcs, which is the minimum spatial unit with homogeneous characteristics. As a consequence, the segmentation of the road was determined by the minimum arc unit on GIS base maps. The length of the road segment is typically short to ensure relatively homogeneous characteristics for the segment. The summary statistics of the road segments by State are shown in table 6.

Table 6. Road segment summary statistics.

State	Minimum	1st Quarter	Median	Mean	3rd Quarter	Maximum	Frequency	Total
WA	0.01 mi	0.14 mi	0.26 mi	0.34 mi	0.43 mi	3.00 mi	1,315 Hz	446.93 mi
MN	0.005 mi	0.086 mi	0.194 mi	0.28 mi	0.37 mi	3.96 mi	889 Hz	251.00 mi
VA	0.02 mi	0.80 mi	1.25 mi	1.36 mi	1.74 mi	4.88 mi	169 Hz	230.24 mi
VT	0.003 mi	0.046 mi	0.09 mi	0.165 mi	0.182 mi	2.40 mi	355 Hz	58.62 mi

1 mi = 1.6 km

For a specific lighting level, there are multiple segments. Longer segments should have more exposure to crashes and more stable estimation. A weighted rate ratio was used to estimate the average NTDCRR for a given lighting level, as shown in the equation in figure 8.

$$\text{Weighted mean crash rate ratio for lighting level l}$$
$$= \sum_i \frac{\text{length of segment i}}{\text{summation of all segment length}} \text{NTDCRR for segment i}$$

Figure 8. Equation. Weighted crash rate ratio.

Statistical Models

The crash rate ratio is a random variable and has its range from 0 to positive infinity. Through log transformation, it can be modeled as a normal distribution as shown in figure 9.

$$\log(\mathrm{Yi}) \sim \mathrm{Normal}\left(\lambda_i, \frac{\sigma^2}{\text{length of segment}}\right)$$

Figure 9. Equation. Normal distribution equation for the crash rate ratio.

Here Y_i is the night-to-day crash rate ratio for road segment i ; λ_i is the expected log crash rate ratio for segment i . The length of segment serves as a weighting factor, such that longer segments would have a larger impact on inference results. The λ_is are linked to lighting levels as shown in figure 10.

$$\lambda_{\mathrm{i}} = \beta_0 + \beta_1 \mathrm{lighting}_{\mathrm{i}}$$

Figure 10. Equation. Regression link for lighting.

The $lighting_i$ is the measured lighting level for segment *i*, and the β values are regression results. There are a couple of ways to define the $lighting_i$ variable: model 1, the average lighting measure for segment *i* (continuous), or model 2, the discretized average lighting measure. Model 1 allows the evaluation of the overall trend of NTDCRRs with increased lighting levels. Model 2 allows the comparison of NTDCRRs among different discretized lighting levels.

Lighting Metrics

The comprehensive lighting data collected in this study allow multiple characteristics of the lighting to be evaluated. In this study, five metrics were used: 1) horizontal illuminance, 2) vertical illuminance, 3) vertical-to-horizontal illuminance ratio, 4) lighting uniformity measure, and 5) luminance. Detailed definitions for each metric are provided in later sections.

The original lighting data were collected based on time (20 Hz), with the spacing of data points dependent on the vehicle's speed. For example, there could be hundreds of data points corresponding to one location when the vehicle was stopped at an intersection. In contrast, when the vehicle was traveling at 65 mi/h (105 km/h), two adjacent data points could be more than 3.3 ft (1 m) apart. Thus, a reasonable approach is to base the analysis on distance instead of data points.

An algorithm was developed to calculate the distance between two data points based on the projected coordinates. The data were then grouped based on spatial distance. The segments were divided into 13.1-ft (4-m)-long sections. The median of all data points within a 13.1-ft (4-m) section was used to represent the lighting level in the section. This approach effectively addressed the uneven spacing caused by vehicle speed and provided a more accurate lighting level measurement.

The mean lighting metrics for the horizontal illuminance, vertical illuminance, vertical-to-horizontal illuminance ratio, and lighting uniformity measure were calculated as the average metric values from the distance-sampled lighting points. Because there were at least two trips for each road segment, the average of these trips was used to represent the mean lighting level in the segment.

Crash Data

Crash data were aggregated into nighttime, daytime, and twilight periods, according to the location, date, crash time, and sunrise/sunset time calculated from the NOAA chart. Only daytime crashes and nighttime crashes were used in the analysis. The summary of crashes by State is shown in table 7.

Table 7. Summary of crash data by State.

State	Number of Years With Crashes	Daytime Crash Sum (Over the Entire Study Period)	Nighttime Crash Sum (Over the Entire Study Period)
WA	5	31,189	11,603
MN	5	13,375	4,853
VA	5	17,013	6,802
VT	6	2,603	587

CHAPTER 2. LIGHTING AND CRASH RELATIONSHIP

One of the first tasks of the project was to evaluate the link between lighting and crash rate. As mentioned, previous research has shown roadway lighting will affect crash risk. Specifically, the relationship being investigated is the link between lighting levels and lighting quality and crash rates. Establishing such a relationship would allow for determining the optimal lighting level for roadways under various traffic conditions. It should be noted that the weather conditions were not included in this analysis and provide the basis for future research.

Currently, there are four criteria to consider in the design of roadway lighting: roadway illuminance (both horizontal and vertical), luminance, and uniformity. Horizontal roadway illuminance is the amount of light falling on the roadway surface; vertical illuminance is the amount of light falling on a vertical surface, such as a pedestrian; luminance is the amount of light perceived by the road user; and uniformity is the ratio of illuminance or luminance values, such as maximum to average, average to minimum, or maximum to minimum. The data collection system for this project was able to measure each of these criteria.

HORIZONTAL ILLUMINANCE

The horizontal illuminance was calculated as the average of four illuminance levels measured by detectors at the top of the data collection vehicle. The mean value for a road segment was based on the average of multiple trips for the road segment. The distribution of the mean values is shown in figure 11.

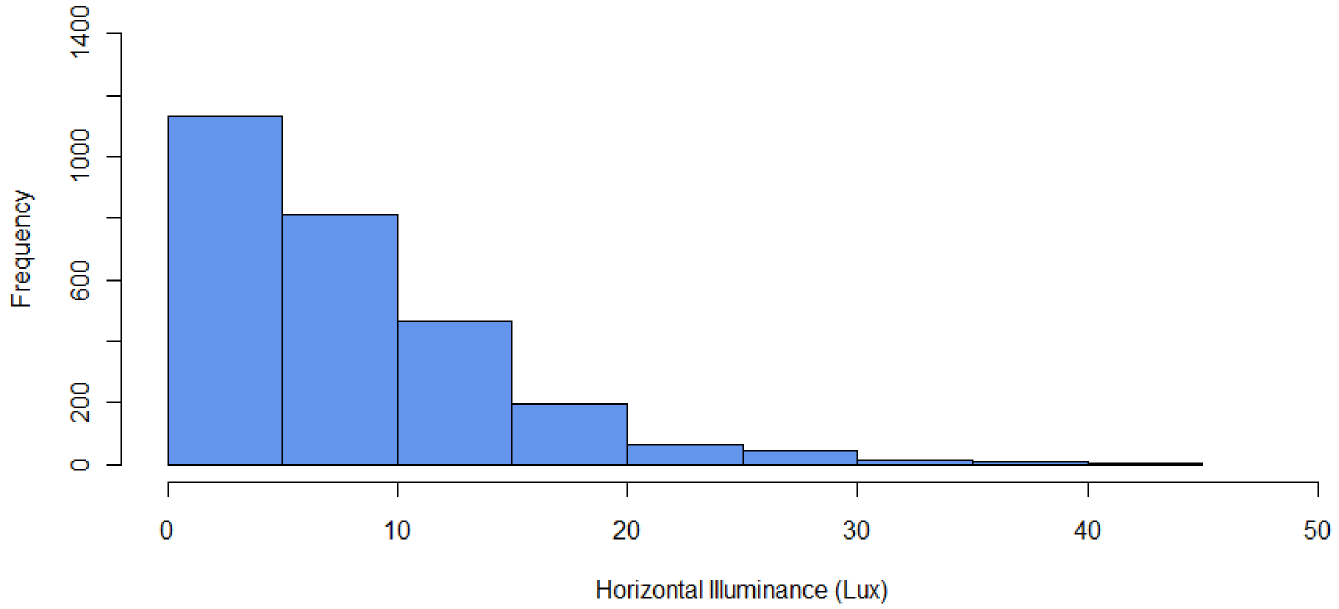


Figure 11. Distribution of mean horizontal illuminance level.

The mean horizontal illuminance values were grouped into eight categories based on the characteristics of roadway lighting and the distribution of lighting for road segment samples, as shown in table 8. Note that the bins for the values in table 8 are different from those in figure 11 because the histogram focuses on the distribution of the samples.

Table 8. Horizontal illuminance lighting level.

Lighting Level	0	1	2	3	4	5	6	7
Range of Mean Horizontal Illuminance Variables (Lux)	0~0.5*	0.5~3	3~6	6~9	9~12	12~15	15~18	> 18

* 0~0.5: segments with mean horizontal illuminance variables between 0 and 0.5 lux.

Figure 12 shows the relationship between the horizontal illuminance level and weighted mean night-to-day crash rate ratio. (The illuminance values are the average for each bin of data.) The weighing method is discussed in figure 8. This analysis includes all the lighting that was captured by the measurement system. The data below 3 lux can be considered indicative of no roadway lighting. These data can also be considered as maintained lighting levels because the systems were measured as-is with no estimation of the impact of the age of the luminaire system. The primary indication from this figure is that there is a distinct relationship between lighting and the NTDCRR.

The linear model results link the NTDCRR to lighting levels, and the results indicated there is a significant decrease in NTDCRR with the increase of average horizontal lighting levels (model 1: regression coefficient = -0.02, *p*-value < 0.001). The comparison of NTDCRRs by discretized lighting levels based on model 2 indicated that the NTDCRRs of lighting levels 0 and 1 are significantly higher than other levels. However, there is no statistically significant difference for lighting levels 2 to 7. This is consistent with the observation from figure 12 that an increase in the lighting level from 5 lux to higher levels does not appear to affect the crash rate ratio. There appears to be a further reduction in the crash rate at approximately 16 lux; however, because only 28 mi (45 km) of data are in this category, the result is not statistically significant. These results indicated that although lighting will benefit road safety, increasing the lighting level does not necessarily always lead to a safer road. There is potentially over-lighting under current practice and an opportunity for adaptive lighting design.

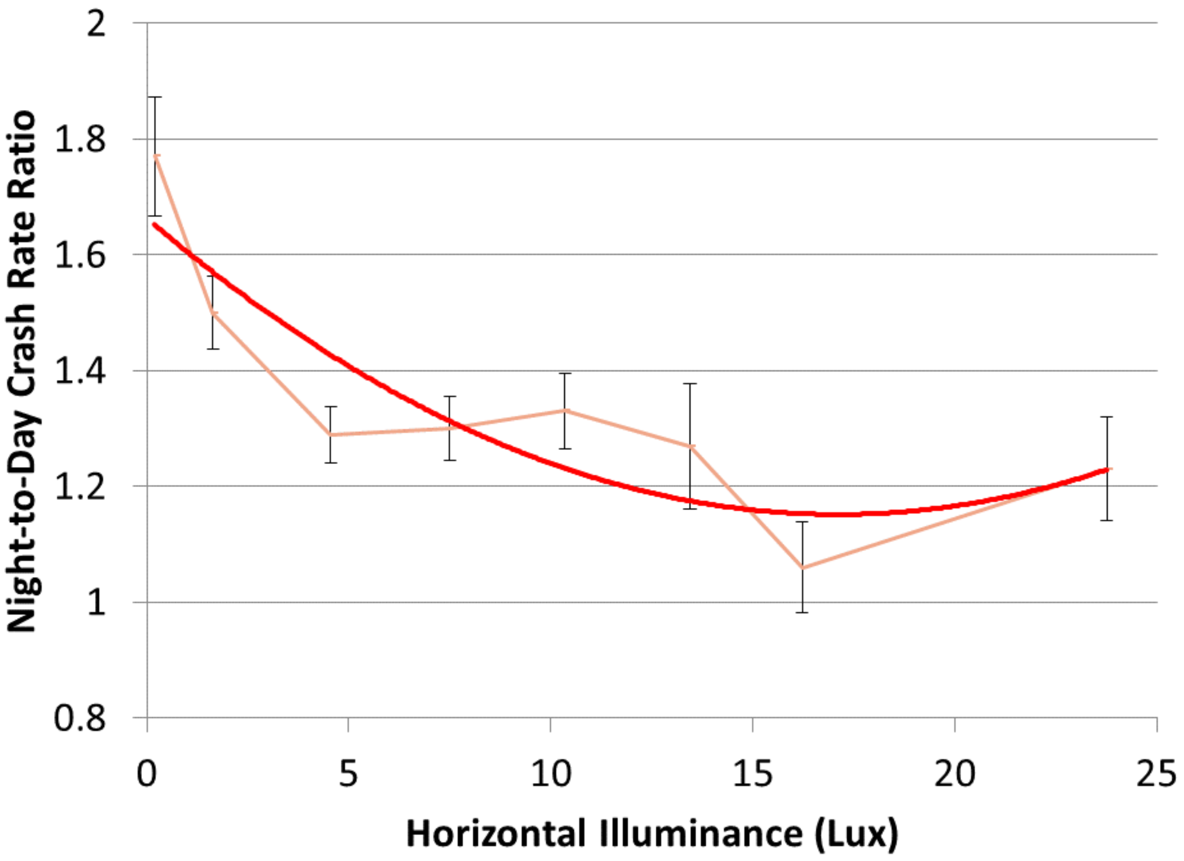


Figure 12. Graph. Relationship between mean horizontal illuminance level and weighted night-to-day crash rate ratio. Best fit line $R^2 = 0.7944$.

Note that in all figures that contain error bars, these bars represent standard error, and the curve fits are second order polynomials.

VERTICAL ILLUMINANCE

The vertical illuminance was based on the illuminance detector positioned behind the windshield inside the vehicle. The tint of the windshield can reduce the illuminance value up to 30 percent.(14) To account for making measurements from inside the vehicle, the measured values of vertical illuminance were multiplied by 1.5. As an example, a measured value of 2.5 vertical lux inside the vehicle is corrected to a value of 3.75 lux outside the vehicle. The distribution of vertical illuminance metrics by road segment is shown in figure 13. According to the relationship between the horizontal and vertical illuminance measures discussed above, the categorization of vertical illuminance is shown in table 9.

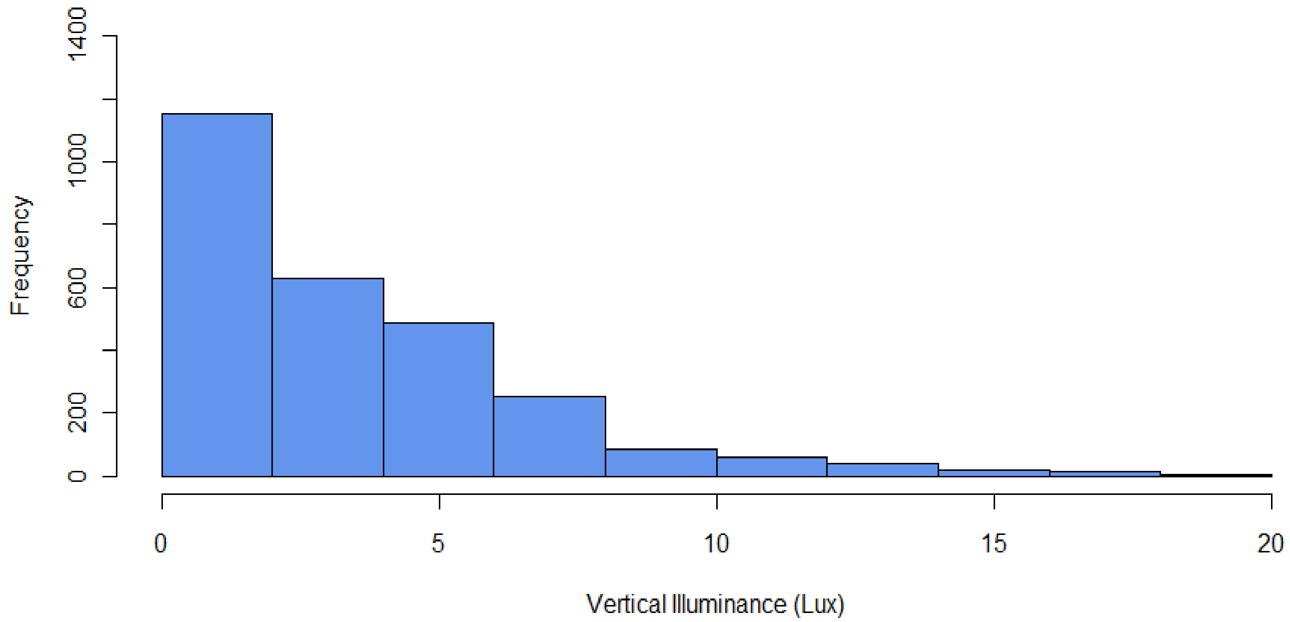


Figure 13. Graph. Distribution of mean vertical illuminance level.

Table 9. Vertical illuminance lighting level.

Vertical Illuminance Level	0	1	2	3	4	5	6	7
Range of Mean Vertical Illuminance (Lux)	0~0.3*	0.3~2	2~4	4~6	6~8	8~10	10~12	>12

* 0~0.3: segments with mean vertical illuminance between 0 and 0.3 lux.

Figure 14 shows the vertical illuminance results compared with NTDCRRs. The relationship of these results to the crash rate ratio is similar to that of the horizontal illuminance. This is an expected result; with the typical optics of a luminaire on the roadway, the horizontal and vertical illuminances are intrinsically linked. The results from the regression model indicated that there is a significant decrease with the increase of lighting levels (model 1 coefficient: -0.04; *p*-value < 0.0001). The comparison using model 2 indicated that the NTDCRRs for lighting levels 0 and 1 are significantly higher than other levels. There is no statistically significant difference among the other levels.

Vertical illuminance, however, has two components that can affect the driver. The first is the highlighting of the vertical surfaces of objects in the roadway, providing contrast and visibility. The second is glare (a bright or disturbing light source that causes discomfort or disables vision), which is caused by light reaching the driver's eye and can limit the driver's visibility. The method used for measuring vertical illuminance more closely represents a measure of glare, however, with the assumption that the vertical illuminance measured from the driver's viewpoint can be related to the visibility provided by the lighting system.

The results of the present investigation show that the minimum required value may be as low as 3 lux (based on a visual inspection of the relationship presented). Previous research has shown that the average vertical illuminance level required for the detection of pedestrians in a midblock crosswalk is 20 lux.(15) This is an interesting comparison in that the lower values of vertical illuminance found in this investigation may indicate that the vertical illuminance level of 3 lux is adequate for drivers to perceive their surroundings, while still not being adequate for the rapid and accurate identification of pedestrians required for the perception of the roadway.

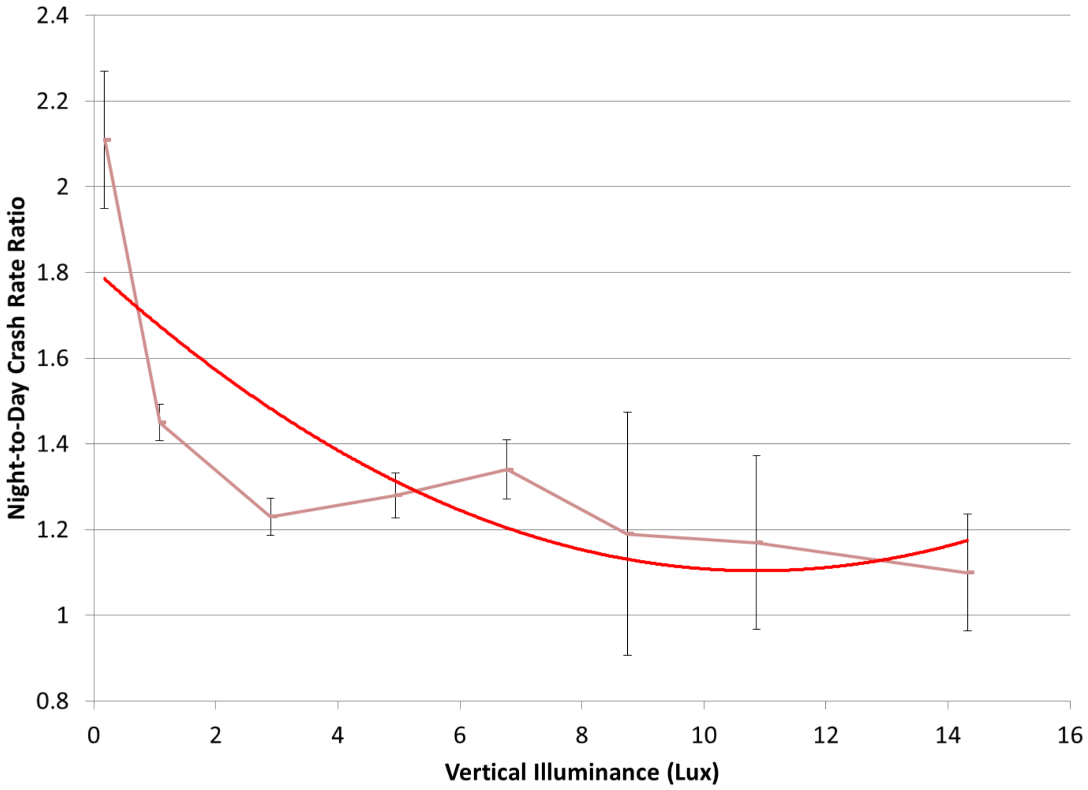


Figure 14. Graph. Relationship between mean vertical illuminance level and weighted night-to-day crash rate ratio.

VERTICAL-TO-HORIZONTAL ILLUMINANCE RATIO

As mentioned, vertical illuminance has a dual impact on the driver: visibility of objects in the roadway and also as a measure of glare. Drivers perceive glare as the difference between bright light sources in the field of view compared with other sources. One measure of the potential impact of glare on the driver is the vertical-to-horizontal illuminance ratio. The distribution of the mean of the vertical-to-horizontal illuminance ratio is shown in figure 15. (A few outliers greater than 5 were censored for clarity.) Because there are no historical data to guide the threshold of classification, the classification was based on an approximately equal number of road segments in each class as shown in table 10.

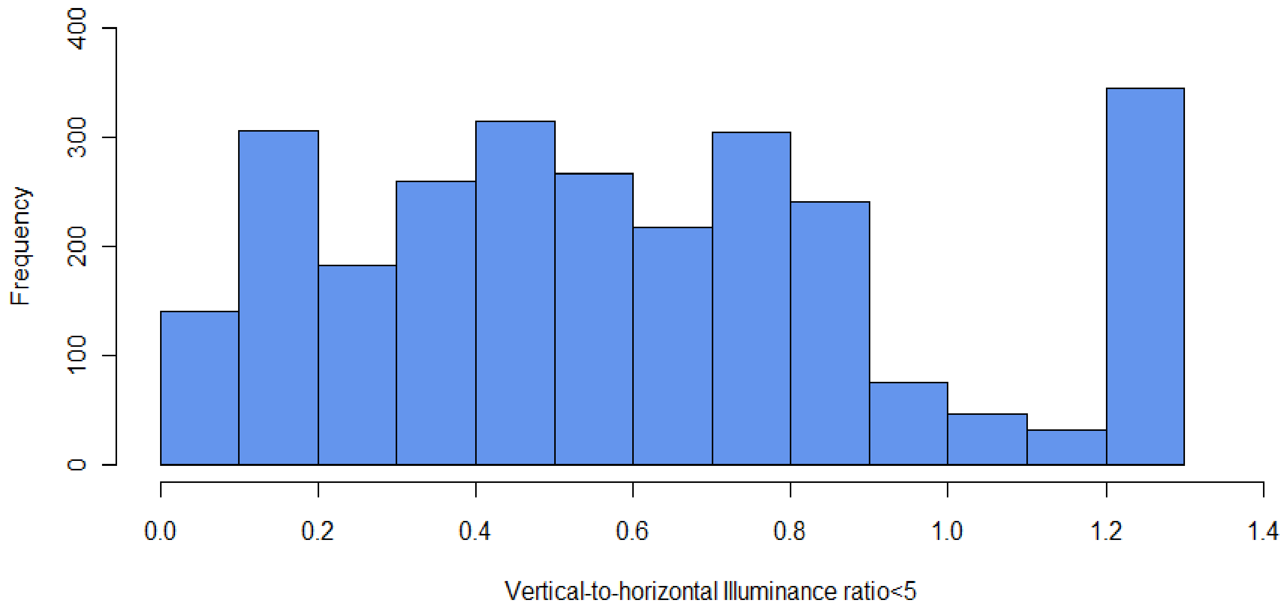


Figure 15. Graph. Distribution of vertical-to-horizontal illuminance ratio (censored at 5).

Table 10. Vertical to horizontal illuminance lighting level.

Vertical to Horizontal Lighting Level	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Mean of Vertical to Horizontal Level	0~0.15*	0.15~0.3	0.3~0.45	0.45~0.55	0.55~0.7	0.7~0.8	0.8~1.2	> 1.2

* 0~0.15: segments with mean of vertical to horizontal level between 0 and 0.15.

Figure 16 shows this relationship between the vertical-to-horizontal illuminance ratio and NTDCRR. As can be seen, there is a general trend of an increasing night-to-day crash rate ratio with an increasing vertical-to-horizontal illuminance ratio. This is expected because the visibility of objects in the roadway can be limited by glare. Because the measured data are limited and do not explore the full potential range of the vertical-to-horizontal ratio, this study cannot fully explore the boundaries of this relationship. However, a maximum ratio of 1.0 vertical-to-horizontal illuminance, and a desired value of less than 0.6 appears to be supported by the data.

The regression analysis indicated that there is no significant association between NTDCRR and vertical-to-horizontal ratio metric (model 1 coefficient: 0.08, *p*-value = 0.11). No statistically significant differences in NTDCRR were detected based on model 2.

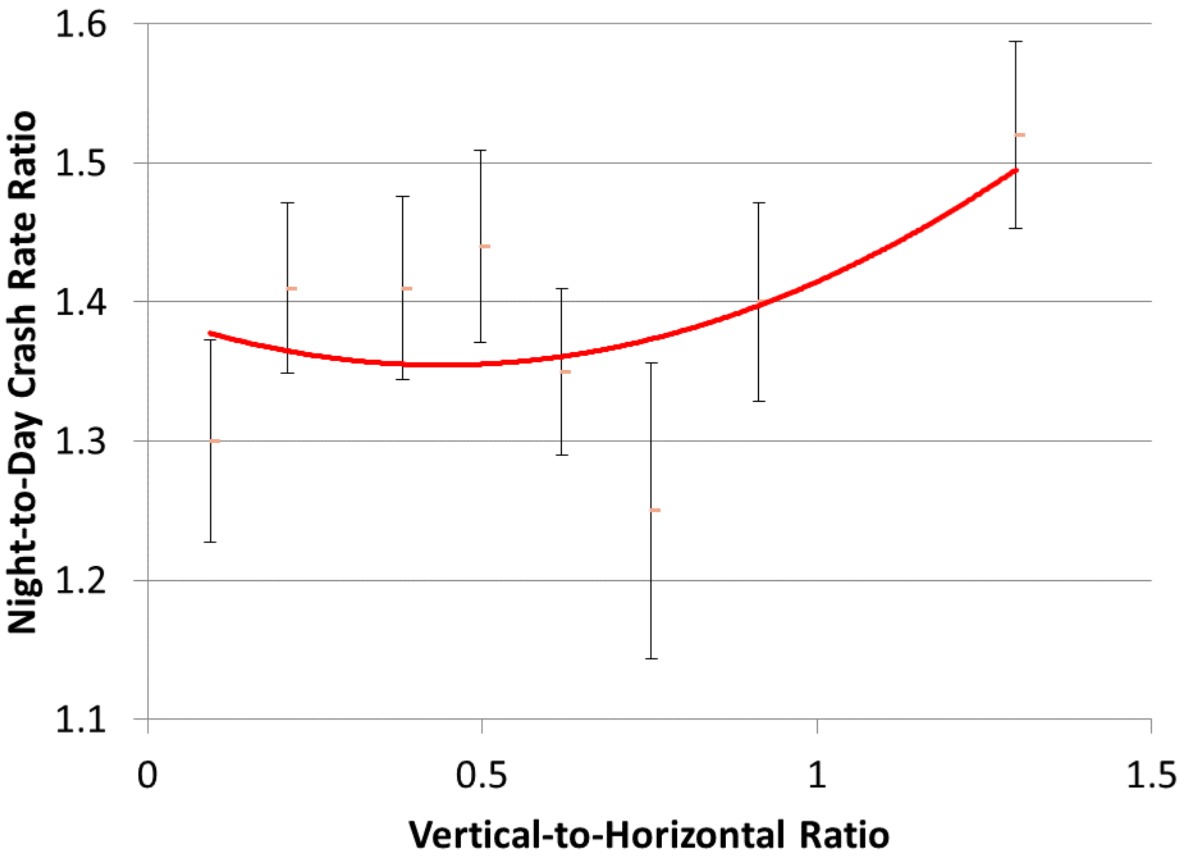


Figure 16. Graph. Relationship between mean vertical-to-horizontal illuminance ratio level and weighted night-to-day crash rate ratio.

UNIFORMITY

The lighting uniformity measure is the difference in local maximum and local minimum lighting levels caused by the location of a lighting pole or other factors. This is different than the UR typically used in the design of roadway lighting. Because the data were measured continuously, there were points where the values dropped to significantly lower values than may be seen in a calculation environment. (Variations for ideal luminaire performance and pole spacing as well as ambient conditions affect the measurement.) As a result, the UR, as traditionally defined, was not usable because of high variation and potential infinite values. Thus, the uniformity difference was used instead.

The team developed an algorithm to identify local maximum and local minimum at road segment level, as illustrated in figure 17. The mean lighting level for the road segment was calculated first. The road segment was then divided into shorter subsegments based on whether the lighting level is above or below the mean lighting level. In this setup, a high lighting subsegment (above mean lighting level) is always adjacent to a low lighting subsegment. The difference between the maximum of the high lighting subsegment and the minimum of the adjacent low lighting subsegment is the base for uniformity measure. Furthermore, the local maximum/minimum value is usually surrounded by many non-extreme values. To alleviate potential bias caused by extreme values, the average of the highest five points and lowest five points in each high/low lighting subsegment was used to calculate the uniformity measure. The uniformity for a segment is defined as the mean of all pairs of difference between local maximum and minimum.

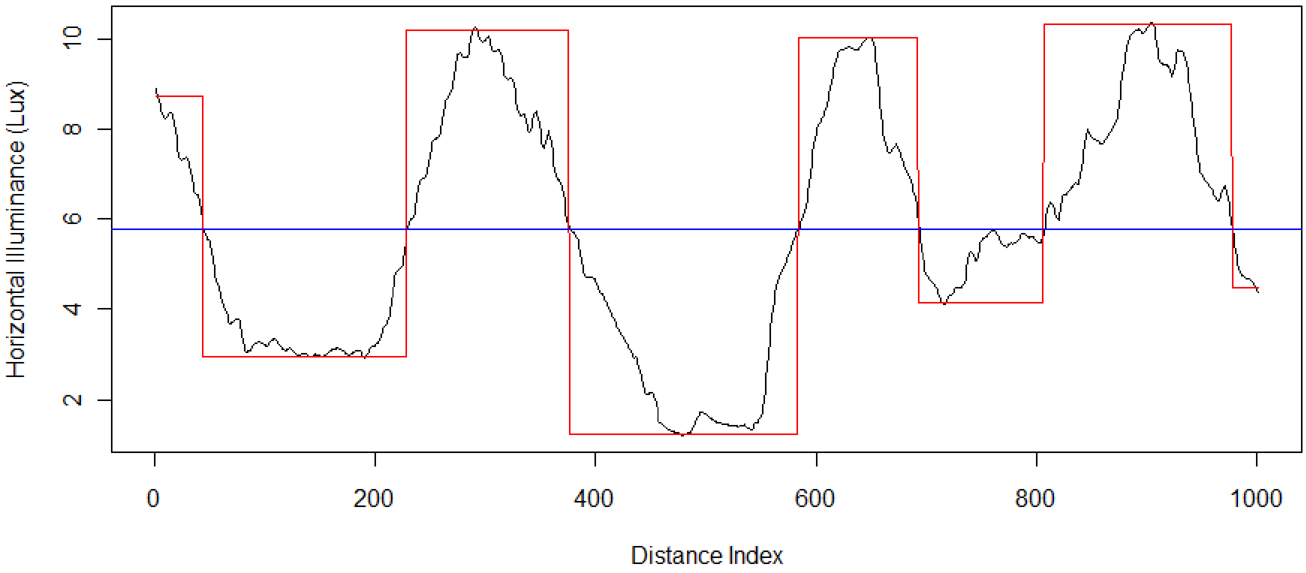


Figure 17. Graph. Uniformity measure. The distance index is a counter used to index the data from the measurement system.

The distribution of the uniformity measure is shown in table 19 (which only shows values up to 20 to avoid outliers). Because there is no information on how the uniformity measure would affect safety, we categorized the uniformity level based on an approximately equal number of segments to ensure a reasonable number of samples in each bin for crash risk evaluation. The categorization of uniformity measure level is shown in table 11.

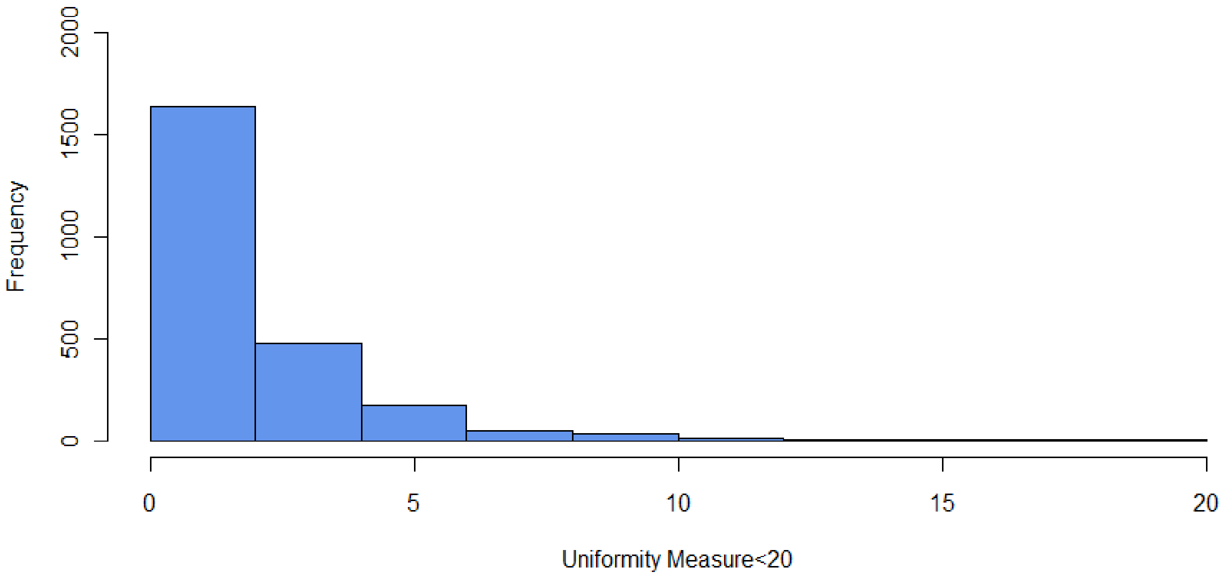


Figure 18. Graph. Distribution of uniformity measure.

Table 11. Uniformity lighting level.

Uniformity Level	0	1	2	3	4	5	6	7
Range of Mean Uniformity	0~0.1*	0.1~0.3	0.3~0.7	0.7~1.1	1.1~1.7	1.7~2.5	2.5~4	> 4

* 0~0.1: segments with mean uniformity measure between 0 and 0.1.

Figure 19 shows the relationship between the uniformity difference and the night-to-day crash rate ratio. The inference does not show a statistically significant pattern (model 1 coefficient: 0.01, *p*-value = 0.13). Results from model 2 indicate the NTDCRR for level 0 is significantly higher than the other levels, with no significant difference among levels 1 to 7.

As a result of the nature of the uniformity difference calculation, the higher the uniformity value, the less uniform the lighting on the roadway. These results indicate that as the uniformity difference increases and the roadway becomes less uniform, the crash rate ratio decreases; however, there may be a limit where additional non-uniformity does not assist and may be a detriment. Other investigations have seen this same result: when the lighting on the roadway is not completely uniform, the potential for greater object contrast on the roadway increases and, as a result, so does the potential for object detection and a reduction in crashes.(16)

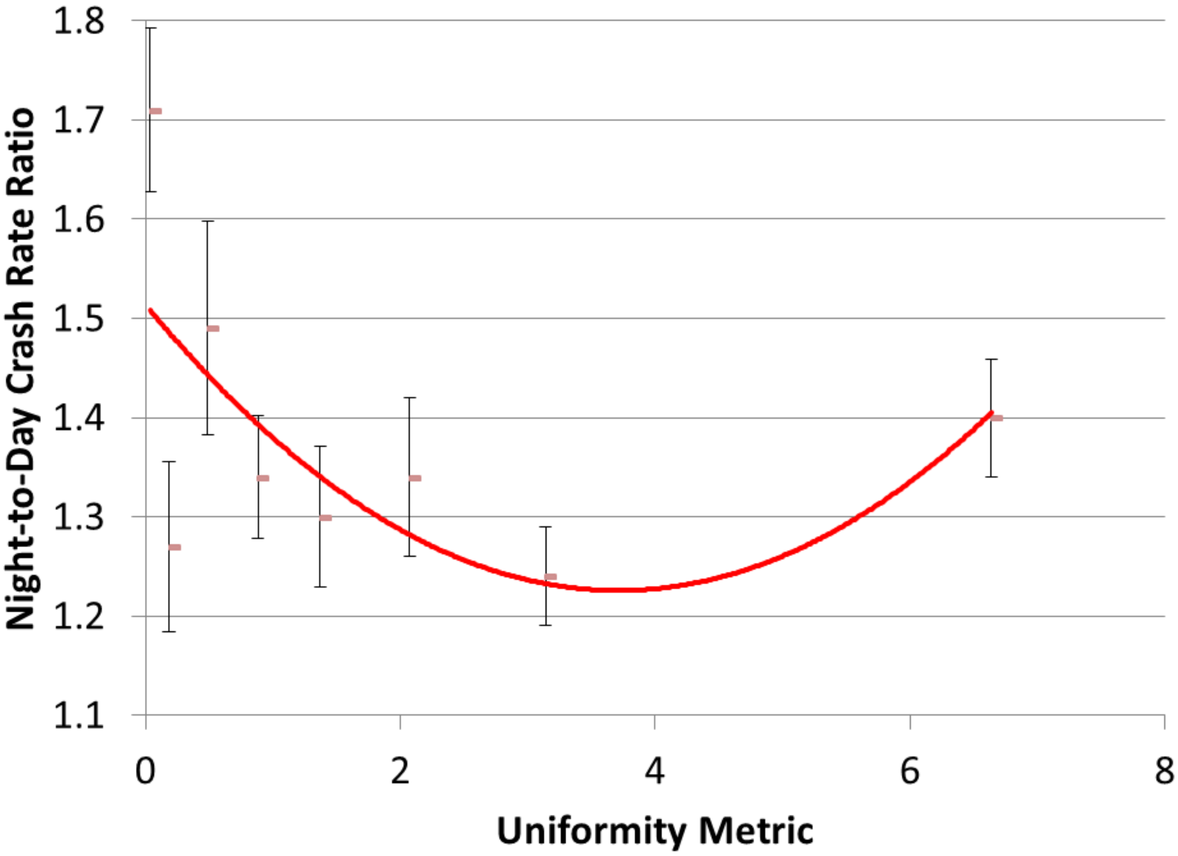


Figure 19. Graph. Relationship between UR level and weighted night-to-day crash rate ratio.

LUMINANCE

The final metric to consider is luminance. The luminance of the roadway was measured from inside the windshield of the vehicle. The transmissivity of the glass can limit luminance inside the windshield by as much as 30 percent.(14) These data were scaled by this factor to allow for comparison with lighting designs, which are measured external to a vehicle.

The luminance reduction program used allows the area of interest to be selected to allow different objects within the same image to be evaluated. For this analysis, the luminance measures were made for all of the visible roadway area, therefore extending the width of the roadway lane laterally and approximately 50 to 250 ft (15.2 to 72.2 m) in front of the vehicle. As a result, it includes the maximums and the minimums—essentially an average of the roadway space, not just the luminance at 272 ft (83 m) from the vehicle as specified by ANSI/IES RP-8-2005.

The distribution of the luminance is shown in figure 20, and the categorization based on the principle of equal number of road segments is shown in table 12.

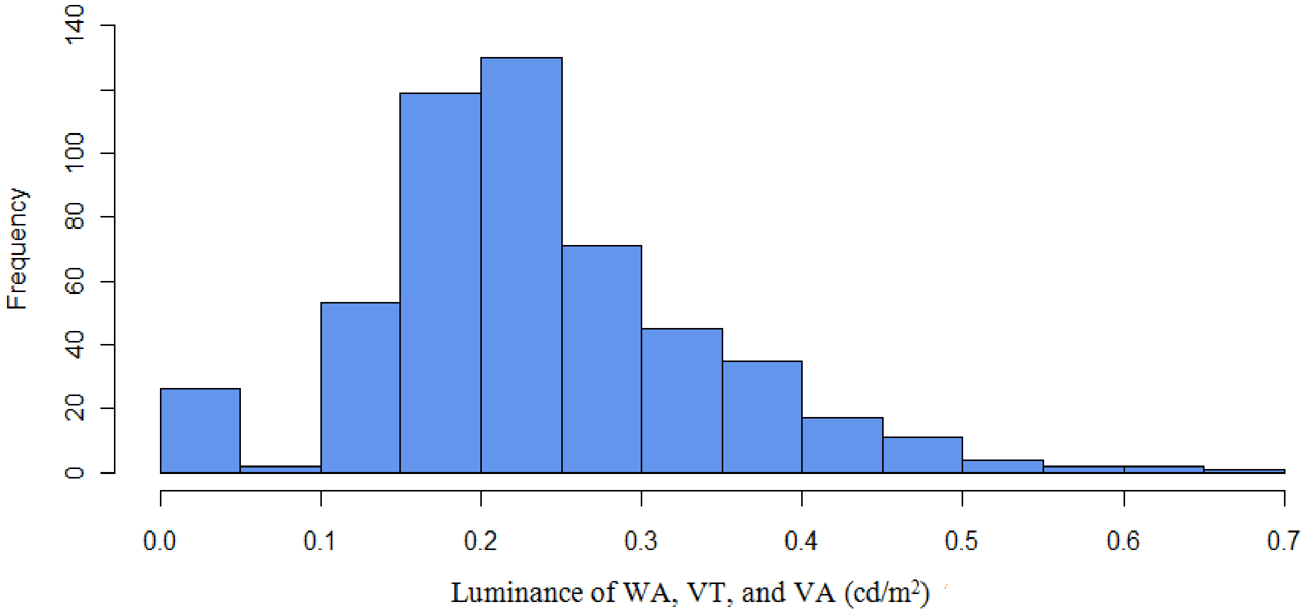


Figure 20. Graph. Distribution of luminance measure.

Table 12. Luminance lighting level.

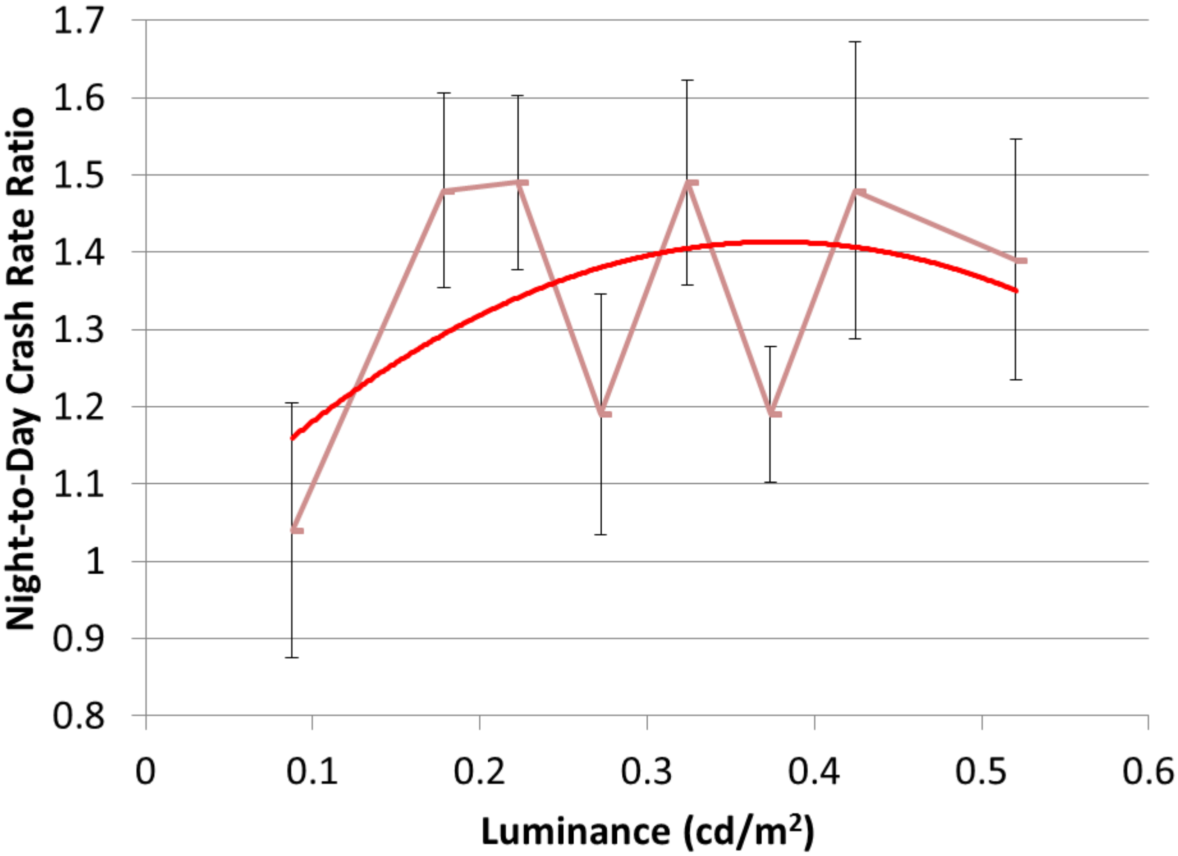
Luminance Level	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Mean of Luminance	0~0.15*	0.15~0.2	0.2~0.25	0.25~0.3	0.3~0.35	0.35~0.4	0.4~0.45	> 0.45

* 0~0.15: segments with mean of luminance between 0 and 0.15.

The relationship between luminance and night-day crash rate ratio is shown in figure 21. There is no significant trend in the relationship between NTDCRR and luminance (model 1 coefficient:

0.23, *p*-value = 0.4). However, comparison with model 2 indicated that the NTDCRR for level 0 is significantly smaller than for other levels.

The relationship of the luminance with the NTDCRR is not what one would expect. The figure shows that an increase in the luminance may increase the crash rate ratio. It is important to note that this luminance measurement includes the vehicle's headlamps, which are not included in a lighting design on a roadway. Because the luminance metric was measured for an area rather than a single point as a design would be, and is likely dominated by the headlamps' performance, it is not clear whether these results can be further evaluated and used as a design recommendation. A significant investigation of the interaction of the roadway luminance with and without headlamps is required to substantiate these values.



1 cd/m^2 = 0.292 ft-lamberts

Figure 21. Graph. Relationship between mean luminance level and weighted night-to-day crash rate ratio.

IMPACT OF ROADWAY TYPE

To fully explore the requirements for the lighting level on a variety of roadway types, the functional class of the roadway from the roadway data was used to further analyze the horizontal-illuminance-to-crash-rate relationship. A linear regression model was applied to the data to determine the impact of the lighting and the functional class. The results are shown in table 13. Overall, the impact of the increased lighting is significant and follows the trend of reducing crash rates. The functional class does not, however, appear to be statistically significant. Note that the functional class was provided in the roadway design data gathered from the State transportation departments as part of the project.

Table 13. Linear regression results for functional roadway class and lighting level.

Linear Regression Statistics for Type 3 Analysis			
Source	**DF**	**Chi-Square**	**Pr > ChiSq**
Lighting	7	39.85	< .0001
Functional class	3	2.26	0.5207
Lighting class	21	26.35	0.1936

To further investigate, a pairwise comparison of the NTDCRRs by lighting level was performed. For each functional class, the lighting levels were all compared with lighting level 0 or level 1. (The base level was selected to be the one with the highest NTDCRRs.) These results by functional class are shown in table 14 through table 17 along with the corresponding lower confidence limit (LCL) and upper confidence limit (UCL). Here the significant differences can be determined from the *p*-values ($p < 0.05$). For the Urban Interstates (table 14), the comparison shows that there is a slight difference from level 1 to 2 but no significant difference beyond level 2. (It is noteworthy that all pairs of levels were compared, but only results with respect to a base level were included in this report.) For the Urban Principal Arterials, the pairwise comparisons show that there seems to be no significant difference between levels 2 and 4. For the Other Principal Arterials, the differences are significant beyond level 5. Finally, for the Minor Arterials, the data are more difficult to analyze because the number of data points was very small, but the difference seems to start at level 6.

Table 14. Pairwise Comparison of lighting level for Urban Interstates.

Lighting Level Comparison	**Ratio of Crash Rate Ratios (CRR(i) / CRR(j)**	**95 percent LCL**	**95 percent UCL**	***p*-Value**
Level 1 versus level 0	0.85	0.73	1.00	0.048
Level 2 versus level 0	0.75	0.63	0.89	0.001
Level 3 versus level 0	0.75	0.63	0.89	0.001
Level 4 versus level 0	0.68	0.55	0.84	0.000
Level 5 versus level 0	0.80	0.65	0.99	0.036
Level 6 versus level 0	0.60	0.41	0.87	0.008
Level 7 versus level 0	0.68	0.40	1.16	0.153

Table 15. Pairwise comparison of lighting level for Urban Principal Arterials.

Lighting Level Comparison	Ratio of Crash Rate Ratios (CRR(i) / CRR(j)	95 percent LCL	95 percent UCL	*p*-Value
Level 0 versus level 1	0.93	0.71	1.21	0.587
Level 2 versus level 1	0.82	0.68	0.98	0.031
Level 3 versus level 1	0.77	0.60	0.97	0.026
Level 4 versus level 1	0.62	0.45	0.85	0.003
Level 5 versus level 1	0.96	0.74	1.25	0.767
Level 6 versus level 1	0.95	0.68	1.32	0.751
Level 7 versus level 1	0.86	0.65	1.13	0.272

Table 16. Pairwise comparison of lighting level for Urban Other Principal Arterials.

Lighting Level Comparison	Ratio of Crash Rate Ratios (CRR(i) / CRR(j)	95 percent LCL	95 percent UCL	*p*-Value
Level 1 versus level 0	0.82	0.60	1.11	0.204
Level 2 versus level 0	0.86	0.65	1.14	0.300
Level 3 versus level 0	0.76	0.56	1.02	0.066
Level 4 versus level 0	0.74	0.52	1.06	0.100
Level 5 versus level 0	0.66	0.46	0.95	0.026
Level 6 versus level 0	0.42	0.20	0.88	0.022
Level 7 versus level 0	0.57	0.41	0.81	0.001

Table 17. Pairwise comparison of lighting level for Urban Minor Arterials.

Lighting Level Comparison	Ratio of Crash Rate Ratios (CRR(i) / CRR(j)	95 percent LCL	95 percent UCL	*p*-Value
Level 1 versus level 0	0.68	0.49	0.94	0.019
Level 2 versus level 0	0.59	0.36	0.94	0.028
Level 3 versus level 0	0.63	0.40	1.00	0.048
Level 4 versus level 0	0.57	0.33	1.00	0.049
Level 5 versus level 0	0.41	0.20	0.83	0.014
Level 6 versus level 0	0.24	0.05	1.18	0.079
Level 7 versus level 0	0.34	0.07	1.59	0.171

Figure 22 shows these results. The dashed horizontal lines in figure 22 highlight the area of similar performance in terms of the lighting system and the relationship to the night-to-day crash rate ratio for each roadway type. Using visual inspection, the results of the pairwise comparison can be verified because this horizontal line can be used to determine the minimum lighting required to optimize safety for each roadway type. Beyond this minimum value, an increase in illuminance does not appear to affect the overall safety of the roadway.

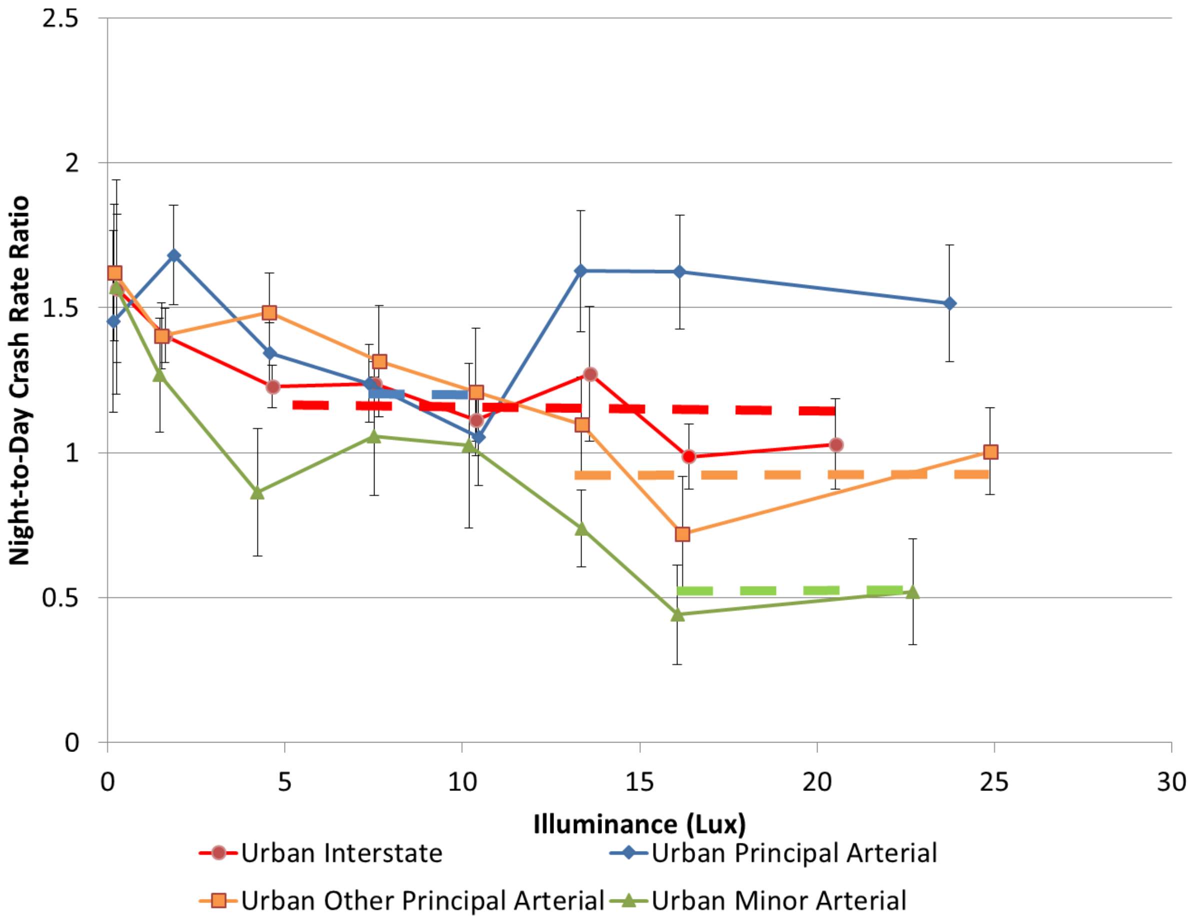


Figure 22. Graph. Relationship between horizontal illuminance and weighted night-to-day crash rate ratio by roadway functional class.

Table 18 shows the minimum horizontal illuminance requirements for the functional classes of roadway, which is determined using both the pairwise comparisons and the visual inspection analysis method.

Table 18. Minimum horizontal illuminance limits from the functional class analysis.

Description	Minimum Illuminance Requirement (lux)
Urban Interstate	5
Urban Principal Arterial	7.5
Other Principal Arterial	13
Minor Arterial	16

Another aspect of figure 22 is the different relationship of the lighting level to the crash rate for the minor arterial. This roadway functional class appears to be more significantly affected by the increase in lighting level than the freeways and the major arterials. The crash rate ratio for the minor arterials drops from 1.5 to 0.5 as the lighting level increases, whereas it only drops to 1.0

for the freeways. This indicates that the minor arterials are safer at night with lighting than during the day. This is likely linked to the lower traffic volume at night and a reduced level of potential conflict with other vehicles at intersections and driveways.

The IES divides roadway lighting recommendations into street and highway, the primary difference being the presence of pedestrians. Applying these classifications to the IES requirements, the minor arterials were classified as streets, and the other functional classifications were classified as highways.[1]

Figure 23 shows the relationship of the crash rate ratio with the lighting level for highways and streets. Obviously, the same relationship exists as mentioned above. The comparison of NTDCRR for lighting category stratified by highway and street is shown in table 19.

Again a pairwise comparison based on model 2 was used to look at the impact of the lighting level for the functional class. For highways, the results were compared with lighting level 3 (6–9 lux). Based on this comparison, significant differences are evident only with level 1 and level 0. This indicates that the minimum required lighting level appears to be in the range of 3–6 lux for highways. Similarly, the street comparison for level 4 shows a significant difference starting at level 5 (12–15 lux), which indicates that the required lighting level is in the range of 12–15 lux. Because the project did not set out to measure the minor arterials, there is not as much data in this category as there is for the highway classification. As a result, the relationship is not as strong as the highway relationship.

Table 19. Comparison of NTDCRR for lighting category stratified by highway and street.

	Horizontal Illuminance Level Comparison	**Ratio of NTDCRR**	**95 percent LCL**	**95 percent UCL**	***p*-Value**
Highway	Level 0 versus level 3	1.34	1.17	1.54	< .0001
	Level 1 versus level 3	1.22	1.08	1.38	0.00
	Level 2 versus level 3	1.07	0.94	1.22	0.33
	Level 4 versus level 3	0.90	0.76	1.07	0.25
	Level 5 versus level 3	1.11	0.94	1.31	0.24
	Level 6 versus level 3	0.96	0.74	1.24	0.75
	Level 7 versus level 3	1.08	0.85	1.37	0.53
Street	Level 0 versus level 4	1.28	0.96	1.70	0.09
	Level 1 versus level 4	0.90	0.67	1.20	0.47
	Level 2 versus level 4	0.79	0.55	1.15	0.23
	Level 3 versus level 4	0.93	0.66	1.30	0.66
	Level 5 versus level 4	0.67	0.43	1.04	0.07
	Level 6 versus level 4	0.44	0.20	0.96	0.04
	Level 7 versus level 4	0.69	0.48	0.99	0.05

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[1] For clarity, this discussion will refer to the IES roadway class as highways so as not to confuse it with the roadway in general.

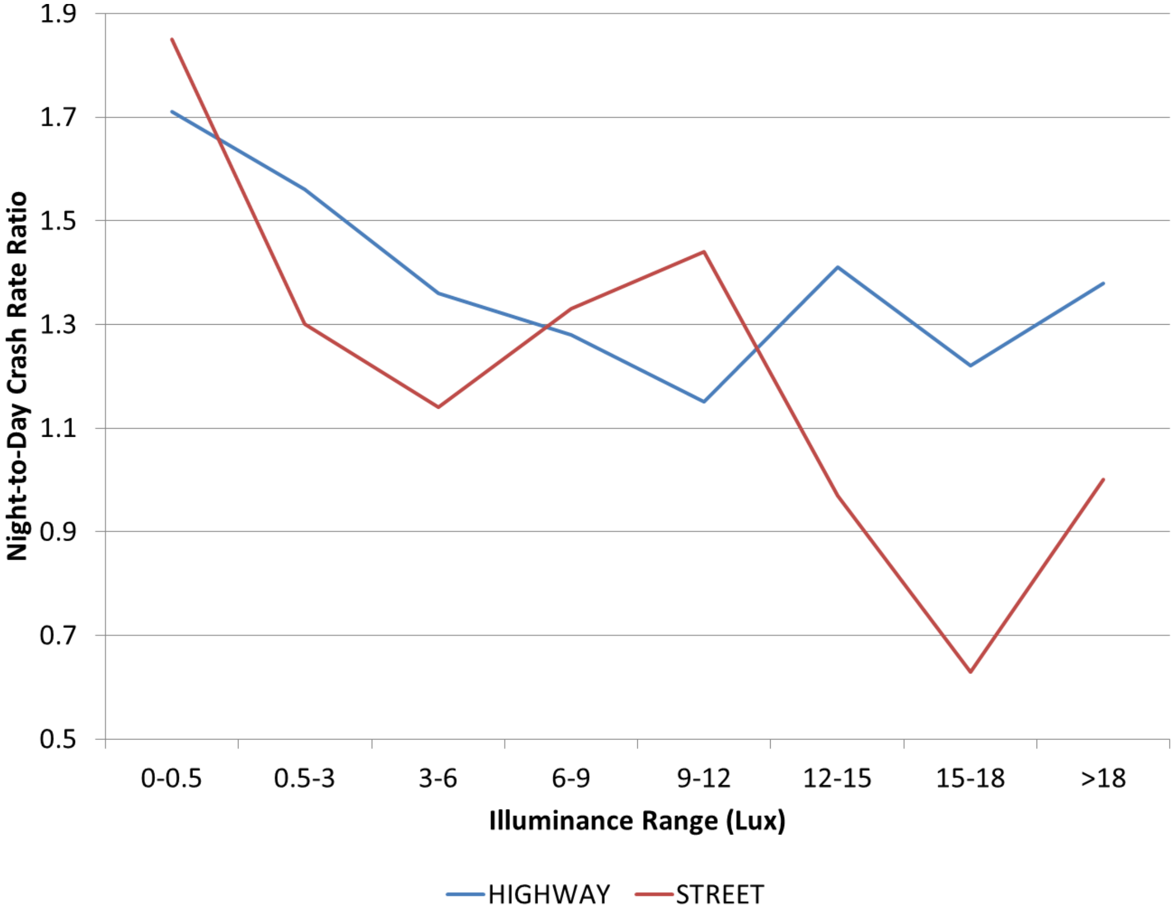

Figure 23. Graph. Relationship between mean horizontal illuminance and weighted night-to-day crash rate ratio.

COMPARISON TO IES STANDARDS

As mentioned, the ANSI/IES RP-8-00 standards provide guidelines for selecting roadway lighting levels. Table 20 provides the recommended illuminance levels from the IES. For comparison with the results of the current study, Freeway Class A is comparable to the Urban Freeway functional class, Freeway Class B is comparable to Major Arterial, Expressway is comparable to Arterial, and Major is comparable to Minor Arterial. Figure 24 shows the comparison of these values with those found in this project. The comparison is made for Road Surface Types R2 and R3, and the high and low range is shown for the pedestrian classes.

Table 20. IES illuminance requirements (ANSI/IES RP-8-00).[(4)]

Road and Pedestrian Conflict Area		Pavement Classification (Minimum Maintained Average Values)			Uniformity Ratio	Veiling Luminance Ratio
Road	**Pedestrian Conflict Area**	**R1**	**R2 and R3**	**R4**		
		lux/fc	**lux/fc**	**lux/fc**	E_{ave}/E_{min}	L_{vrnax}/L_{avg}
Freeway Class A	No Conflict	6.0/0.6	9.0/0.9	8.0/0.8	3.0	0.3
Freeway Class B	No Conflict	4.0/0.4	6.0/0.6	5.0/0.5	3.0	0.3
Expressway	High	10.0/1.0	14.0/1.4	13.0/1.3	3.0	0.3
	Medium	8.0/0.8	12.0/1.2	10.0/1.0	3.0	0.3
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0	0.3
Major	High	12.0/1.2	17.0/1.7	15.0/1.5	3.0	0.3
	Medium	9.0/0.9	13.0/1.3	11.0/1.1	3.0	0.3
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0	0.3
Collector	High	8.0/0.8	12.0/1.2	10.0/1.0	4.0	0.4
	Medium	6.0/0.6	9.0/0.9	8.0/0.8	4.0	0.4
	Low	4.0/0.4	6.0/0.6	5.0/0.5	4.0	0.4
Local	High	6.0/0.6	9.0/0.9	8.0/0.8	6.0	0.4
	Medium	5.0/0.5	7.0/0.7	6.0/0.6	6.0	0.4
	Low	3.0/0.3	4.0/0.4	4.0/0.4	6.0	0.4

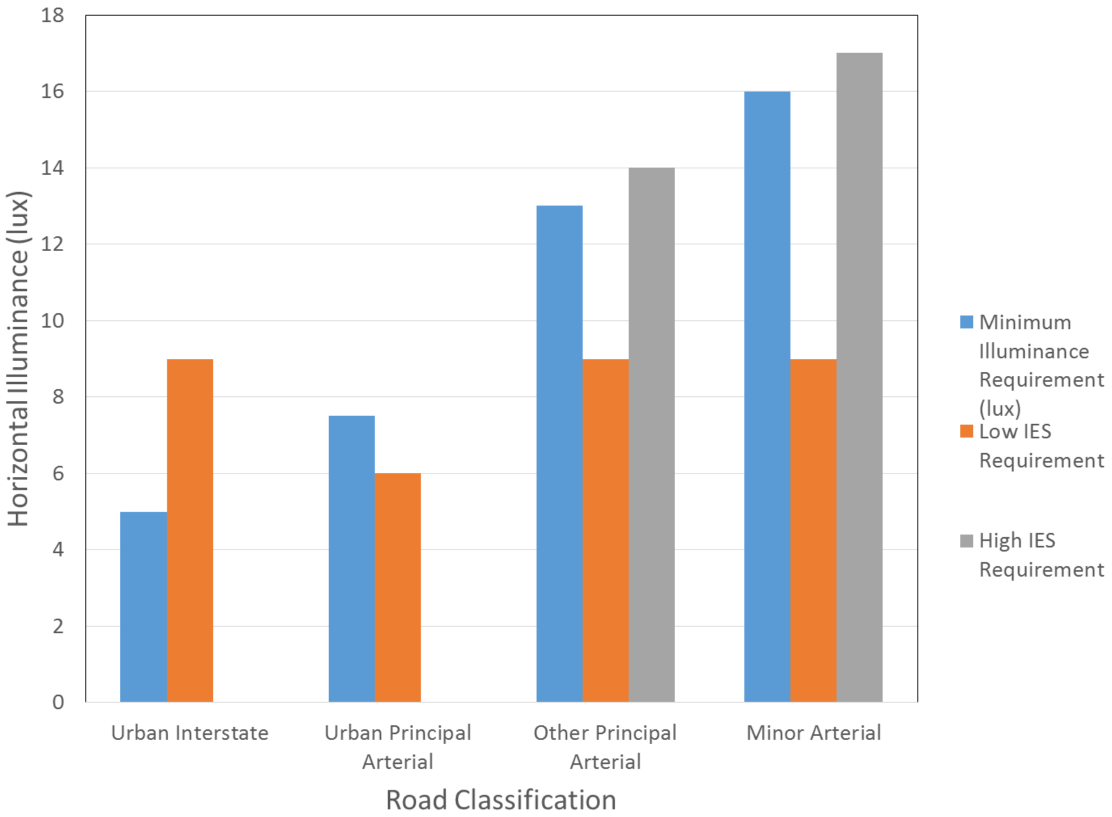

Figure 24. Graph. Comparison of the IES requirements with the results of the crash analysis.

One of the more striking results is that the calculated required lighting level for the urban freeways is significantly less than the IES-recommended level. A level of 4 lux was required, whereas the recommendation is 9 lux. This indicates a possible opportunity to reduce lighting on this class of roadway by more than 50 percent. These results suggest the IES recommended lighting level could be reduced for Urban Interstates, but the existing recommendations are suitable for the other classifications. Additional research is required to fully investigate the requirements for detection of pedestrians.

HOURLY ANALYSIS

The other aspect of the lighting impact that is of interest is the relationship to the time of day. The hypothesis is that as the usage of roadways and streets changes during the night, there is the potential to reduce or adapt lighting to the conditions on the roadway. This might include the adjustment of the lighting to traffic or pedestrian volumes. To more fully investigate this issue, the crash rate by the time of day was examined, along with the hourly traffic volume.

The first step of this analysis was to gather data for the crashes and crash rate for the time of day. Only the crashes that occurred at night were included in this analysis. The nighttime was defined by using the National Weather Service sunrise and sunset times. This analysis was also performed only for the State of Washington, which had the most reliable hourly crash and volume data. Figure 25 shows the total number of crashes during hours of dark for the years

2004 to 2008, separated by hour of the day. As predicted, the total number of crashes diminishes during the nighttime period, with the minimum occurring between 3 and 4 a.m.

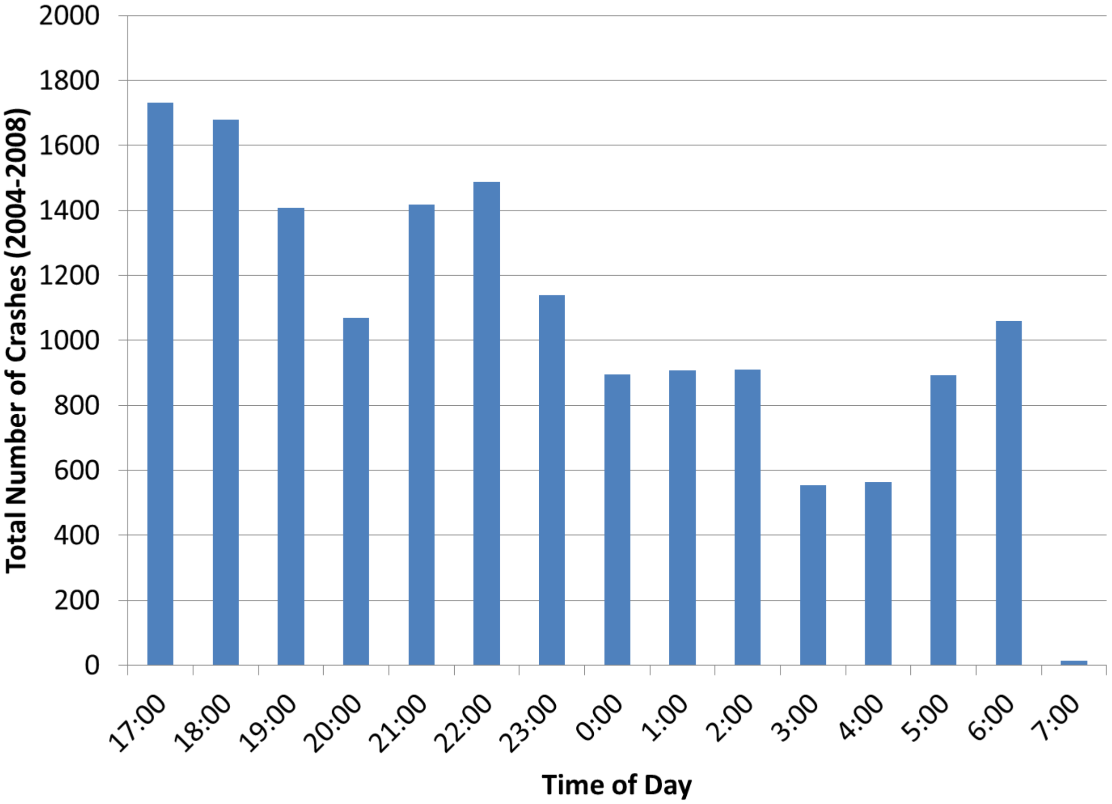

Figure 25. Graph. Total number of crashes for Washington from 2004 to 2008 by time of day.

As the traffic volume diminishes through the night, the number of crashes per vehicle mile varies. Figure 26 shows the average crash rate (number of crashes per million vehicle miles traveled) by the time of day for the same data set. The peak at 2 a.m. is significant and may be caused by several factors external to the lighting condition, such as fatigue and alcohol use.

This relationship of the overall number of crashes and the crash rate is an interesting result because it indicates that minimizing the crash rate for the hours from midnight to 3 a.m. will not have as great an impact on reducing injuries and loss of life as can be achieved by reducing the overall number of crashes in the evening hours.

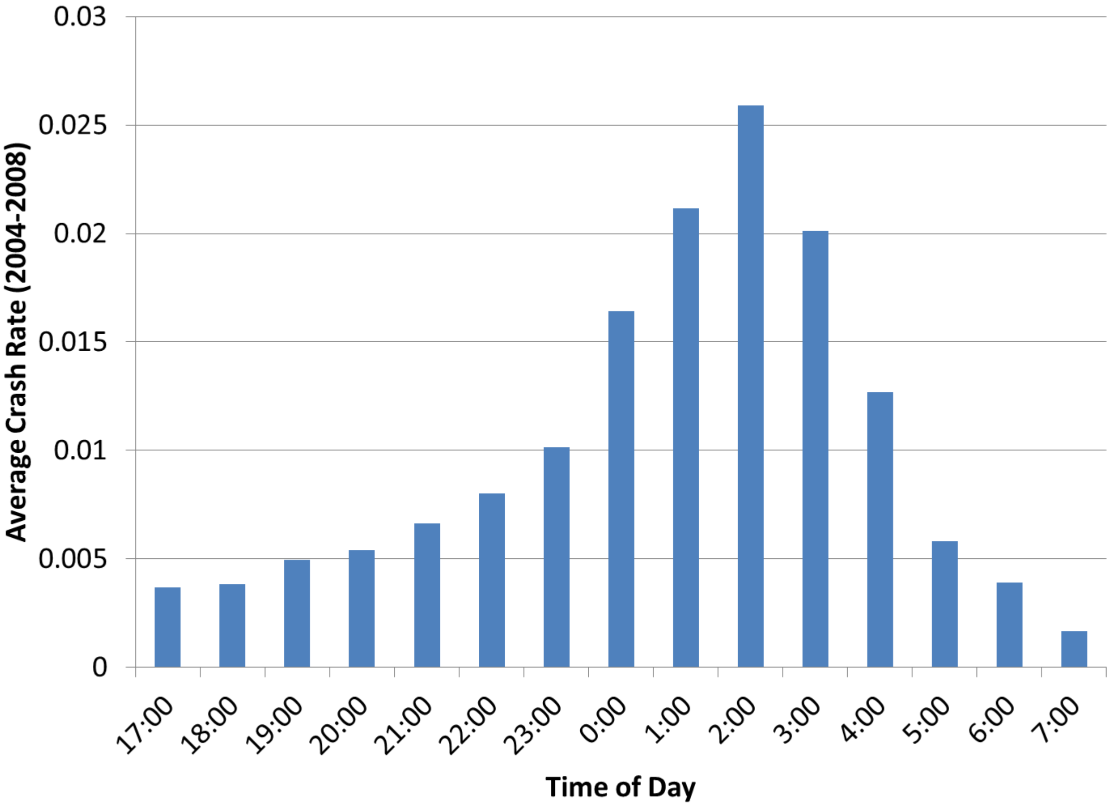

Figure 26. Graph. Average crash rate by time of day for Washington from 2004 to 2008.

The relationship between crash rate and time of day indicates that factors other than darkness influence the crash rate. This implies that some level of crashes will occur regardless of the presence of lighting and may be related to fatigue, alcohol, and other factors.

SUMMARY

This analysis shows that there is the potential to reduce lighting on roadways during periods of reduced traffic and potential conflict while maintaining the overall level of roadway safety. The data also show there is a potential to reduce standard lighting levels by as much as 50 percent for the Urban Interstate functional class.

CHAPTER 3. LIGHTING LEVEL SELECTION METHODOLOGY

The system that provides the most flexibility in terms of adaptive lighting is the system proposed by the CIE.(11) This system provides both a methodology to select the lighting design level and a method of adapting the lighting level based on specified criteria for individual roadways.

During the course of this project, the parameters of the lighting system were established based on the criteria of the system. The collected data were explored for aspects of the lighting system that are statistically significant to the crash rate and the NTDCRR. As a result of evaluating these classification systems and the data from this research, a new methodology has been developed based on an analysis of vehicle crashes and lighting level.

The system proposed here is a more complete classification system, which is needed to fully apply the benefits of adaptive lighting for roadways. The methods presented here are based on the CIE method documented in CIE 115.(11) However, the CIE did not provide parameters to define each of the classification levels, and these have been added to the tables. Additional metrics were added, such as links to the IES requirements and considerations of traffic volume, geometric design, and pedestrian volumes. There was also a reduction in the number of lighting classes to reduce the possibility of over-lighting and adding additional complexity.

Three different selection criteria are used for the lighting level based on the type of facility being designed. The IES separates design criteria into roadways, streets, and residential or pedestrian facilities as follows:

- Roadway lighting is provided for freeways, expressways, limited access roadways, and roads on which pedestrians, cyclists, and parked vehicles are generally not present. The primary purpose of roadway lighting is to help the motorist remain on the roadway and help with the detection of obstacles within and beyond the range of the vehicle’s headlamps.

- Street lighting is provided for major, collector, and local roads where pedestrians and cyclists are generally present. The primary purpose of street lighting is to help the motorist identify obstacles, provide adequate visibility of pedestrians and cyclists, and assist in visual search tasks, both on and adjacent to the roadway.

- Residential/pedestrian area lighting is provided primarily for the safety and security of pedestrians and not specifically for the driver. These facilities typically have driving speeds less that 25 mi/h (40 km/h), at which speed vehicle headlamps provide adequate lighting for the driver.(17) It should be noted that the recommended levels in this lighting category are measured in vertical illuminance rather than luminance on the roadway. Previous research has shown that vertical illuminance is the best metric for pedestrian and object visibility.(15)

Once the facility type has been selected, the characteristics of the facility are used as weighting functions to determine the requirements of the lighting system. The sum of these weighting values is then subtracted from a base value. This result determines the lighting class. The lighting level is then determined from the lighting class. The equation for the lighting design class is shown in figure 27.

$$Lighting\ Class = Base\ Value - \sum Weighting\ Values$$

Figure 27. Equation. Lighting class.

It is important to note that the base value changes based on the facility type. In this calculation, if the result is not a whole number, the next lower positive whole number is used (e.g., an H3.5 would use the H3 values). Negative numbers would result in applying the highest lighting level class. Similarly, if the calculated class number is higher than the highest class number, the highest class number is used.

Tables for the weighting parameters for roadway, street, and residential/pedestrian facility types are shown in table 21, table 23, and table 25, respectively. Similarly, lighting design levels based on the lighting class for roadway, street, and residential/pedestrian facilities are shown in table 22, table 24, and table 26, respectively. The base values for each of the facility types are also provided below.

For an adaptive lighting system in which the lighting level is changed based on the conditions of the roadway, the weighting factors are changed as the roadway conditions change, which determines a different lighting class and therefore a different required design level.

SELECTION CRITERIA

The following sections describe the criteria. The minimum values shown in the results of the data collection and analysis provide the basis for this system; additional lighting levels may be required to meet the requirements of the selection methodology.

Speed

Previous research has shown that drivers' visual behavior changes based on the roadway conditions.(18) This research modeled the eye glance behavior of drivers in various roadway conditions. The results showed that as the roadway speed increases, the driver's eye glance pattern becomes restricted to a narrower range of glances. This results in blurring the peripheral field of view and limiting the visual field of the driver at higher speeds. As a result, it is recommended that a higher lighting level be used for roadways with higher speeds.

The literature shows that there is a tradeoff.(19) Drivers have a tendency to increase their driving speed when lighting is present. However, drivers moving at higher speeds will likely benefit from higher lighting levels.

Traffic Volume

In the data analysis, the roadway ADT was not found to be significantly linked to the night-to-day crash rate ratio. In fact, in some of the analyses, the lighting level actually showed less impact at higher traffic volumes. This relationship is actually predictable. At high volumes, a cooperative safety effect is evident.(20) With increasing traffic volume, there is a reduction in crashes until the point where the traffic volume becomes saturated and the crash rate begins to increase. These data indicate that at certain volumes, the vehicles in front of a driver provide a clear path and limit the potential for a crash.

The impact of ADT for highway and street conditions is shown in figure 28 and figure 29. (Note that these figures are using the AADT as a surrogate for ADT.) In these figures, the blue line represents the lowest ADT but also the highest crash rate. The lighting level has an impact on reducing crash risk for the roadways, but no specific improvement level can be determined. As a result, it is recommended that the lighting level be increased on roads with high ADT and reduced on roadways with low ADT.

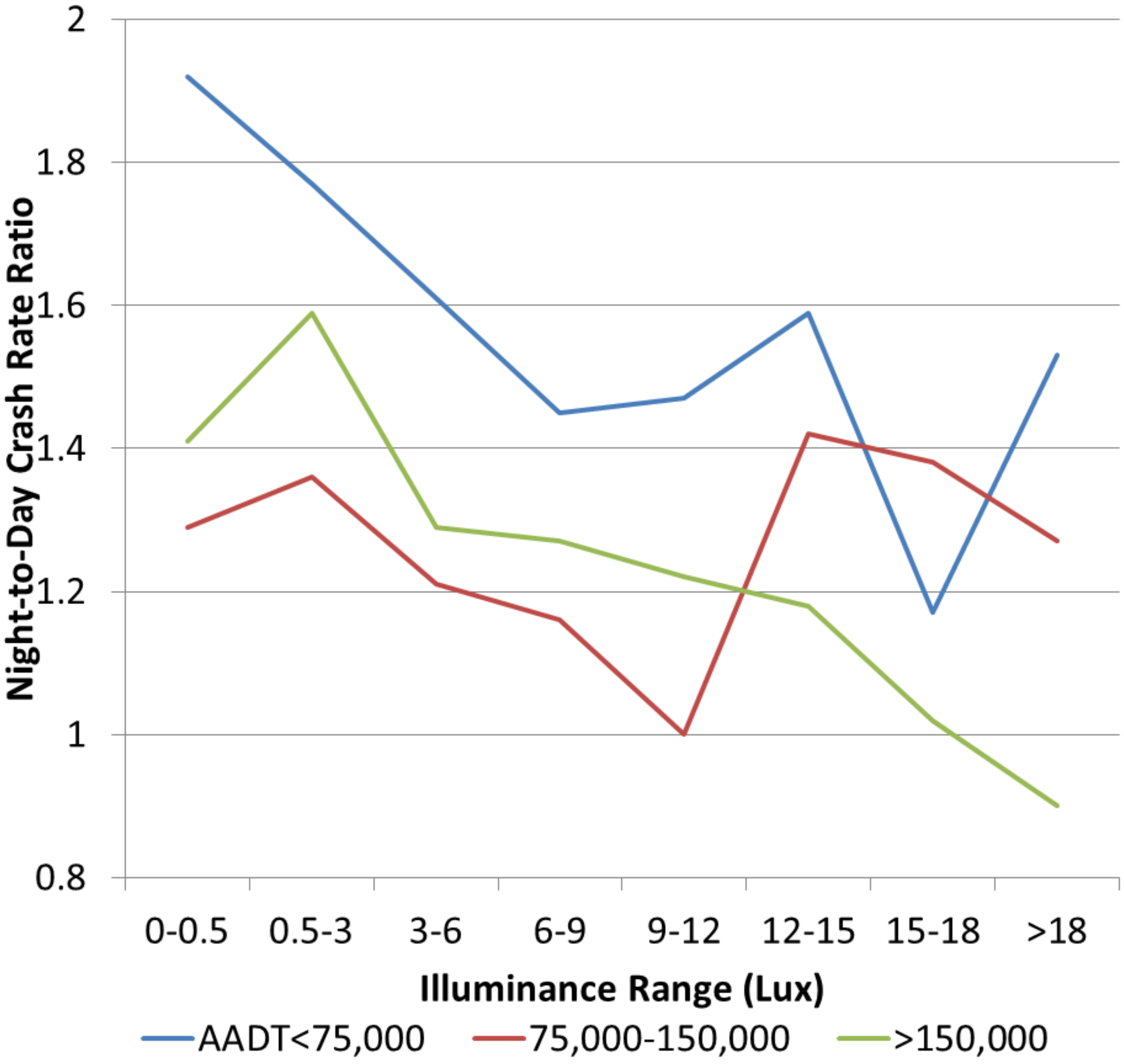

Figure 28. Graph. Relationship between mean lighting level and weighted night-to-day crash rate ratio for highways by AADT.

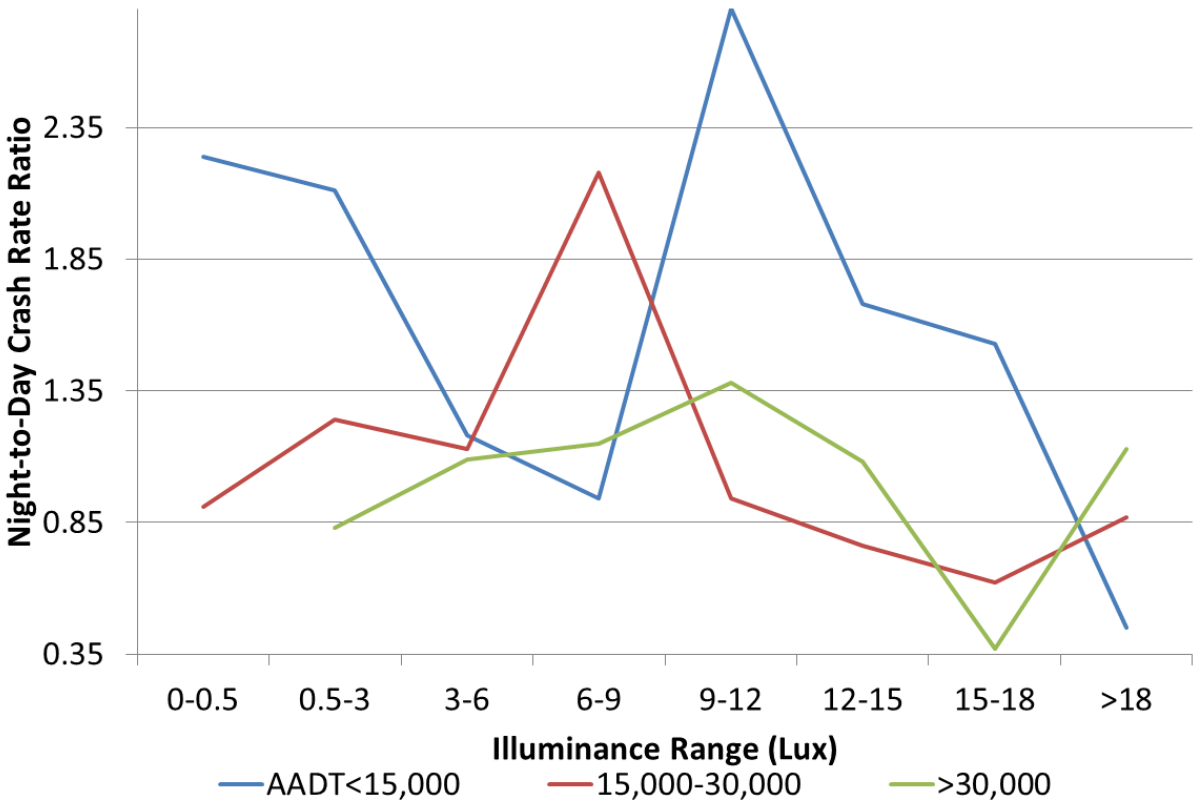

Figure 29. Graph. Relationship between mean lighting levels and weighted night-to-day crash rate ratio for streets by AADT.

Presence of a Median

The presence of a median in the roadway is significant because it blocks the glare from the other side of the roadway. Oncoming vehicles cause drivers both discomfort glare and disability glare. Research has shown that lighting can overcome the impact of this glare.(15) A high barrier or wide median can block or limit glare from oncoming vehicles. In these cases, the glare from the other vehicles is limited, so less light on the roadway is required. As a result, the weighting factor for the presence of a barrier allows the light level to be reduced if opposing glare is blocked.

Interchange Density

This factor considers the number of vehicles that enter and exit a roadway at legitimate intersections, driveways, and interchanges. Griffith showed that the impact of lighting only the interchanges for urban freeways is 12 percent less effective than lighting the entire roadway, whereas not lighting the roadway had a 50-percent impact on safety.(2) This indicates that lighting has a much greater impact at interchanges than in the other segments of a roadway. As a result, a roadway with closely spaced interchanges requires a higher lighting level than a roadway with greater spacing between interchanges. The weighting parameter for interchange density allows a lower lighting level for roadways with greater spacing between interchanges and a higher lighting level for roadways with closely spaced interchanges. Because of a lack of references regarding the relationship between lighting, safety, and density of at-grade intersections, the weighting parameter for interchange density is also used for intersections.

Ambient Luminance

The ambient luminance refers to the amount of light around roadways. Ambient light tends to come from many directions and usually has a high vertical component. To limit the vertical-to-horizontal illuminance ratio, the lighting level on the roadway should be increased to account for the higher ambient lighting condition. The weighting function for this parameter is based on the IES Lighting Zones (LZ), defined as follows.(4)

LZ0: No ambient lighting

LZ0 represents areas where the natural environment will be seriously and adversely affected by lighting. Effects include disturbing the biological cycles of flora and fauna and detracting from human enjoyment and appreciation of the natural environment, although human activity is less important than nature. The vision of human residents and users is adapted to the total darkness, and they expect to see little or no lighting. When not needed, lighting should be extinguished, although lighting is not typically used in an LZ0 condition.

LZ1: Low ambient lighting

LZ1 represents areas where lighting might adversely affect flora and fauna or disturb the character of the area. The vision of human residents and users is adapted to low light levels. Lighting may be used for safety and convenience, but it is not necessarily uniform or continuous. After curfew, lighting may be extinguished or reduced as activity levels decline.

LZ2: Moderate ambient lighting

LZ2 represents areas of human activity where the vision of human residents and users is adapted to moderate light levels. Lighting may typically be used for safety and convenience, but it is not necessarily uniform or continuous. After curfew, lighting may be reduced as activity levels decline.

LZ3: Moderately high ambient lighting

LZ3 represents areas of human activity where the vision of human residents and users is adapted to moderately high light levels. Lighting is generally desired for safety, security, or convenience, and it is often uniform and/or continuous. After curfew, lighting may be reduced as activity levels decline.

LZ4: High ambient lighting

LZ4 represents areas of human activity where the vision of human residents and users is adapted to high light levels. Lighting is generally considered necessary for safety, security, or convenience, and it is mostly uniform and/or continuous. After curfew, lighting may be reduced in some areas as activity levels decline.

Guidance

This parameter refers to the quality of the signage and pavement markings in the area to be lighted. Minimum marking and signage levels have been determined for both dry and wet conditions in a variety of tests. One of these conditions included lighting as a parameter in the evaluation.(21) This research showed that lighting increased the visibility of the pavement markings in all conditions. Lighting, therefore, is required when lane delineation and guidance are poor.

The weighting value for the guidance system allows a lower lighting level where marking and sign retroreflectivity are maintained at the Federal recommended minimums.

Pedestrian Presence

This parameter is applied only in the street and pedestrian roadway categories; highways are not expected to have pedestrians. The eye-tracking research mentioned earlier found that the eye behavior in areas where pedestrians are present expands to include a much wider area of the roadway and that the peripheral vision of the driver is more important. As with the interchange and intersection parameter, the potential for conflict increases with additional pedestrians. The lighting level is then increased based on the number of pedestrians along the roadway. The lighting levels should therefore be increased with additional pedestrian presence.

Presence of Parked Vehicles

Like pedestrians and the intersections, parked vehicles provide an additional potential form of conflict. Pedestrians and other vehicles can appear around parked vehicles, so additional lighting should be provided in these areas.

Facial Recognition

This final parameter should be used very carefully. To provide adequate lighting for the recognition of faces, additional lighting is required. Research has shown that light levels in excess of 30 vertical lux are required to adequately recognize faces. It is unclear when facial recognition would not be important in a residential or pedestrian (P-class) environment, but if an agency or authority determines that it is not important, the lighting level can be reduced.

DESIGN CRITERIA FOR ROADWAYS (H-CLASS)

Base Value for Class: 5

Table 21. Roadway design level selection criteria.

Parameter	**Options**	**Criteria**	**Weighting Value**
Speed	Very High	> 60 mi/h (100 km/h)	1
	High	45–60 mi/h (75–100 km/h)	0.5
	Moderate	< 45 mi/h (75 km/h)	0
Traffic Volume	High	> 30,000 ADT	1
	Moderate	10,000–30,000 ADT	0
	Low	< 10,000 ADT	-1
Median	No	No median	1
	Yes	Must be glare blocking	0
Intersection/Interchange Density	High	< 1.5 mi (2.5 km) between intersections	1
	Moderate	1.5–4 mi (2.5 km–6.5 km) between intersections	0
	Low	> 4 mi (6.5 km) between intersections	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Guidance	Good	> 100 mcd/m^2 lx	0
	Poor	< 100 mcd/m^2 lx	0.5

Table 22. H-class lighting design levels.

Class	**Average Luminance (cd/m^2)**	**Max UR (avg/min)**	**Max UR (max/min)**	**Veiling Luminance Ratio**
H1	1	3	5	0.3
H2	0.8	3.5	6	0.3
H3	0.6	3.5	6	0.3
H4	0.4	3.5	6	0.3

1 cd/m^2 = 0.292 ft-lamberts

DESIGN CRITERIA FOR STREETS (S-CLASS)

Base Value for Class: 6

Table 23. Street design level selection criteria.

Parameter	**Options**	**Criteria**	**Weighting Value**
Speed	High	> 45 mi/h (70 km/h)	1
	Moderate	35–45 mi/h (55–70 km/h)	0.5
	Low	< 35 mi/h (55 km/h)	0
Traffic Volume	High	> 15,000 ADT	1
	Moderate	5,000–15,000 ADT	0
	Low	< 5,000 ADT	-1
Median	No	No median	1
	Yes (or one-way)	Must be glare blocking	0
Intersection/Interchange Density	High	> 5 per 1 mi (1.6 km)	1
	Moderate	1–5 per 1 mi (1.6 km)	0
	Low	< 1 per 1 mi (1.6 km)	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Guidance	Good	> 100 mcd/m^2 lx	0
	Poor	< 100 mcd/m^2 lx	0.5
Pedestrian/Bicycle Interaction	High	> 100 pedestrians per h	2
	Moderate	10–100 pedestrians per h	1
	Low	< 10 pedestrians per h	0
Parked Vehicles	Yes	Parked vehicles present	1
	No	No parked vehicles present	0

Table 24. S-Class lighting design levels.

Class	**Average Luminance (cd/m^2)**	**Max UR (avg/min)**	**Max UR (max/min)**	**Veiling Luminance Ratio**
S1	1.2	3	5	0.3
S2	0.9	3.5	6	0.4
S3	0.6	4	6	0.4
S4	0.4	6	8	0.4
S5	0.3	6	10	0.4

1 cd/m^2 = 0.292 ft-lamberts

DESIGN CRITERIA FOR RESIDENTIAL/PEDESTRIAN AREAS (P-CLASS)

Base Value for Class: 6

Table 25. Residential/pedestrian design level selection criteria.

Parameter	Options	Criteria	Weighting Value
Speed	High	> 45 mi/h (70 km/h)	1
	Moderate	35–45 mi/h (55–70 km/h)	0.5
	Low	< 35 mi/h (55 km/h)	0
Traffic Volume	High	> 7,500 ADT	0.5
	Moderate	3,000–7,500 ADT	0
	Low	< 3,000 ADT	-0.5
Intersection/Interchange Density	High	> 5 per 1 mi (1.6 km)	1
	Moderate	1–5 per 1 mi (1.6 km)	0
	Low	< 1 per 1 mi (1.6 km)	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Pedestrian/Bicycle Interaction	High	> 100 pedestrians per h	1
	Moderate	10–100 pedestrian per h	.5
	Low	< 10 pedestrians per h	0
Parked Vehicles	Yes	Parked vehicles present	.5
	No	No parked vehicles present	0
Facial Recognition	Required	Facial recognition required	1
	Not Required	Facial recognition not required	0

Table 26: P-class lighting design levels.

Class	E Average (Lux)	E Vertical (minimum point)	Ratio E_{avg}/E_{min}
P1	10	5	4
P2	5	2	4
P3	4	1	4
P4	3	0.8	6
P5	2	0.6	10

Conflict Areas

Lighting for other conflict areas, such as intersections and crosswalks, can also be adjusted in relation to the roadway, street, and residential/pedestrian lighting levels. For example, the lighting level recommended for intersections included in ANSI/IES RP-8-00 is the sum of the lighting levels of the intersecting roads.(4) If the intersecting roads have had a change in use, allowing a reduction in lighting levels, lighting at the intersection would also be reduced.

CHAPTER 4. ADAPTIVE LIGHTING

As mentioned, adaptive lighting is the adjustment of lighting based on the current conditions of the roadway. The following parameters can change through the night and can influence the lighting level required to maintain safety:

- Traffic volume.
- Pedestrian and bicycle presence.
- Parked vehicles.
- Ambient conditions.
- Pedestrian safety and security

As these conditions change, the roadway class may be reevaluated and the lighting requirements adjusted. For an adaptive lighting solution to produce a financial benefit, the lighting system must have the following components:

- Dimmable-controls-ready luminaire.
- Control system, either central or localized on each luminaire.
- Localized metering or a negotiated adaptive lighting electricity rate.

The recommended technological approach to adaptive lighting is dimming. In the past, reduced lighting on roadways was typically accomplished through switching or “half-code” lighting, in which every other luminaire or the luminaires on one side of the roadway are turned off or removed. This is not considered an acceptable solution, because it is not possible to meet design criteria for uniformity and glare control using half-code lighting. In contrast, dimming a luminaire allows the light level to be adjusted without upsetting the other design criteria. Dimming luminaires are typically capable of dimming from 100-percent output to anywhere between 50 and 10 percent of maximum output, depending on the light source technology.

Monitoring the lighting system and the current lighting level is an integral part of the lighting control system implementation. Linking a monitoring system to the control system provides continuous feedback on the current condition of the lighting system. These types of control systems allow control of the lighting level as an asset.

The impact of weather was not included in this project. While the number of crashes in adverse conditions can be determined, exposure of the driver to weather conditions cannot be calculated. Accordingly, crash rates have not been established for various weather conditions. Other studies that have considered crashes on wet roads found that they significantly affected object visibility in the presence of adaptive lighting.(16) At present, it is recommended that during periods of adverse weather, the lighting level should be at the design level.

Using the light level selection methodology, when one of the parameters changes in the table, the lighting class would be recalculated and the lighting level could be changed. Obviously, not all criteria will change; some may change nightly (Pedestrian Usage), and some may change over a long period of time (Guidance).

TRAFFIC VOLUME CONSIDERATION FOR ADAPTIVE LIGHTING

The traffic volume parameter in the selection of the lighting level is ADT. While this is an effective parameter for warranting lighting, it is not practical for the application of adaptive lighting. ADT does not provide insight into the change in traffic levels over the course of the day. An analysis of the hourly traffic volumes was undertaken to provide data for the selection of the lighting level based on an immediate condition rather than the ADT.

In this analysis, the hourly traffic volume and the hourly crash rates were used to identify the relationship between traffic volume and the lighting system. The results are shown in figure 30. As before, it was determined that there was no overall relationship with the lighting level. There was some variation, but in general, the lighting level did not affect safety. However, it is noteworthy that the general safety of the roadway is affected by the hourly traffic volume, with the lowest volume road having a higher relative crash rate than higher volume roads. The ADT metric produced a similar result. Again, it is believed that this represents a form of cooperative safety on roadways with significant vehicle volume, meaning that as the traffic volume increases, the presence of other vehicles reduces the crash rate until the roadway is saturated, at which point the crash rate increases.(20)

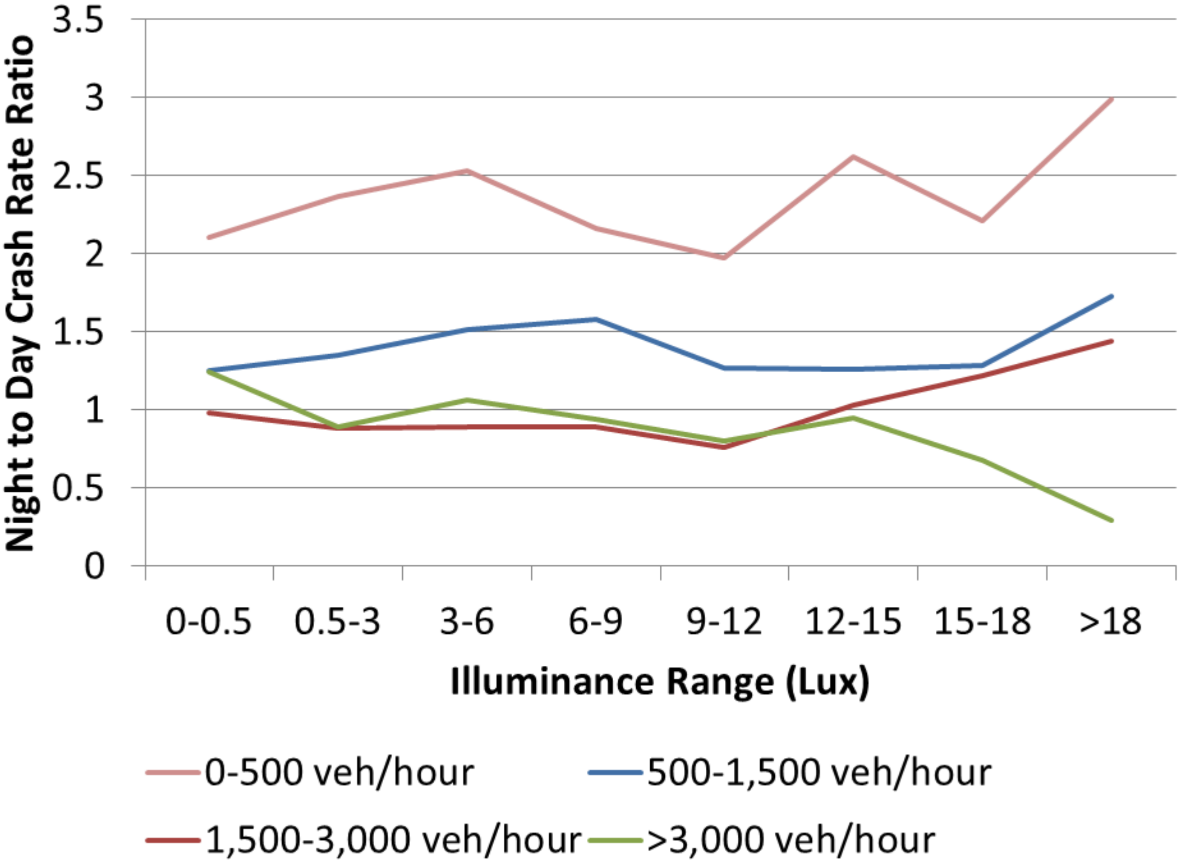

Figure 30. Graph. Relationship between mean hourly traffic flow and weighted night-to-day crash rate ratio.

Because of the lack of relationship between lighting level and hourly traffic volume, there is flexibility in how the lighting level may be changed as traffic volume changes. There is no one performance measure that defines the complexity of the operation of the traffic stream, but the level of service (LOS) is commonly used to translate this complexity into a simple categorical system from A to F.(22) LOS A describes primarily free flow operations where vehicles are only dependent on their ability to maneuver within the traffic stream. As the LOS deteriorates, the ability to maneuver within the traffic stream becomes more restrictive, and drivers experience a reduced comfort level until reaching LOS F, which describes breakdown or unstable flows.

It is important to differentiate between the different operational conditions of a road's uninterrupted flow facilities and interrupted flow facilities. Uninterrupted flow facilities have no fixed cause of delays. These types of operations include freeways and multilane highways (four to six lanes in each direction and posted speed limits between 40 and 55 mi/h (64 to 89 km/h)) and urban streets with two or more lanes in each direction that have traffic signals spaced an average of 2 mi or more apart. For this type of facility, LOS is defined by density (passenger cars (pc)/mi/lane) computed as the flow rate (pcphpl (passenger cars per hour per lane)) divided by the speed (mi/h). Several factors affect the LOS, including the free flow speed, terrain and road geometric characteristics, percentage of heavy vehicles, and driver population factors.

The resulting calculations for the volume for uninterrupted flow for highway and streets by the LOS are shown in table 27. These values are the threshold values where the LOS transitions from one level to another.

Table 27. Threshold traffic volume per direction based on LOS transitions.

LOS	**Threshold Density**	**Highway[1] Two Lanes**	**Street[2] Two Lanes**
A to B	11	1,310	900
B to C	18	2,150	1,520
C to D	26	2,990	2,200
D to E	35	3,730	2,910
E to F	45	4,320	3,560

[1] Lane width 12 ft (3.7 m), 6–ft (1.8-m) lateral clearance, 5 percent trucks, level terrain, population factor 1, PHF 0.94, 3 ramps per mi, speed 65 mi (105 km/h).

[2] Lane width 12 ft (3.7 m), 6–ft (1.8-m) lateral clearance, 3 percent trucks, level terrain, population factor 1, PHF 0.95, 20 access points per mi, speed 45 mi (72 km/h).

For real-time operations, the agency can compute density using loop detector data and create its own threshold values based on the loop detector data.

Contrary to uninterrupted flow, interrupted flow facilities have fixed causes of periodic delay, such as traffic signals that make the traffic stop periodically independent of the level of traffic. In this case, the traffic flow patterns are the results not only of vehicle interactions but also of the traffic control used at the intersections and the frequency of access points. Signal timing and the prevailing conditions affect the operations and observed volumes. The resulting calculations for the volume for interrupted flow for streets and residential is shown in table 28.

Table 28. Threshold traffic volume per direction based on LOS transitions for interrupted flow.

LOS	Street[1] Two Lanes	Residential[2] One Lane
B	N/A	N/A
C	1,060	290
D	1,850	760
E	1,890	990

[1] Traffic cycle length 120 s, weighted average green time g/C 0.45, 10 percent of left turns, 10 percent of right turns, signal spacing 1,500 ft (457.2 m), number of access points/mi 10, posted speed 45 mi/h (72 km/h), saturation flow rate 1,900 pcphpl, facility length 2 mi (3.2 km).

[2] Traffic cycle length 120 s, weighted average green time g/C 0.45, 10 percent of left turns, 0 percent of right turns, 1,050 ft (320 m) signal spacing, 20 access points/mi, posted speed 30 mi/h (48 mi/h), saturation flow rate 1,900 pcphpl, facility length 2 mi.

N/A = not applicable.

The criteria for hourly adjustment of the lighting level, as a result of the above calculations, based on traffic volume, are shown for roadways, streets, and residential areas in table 29, table 30, and table 31, respectively. These values are rounded values based on the transition from LOS B to C and the transition from LOS C to D. These levels were selected because they represent when the road reaches maximum free flow (B to C) and when crash rates begin to increase (C to D).(22) These values are recommended initial levels, and the agency is encouraged to produce new thresholds based on the specific conditions of the facility where the system will be implemented.

Table 29. Hourly traffic flow criteria for roadways.

Parameter	Options	Criteria	Weighting Value
Traffic Volume	High	> 2,000 vehicles hourly	1
	Moderate	1,000–2,000 vehicles hourly	0
	Low	< 1,000 vehicles hourly	-1

Table 30. Hourly traffic flow criteria for streets.

Parameter	Options	Criteria	Weighting Value
Traffic Volume	High	> 1,500 vehicles hourly	1
	Moderate	750–1,500 vehicles hourly	0
	Low	< 750 vehicles hourly	-1

Table 31. Hourly traffic flow criteria for residential/pedestrian roads.

Parameter	Options	Criteria	Weighting Value
Traffic Volume	High	750 vehicles hourly	0.5
	Moderate	300–750 vehicles hourly	0
	Low	300 vehicles hourly	-0.5

An agency may choose to recalculate these limits for its own specific roadway conditions.

APPROACHES TO ADAPTIVE LIGHTING TIMING

In terms of the trigger for adapting the lighting system, two approaches are typically used. The first is curfews, in which the lighting system changes at a predetermined time, and the other is monitoring of the roadway environment.

Curfews

Curfews are used to adapt lighting systems during defined time periods. These curfew times should be established based on an evaluation of the parameters of interest. An average of the traffic and pedestrian volumes can be evaluated on an hourly basis and used to determine the timing of the adaptive changes. The adaptive cycle should also be able to be overwritten to allow special events.

Roadway Monitoring

Active monitoring of the roadway through pedestrian counts and vehicle counts is an alternative to curfews. Active monitoring would require loop detectors or review of roadway video to determine the roadway criteria that would then drive the light level selection.

The resource requirements for a control and monitoring system may be significant, although they may become less demanding if connected vehicle and connected infrastructure technologies provide a new source of traffic and pedestrian volumes.

OTHER CONSIDERATIONS FOR ADAPTIVE LIGHTING

The size of the area of the lighting system to be adapted must be considered. Dimming of the roadway system can occur broadly over all the roadways within a given area, or selective dimming of sections of the roadway network can be implemented, based on an analysis of needs.

In general, dimming a large area will maintain a constant lighting level throughout the roadway so that drivers will not experience a bright lighting condition on one roadway and then turn onto a dark roadway and be forced to significantly transition their eye adaptation level, which can be uncomfortable and dangerous. However, dimming a large area may also cause some areas to be too dark.

It is recommended that each street be evaluated in terms of its lighting needs. However, the difference in lighting classes for streets in a given vicinity should be no greater than two. It is also recommended that residential areas be adapted to a single lighting level. For roadway facilities, each roadway should be assessed individually, but drivers should not experience greater than a two-level change in the lighting class. Transitions on roadways should be a maximum of 1 class per mi of travel.

CHAPTER 5. CONCLUSIONS

The design criteria defined in this report provide the basis for development of a method for selecting lighting level in the roadway based on time and traffic as well as for the implementation of adaptive lighting. These criteria are based on the analysis of safety in the roadway based on the lighting level. General conclusions are as follows:

- This research verified a strong relationship between safety and the presence of lighting.
- The relationship of the actual lighting level to safety was not as strong as the no-lighting condition. This provides flexibility in the selection of lighting based on design criteria while maintaining the safety level.
- The current lighting levels may be higher than required for safety on the roadway. For interstates and freeways, there is a potential to reduce the lighting level by as much as 50 percent from the current recommended practices.
- A method was developed, based on previous work, to provide both lighting level selection criteria and a method for adaptive lighting selection.

CHAPTER 6. LIMITATIONS AND FUTURE RESEARCH

There are significant limitations to the data collected for these analyses. The purpose of the project was to investigate the impact of lighting on roadway safety and to establish the possibility of reducing lighting on the roadway. This effort focused on interstates and major arterials. Although other roadway types were analyzed, there was a limited number of samples and as a result the statistical power is limited. Several statistical analyses were performed on this data set, including the impact of number of lanes, median type, interchange type, and intersection type. The stratification of the data results in limited sample sizes and limited reliability in the statistical analyses. As such, several of the analyses that were conducted are not documented in this report and are not used as part of the design criteria.

Limitations to the data set include the following:

- Measurements of minor arterials were conducted as part of the routing for the other data collection activities. As a result, very few sites included the minor arterials.
- Specific roadway characteristics, such as median type, number of intersections, and pedestrian levels, were not collected. Rather, this information was drawn from the provided databases, which had limitations to the accuracy of the data and were not consistent across all States.
- The results were analyzed based on the roadway design data that were part of the natural variety of roadway designs encountered as part of the data collection routing. Specific roadway criteria were not sought, which produced an imbalance in the sample size of the resulting data sets.
- As the analyses for these items moved forward, not all the data categories had enough data for stable evaluation of the results. Most of the criteria for selecting the lighting level have been established based on the available literature rather than on specific results of this analysis. This is particularly true for the recommendations for residential and pedestrian areas.

To overcome these limitations, the following future research efforts are recommended:

- Measurement of a significantly larger number of miles and crash data in terms of lighting performance.
- Selection and verification of additional sites in terms of roadway design and geometric features. These need to be included in the database and standardized across States.
- Investigation of additional major arterials and minor arterials.
- Further consideration of residential roadways. These have a significant amount of the roadway lighting in place, and proper consideration needs to be given to these roadways not only in terms of vehicle usage but also for safety and security.
- A research effort that includes weather and atmospheric conditions.

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REFERENCES

1. U.S. Department of Transportation, *Reduced Lighting on Freeways During Periods of Low Traffic Density*, Publication No. FHWA-RD-86-018, Federal Highway Administration, Washington, DC, 1985.

2. Griffith, M.S., *Comparison of the Safety of Lighting Options on Urban Freeways*, Federal Highway Administration, Washington, DC, 1994.

3. Janoff, M.S., Staplin, L.K., and Arens, J.B., "The Potential for Reduced Lighting on Roadways," *Public Roads, 50*(2), 1986, pp. 33–42.

4. ANSI/IES (2000, reaffirmed 2005), *American National Standard Practice for Roadway Lighting* (RP-8-00), 2000 (reaffirmed 2005).

5. Box, P.C., "IERI Project 85-67: Relationship Between Illumination and Freeway Accidents," *Illuminating Engineering, 66*(5), 1971, pp. 365.

6. Box, P.C., "Major Road Accident Reduction by Illumination," *Transportation Research Record 1247*, Transportation Research Board, National Research Council, Washington, DC, 1989, pp. 32–38.

7. Hilton, M.H., *A Comparison of Full and Partial Lighting on Two Sections of Roadway* (VHTRC 80-R52), Virginia Highway & Transportation Research Council, Charlottesville, VA, 1980.

8. Richards, S.H., "The Effects of Reducing Continuous Roadway Lighting to Conserve Energy: A Case Study," *SAFE Journal, 9*(1), 1979, pp. 24–26.

9. Monsere, C.M., Yin, T., and Wolfe, M., *Understanding the Safety Effects of Roadway Illumination Reductions*, Portland State University for Oregon Department of Transportation, Salem, OR, 2007.

10. Boyce, P.R., Fotios, S., and Richards, M., "Road Lighting and Energy Saving," *Lighting Research and Technology, 41*(3), 2009, pp. 245–260.

11. Commission Internationale de l'Eclairage, *Lighting of Roads for Motor and Pedestrian Traffic* (CIE 115:2010, 2nd ed.), International Commission on Illumination, Vienna, Austria, 2010.

12. Meyer, J., Gibbons, R., and Edwards, C., *Development and Validation of a Luminance Camera* (09-UL-003), National Surface Transportation Safety Center for Excellence, Blacksburg, VA, 2009, retrieved from http://scholar.lib.vt.edu/VTTI/reports/Luminance_Camera_021109.pdf.

13. Gibbons, R. and Edwards, C., *Advanced Street Lighting Technologies Assessment Project–City of San Jose*, prepared by Mutmansky, M., Givler, T., Garcia, J., and Clanton, N., Virginia Tech Transportation Institute, Blacksburg, VA, 2010.

14. Denial of Petition for Rulemaking, Federal Motor Vehicle Safety Standards, 62 Fed. Reg. 184 (Sep. 23, 1997), pp. 49,663–49,664.

15. Gibbons, R.B., Edwards, C., Williams, B., and Andersen, C.K, *Informational Report on Lighting Design for Midblock Crosswalks*, FHWA-HRT-08-053, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2008.

16. Clanton, N., Gibbons, R., Garcia, J., and Terry, T., *Evaluation of Adaptive Lighting in the City of Seattle*, Northwest Energy Efficiency Alliance, Portland, OR, in press, 2014.

17. Hankey, J.M., Blanco, M., Gibbons, R.B., McLaughlin, S.B., and Dingus, T.A., *Enhanced Night Visibility Series, Volume I: Executive Summary* (FHWA HRT-04-132), FHWA, Washington, DC, 2005.

18. Gibbons, R.B., Edwards, C.J., Bhagavathula, R., Carlson, P.J., and Owens, D.A., *Visual Modeling: Exploring Relationships Between Nighttime Driving Behavior and Roadway Visibility Features* (Paper 12-3783), presented at the Transportation Research Board Annual Meeting, Washington, DC, January 2012.

19. Assum, T., Bjørnskau, T., Fosser S., and Sagberg, F. "Risk Compensation—The Case of Road Lighting," *Accident Analysis & Prevention, 31*(5), 1999, pp. 545–553, http://dx.doi.org/10.1016/S0001-4575(99)00011-1.

20. Lord, D., Manar, A., and Vizioli, A., "Modelling Crash-Flow Density and Crash-Flow V/C Ratio Relationships for Rural and Urban Freeway Segments," *Accident Analysis and Prevention, 37*, 2005, pp. 185–199.

21. Gibbons, R.B., Hankey, J.M., and Pashaj, I., *Wet Night Visibility of Pavement Markings* (VTRC 05-CR4), Virginia Transportation Research Council, Charlottesville, VA, October 2004.

22. Transportation Research Board, *HCM 2010: Highway Capacity Manual 2010*, retrieved from http://hcm.trb.org.

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