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16. Abstract

Roadway lighting is provided on selected highways to improve the visibility of the nighttime environment. Roadway lighting is typically warranted on the basis of the daily traffic volume. However, in the early-morning hours, the traffic volumes may be so low as to diminish the need for roadway lighting. At present, the lighting infrastructure in place on Texas Department of Transportation (TxDOT) highways is not well suited to being dimmed. As a result, turning off roadway lighting during early morning hours is the only option. This concept is known as a lighting curfew for purposes of this research project. The lighting curfew section of the TxDOT 2003 Illumination Manual does not provide specific guidelines or criteria for implementing lighting curfews. Although lighting curfews are of interest around the country, no state has developed guidelines for lighting curfews, nor are there national guidelines at this time. The most significant potential benefits of lighting curfews include reduced power consumption and reduced light pollution.

This project focused upon developing guidelines for implementing lighting curfews on urban freeways, which have the potential to impact TxDOT's ability to manage its lighting infrastructure in an advantageous manner. The guidelines developed through this project identify threshold criteria under which freeway main lane lighting can be turned off. The guidelines also identify conditions or exceptions under which lighting curfews should be suspended, modified, canceled, or not used at all (such as periods of inclement weather or during a major late-night event).

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GUIDELINES FOR FREEWAY LIGHTING CURFEWS

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was H. Gene Hawkins, Jr., P.E. #61509. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1:
INTRODUCTION

BACKGROUND

Roadway lighting is provided on selected highways to improve the visibility of the nighttime environment. The primary benefit expected from roadway lighting is improved safety, but there are other benefits as well, including security and beautification. The need for roadway lighting on Texas highways is based on warrants that are defined in the Texas Department of Transportation (TxDOT) *Highway Illumination Manual* (TxDOT 2003 Illumination Manual) (*1*). This manual includes a section on lighting curfews, which is a concept where lighting is reduced (dimmed or trimmed) or turned off during periods with reduced demand for lighting (throughout this report, the term *lighting curfew* is used to describe the concept of reducing or eliminating lighting during some portion of the nighttime hours). The term *adaptive lighting* is also used to describe a similar concept where lighting levels are adapted to the needs over time. The periods of reduced lighting demand are typically associated with a decrease in the traffic volume on the roadway and generally occur during the late night and/or early morning hours when traffic volumes have decreased to the point that lighting may not provide the intended benefits. The potential benefits to be realized from lighting curfews include:

- Reduced energy consumption and associated electrical costs.
- Reduced lighting spillover off the right-of-way and into the atmosphere (reduction in light pollution).

At present, the lighting infrastructure in place on TxDOT highways is not well suited to being dimmed. As a result, the primary options for implementing lighting curfews with the current infrastructure are to turn lights off at some point during the night or to turn off individual light fixtures in a cluster (known as trimming), such as turning off some of the lights in a high mast assembly. Future lighting technologies are expected to provide a more effective means of operating lighting at less than full lighting levels (known as dimming). However, the lighting curfew section of the TxDOT 2003 Illumination Manual does not provide specific guidelines or criteria for implementing lighting curfews. Although lighting curfews are of interest around the country, no state has developed guidelines for lighting curfews, nor are there national guidelines at this time.

RESEARCH OBJECTIVES

This project focused upon providing guidelines for implementing lighting curfews on urban freeways, which have the potential to impact TxDOT's ability to manage its lighting infrastructure in an advantageous manner. The guidelines developed through this project identify threshold criteria under which freeway main lane lighting can be turned off. The guidelines also identify conditions or exceptions under which lighting curfews should be suspended, modified, canceled, or not used at all (such as periods of inclement weather or during a major late night event). In developing guidelines, the research team considered the impact of lighting curfews on safety, as well as practical considerations of lighting curfews.

SUMMARY OF RESEARCH ACTIVITIES

During the course of the project, the research team conducted several activities that led to the development of guidelines for lighting curfews. These activities are summarized below and described in more detail in the chapters of this report.

In the initial research activities, the research team documented current practices through a review of related literature and an evaluation of current practices at TxDOT and other agencies. The initial research effort also included conducting a kick-off meeting with TxDOT staff in which the group identified TxDOT's needs, priorities, requirements, critical issues, and challenges related to this research project. It was at the initial kick-off meeting that the research team and TxDOT project advisors decided to focus the research on urban freeways and to avoid lighting curfews at sites with heavy pedestrian traffic. The research team started the project by reviewing literature on freeway continuous lighting in terms of overall lighting design and safety aspects of roadway lighting. The research team also conducted surveys for current practices for lighting curfews in other states and countries and lighting practices in selected TxDOT districts. Along with these current practices of lighting, the research team also addressed recent developments that may impact roadway lighting, and impacts of environmental and other non-technical factors on lighting operation. Chapter 2 documents the information identified during the review of current practices.

The research team next evaluated lighting conditions at various field locations to evaluate the performance of current lighting and factors that should be considered in later evaluations related to safety analysis and visibility assessments. The information included roadway segments with and without lighting, roadway geometry, the general type of lighting present on each roadway (continuous or safety lighting), lighting characteristics (spacing, height, and location), the availability and proximity of traffic volume data on an hourly basis near the identified locations (availability of permanent count stations on the roadway or other hourly count volume). Chapter 3 includes information identified through these efforts.

The primary focus of this research project was an assessment of the safety (crash) implications of reducing or turning off lighting during certain portions of the nighttime period. In the safety analysis task, the research team attempted to analyze the relationship between roadway lighting and freeway safety. The research team conducted extensive data collection, analyzed hourly crashes (crash frequency and crash rate) with and without lighting during the early morning hours, and evaluated crash impacts by using the *Highway Safety Manual* (*2*) procedures to predict crash trends. Chapter 3 also includes detailed descriptions of the safety analysis.

The research team felt that it was important and appropriate to address visibility as part of this research project. Instead of conducting a detailed analysis of lighting visibility using human subjects, the research team conducted a limited visibility assessment. In this task, the research team collected photometric data through static measurement for luminance data and dynamic measurement for illuminance data. Chapter 3 describes the visibility evaluation data collection and analysis.

While identifying the factors that affect lighting curfews, the research team also tried to quantify the potential benefits and costs of turning off roadway lighting. The research team estimated the electricity savings and crash costs associated with various lighting curfew scenarios. This analysis is also described in Chapter 3.

Once armed with data and information associated with a wide range of perspectives on lighting curfews gained from preceding research tasks (results are summarized in Chapter 4), the research team performed a feasibility assessment of lighting curfews and developed preliminary guidelines. The assessment identified factors that should be considered in evaluating lighting curfew feasibility and determined what data were available to evaluate each factor. The research team also developed a benefit-and-cost relationship for lighting during the hours of the nighttime period. Based on the feasibility assessment, the research team developed preliminary guidelines that considered the full range of factors related to lighting curfews. The preliminary guidelines provided threshold criteria of traffic volume or time of day to indicate the conditions under which lighting could be turned off or reduced. The guidelines also identified permanent (such as a case where lighting is needed due to severe roadway geometry) and temporary (such as during a hurricane evacuation) conditions under which lighting should be maintained throughout the nighttime period. Chapter 5 presents the developed preliminary guidelines.

CHAPTER 2:
CURRENT PRACTICE

CURRENT LIGHTING PRACTICES

Current roadway lighting practices follow various lighting guidelines that specify the process of lighting design and installation. Two major components of these guidelines are lighting warrants and design criteria. The former determine whether the proposed lighting system is justified for the eligible roadway locations, and the latter specify the requirements of lighting installation and illumination performance.

Overview of Lighting Guidelines

In the US, one of the oldest roadway lighting guidelines is the *Principles of Streetlighting* published by the Illuminating Engineering Society-American National (IESNA) Standards Institute in 1928. Following the guidelines are three versions of the IESNA Code of Streetlighting in 1930, 1935, and 1937. These publications give principles for two other documents that recommend practices of street and highway lighting published in 1940 and 1945 (*3*). In 1947, IESNA published the first version of *American National Standard Practice for Roadway Lighting* (IESNA RP-8-1947 lighting guide), which provides specific lighting criteria and design methods (*3*). The American Association of State Highway and Transportation Officials (AASHTO) published *An Informational Guide for Roadway Lighting* in 1969 (*4*) to also specify individual lighting warranting conditions that are not included in the IESNA RP-8-1947 lighting guide. The National Cooperative Highway Research Program (NCHRP) report 152 published in 1974, entitled *Warrants for Highway Lighting* (NCHRP 152 report) (*5*), introduces lighting warrants based on comprehensive ratings of roadway factors such as geometrics, operation, environment, and crashes. The Federal Highway Administration (FHWA) published the *Roadway Lighting Handbook* in 1978 and the *Roadway Lighting Handbook, Addendum to Chapter Six: Designing the Lighting System Using Pavement Luminance* in 1983 in conjunction with later-version lighting guides published by IESNA and AASHTO (the IESNA RP-8 lighting guide published in 1977 and the AASHTO lighting guide published in 1976) and the NCHRP 152 report. This FHWA handbook, for the first time, satisfied the need of an all-inclusive manual covering most aspects of public roadway lighting in the US (*6*). Since then, these early versions of documents have been updated to keep up with the progress of research and practices and have been continuously referred by most state departments of transportation (DOTs) in their roadway lighting handbooks or guidelines.

The International Commission on Illumination (CIE) publication *Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic* (CIE 115-1995 lighting guide) (*7*), similar to the IESNA RP-8 lighting guide, provides luminance and illuminance criteria but no lighting warrants. As a revision and update of the CIE 115-1995 report, the CIE 115-2010 report introduces adaptive lighting guidelines for roadways (*8*). The CIE 115-1995 lighting guide is an important document cross-referenced by many of the US lighting guidelines, and it is also widely referenced in lighting standards or guidelines of many other countries such as European Union, Canada, and China. Canada uses the *Guide for the Design of Roadway Lighting* (TAC lighting guide) that was published by the Transportation Association of Canada (TAC) in 2006, the majority of which is based on recommended practices by IESNA and CIE (*9*). Most European countries implement their lighting practices according to the European Standard EN 13201-2003 *Roadway Lighting* published by the European Committee for Standardization (CEN) (*10*, *11*). Australia and New Zealand have very comprehensive roadway lighting standards in the AS/NZS 1158 roadway lighting standard series from Standard Australia (*12*). China and Japan refer to the CIE and IESNA guidelines for their own lighting design methods and criteria (*13*, *14*, *15*). Table 1 lists the major lighting guidelines currently in use around the world.

Table 1. Major Roadway Lighting Guidelines.

Countries	Standards
Internationally accepted	CIE 115-1995 "*Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic*" (*7*) CIE 115-2010 "*Lighting of Roads for Motor and Pedestrian Traffic*" (*8*)
United States	AASHTO 2005 "*Roadway Lighting Design Guide*" (*16*) NCHRP 152-1974 "*Warrants for Highway Lighting*" (*5*) ANSI/IESNA RP-8-2000 "*American National Standard Practice for Roadway Lighting*" (*3*)
Canada	TAC 2006 "*Guide for the Design of Roadway Lighting*" (*9*)
European Union	EN 13201-2:2003 "*Road Lighting*" (*11*)
Australia and New Zealand	AS/NZS 1158.0:2005 "*Lighting for roads and public spaces*" (*12*)
China	JT/T 367-1997 "*The Technical Conditions for Highway Lighting*" (*13*) CJJ 45-2006 "*Standard for Lighting Design of Urban Road*" (*14*)
Japan	JIS Z9111-1988 "*Lighting for Roads*" (*15*)

Most lighting guidelines define two types of lighting systems: safety lighting and continuous lighting. Safety lighting may be provided at interchanges, intersections, or other roadway points of nighttime hazard to address a specific safety concern. On freeways, safety lighting may cover part of an interchange (acceleration and deceleration lanes, ramp terminals, or other hazardous areas), a complete interchange (main lanes, direct connections, and ramp terminals), or other spot locations with complex geometry or raised channelization. In comparison, continuous lighting is installed over an extended length of roadway to improve general safety and visibility. Continuous lighting on freeways provides relatively uniform illumination on all main lanes and all interchange areas.

Lighting warrants specify the conditions at eligible roadway locations to justify the need for and expense of roadway lighting. Generally, there are two types of continuous lighting warranting methods: 1) warranting by individual criteria, such as roadway types, average daily traffic (ADT), interchange spacing, segment length, speed limit, crash rate, land use and geometry, or the combination of some of these individual criteria; and 2) warranting by comprehensive rating for roadways with or without controlled access, each of which has four classification factors, i.e., geometry, operation, environment, and crashes. The AASHTO 2005 lighting guide and a majority of other lighting guidelines specify the first type of warrants, and the NCHRP 152 report and the Canada TAC lighting guide describe the second type of warrants.

Once the conditions at eligible roadway segments justify a proposed lighting system, proper lighting design methods should guide detailed lighting design for equipment selection and installation. The lighting design method may be the illuminance method, the luminance method, or the small target visibility (STV) method. The illuminance design method calculates the amount of light on the roadway surface and may be used for roadways with pedestrian-vehicle conflicts, such as sidewalks, bikeways, intersections, and continuous lighting (*3, 16*). The luminance design method calculates the amount of light directed to the driver to predict the luminance of the roadway and is often used for vehicular conflict areas (*3, 7, 16*). The STV method is first proposed by the IESNA RP-8-1990 lighting guide and adopted by the IESNA RP-8-2000 guide, the CIE 115-1995 guide, and the TAC 2006 guide. This method calculates the ratio of the real difference in luminance between the target and its background to the luminance difference needed between the target and its background. A majority of the lighting guidelines adopt the illuminance method and/or the luminance method, while the STV method is not broadly applied as a design criterion among countries.

TxDOT Lighting Guidelines

While the TxDOT 2003 Illumination Manual refers to the AASHTO "*An Informational Guide for Roadway Lighting*" (AASHTO 1984 lighting guide) (*17*) for lighting warrants and design criteria, TxDOT engineers also use the AASHTO "*Roadway Lighting Design Guide*" (AASHTO 2005 lighting guide) (*16*), a replacement of the AASHTO 1984 lighting guide, in lighting designs. Warrants for continuous lighting are almost the same in the two guides, but the design criteria are slightly different.

TxDOT Warrants for Continuous Lighting

Continuous lighting warrants in the TxDOT 2003 Illumination Manual (*1*) adopt the individual criterion method from the AASHTO 1984 lighting guide (*17*). Note that continuous lighting warranting criteria of the AASHTO 2005 lighting guide do not differ much from the AASHTO 1984 version. The AASHTO 1984 lighting guide specifies individual warranting criteria for continuous lighting on freeways but not for roadways other than freeways. It suggests that for partial or non-access-controlled roadways, lighting, not necessarily continuous lighting, may be considered when the night-to-day crash rate ratio is higher than the state average. The TxDOT 2003 Illumination Manual provides continuous lighting warrants for full access-controlled urban multi-lane freeways and partial access-controlled urban multi-lane arterials. Non-access-controlled roadways are not eligible for continuous lighting, and continuous lighting for bikeways and pedestrian ways depends on funding availability. TxDOT does not normally light frontage roads (*1*).

Individual warranting criteria for continuous lighting in the TxDOT guidelines could be categorized into three groups: traffic volume criteria, roadway related criteria, and safety criteria. TxDOT assesses roadway conditions in terms of criteria described in four cases, and continuous lighting may be warranted under any one of four cases. Case 1 (CL-1) specifies the threshold value for average daily traffic; Case 2 (CL-2) and Case 3 (CL-3) describe the requirements of roadway related criteria (interchange spacing, adjacent roadway lighting and land development, crossroad spacing, and cross-section elements); and Case 4 (CL-4) gives requirements of the ratio of night-to-day crash rate. Table 2 lists the continuous lighting warrants from the TxDOT 2003 Illumination Manual (*1*).

Table 2. TxDOT Continuous Lighting Warrants for Freeways.

Individual Criteria	Case No.	TxDOT Warrants (1)
Traffic Volume	CL-1	Average daily traffic (ADT) ≥ 30,000 vpd
Roadway Related Factors	CL-2	≥ 3 interchanges with average spacing ≤ 1.5 miles and adjacent to substantial urban areas
	CL-3	≥ 2 miles freeway segment passing through areas with two or more of the following characteristics: • Lit street grid visible from the freeway • A series of developments, e.g., streets, residential and parking areas • Lit cross streets ≤ 0.5 mile apart • Width of freeway cross-section elements below desirable levels
Safety	CL-4	Night-to-day crash rate ratio ≥ 2.0 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

TxDOT Design Method and Criteria for Continuous Lighting

After warranting conditions for continuous lighting are met, TxDOT mainly uses the illuminance method for lighting design of typical roadways, while allowing design engineers to use the luminance method in addition to or in lieu of the illuminance method. The TxDOT 2003 Illumination Manual points out that the STV method should not be used (*1*).

As TxDOT may use both the AASHTO 1984 and AASHTO 2005 lighting guides for lighting design, Table 3 shows a summary of lighting levels from the two guides to compare the requirements for freeway continuous lighting. Both guides provide the illuminance and luminance methods, as well as the additional veiling luminance ratio for each method. The illuminance method requires the minimum level of average maintained illuminance, minimum illuminance, and maximum uniformity ratio. The luminance method requires the minimum level of average maintained luminance and maximum uniformity ratio. The AASHTO 1984 lighting guide provides one set of average maintained illuminance levels for all freeways (*17*), while the AASHTO 2005 lighting guide's requirements vary by types of pavement surfaces (*16*). The AASHTO 2005 lighting guide also has higher upper limits for average maintained illuminance and luminance levels than the AASHTO 1984 lighting guide (*16, 17*).

Table 3. AASHTO Guide Illuminance and Luminance Criteria for Continuous Lighting.

Roadway Type	**General Land Use**	**Illuminance Method**			**Luminance Method**			**Additional**
		E_{avg}* (lux) (min)	E_{min} (lux) (min)	Uniformity	L_{avg} (cd/m^2) (min)	Uniformity		Veiling Luminance**
				E_{avg}/E_{min} (max)		L_{avg}/L_{min} (Max)	L_{max}/L_{min} (Max)	$L_{v(max)}/L_{avg}$ (Max)
AASHTO 1984 Lighting Guide (17)								
Freeway	All	6~9	2	3:1 or 4:1	0.4~0.6	3.5:1	6:1	0.3:1
Expressway	Commercial	10~14	As uniformity ratio allows	3:1	1.0	3:1	5:1	0.3:1
	Intermediate	8~12			0.8	3:1	5:1	0.3:1
	Residential	6~9			0.6	3.5:1	6:1	0.3:1
Major Arterial	Commercial	12~17		3:1	1.2	3:1	5:1	0.3:1
	Intermediate	9~13			0.9	3:1	51	0.3:1
	Residential	6~9			0.6	3.5:1	6:1	0.3:1
Collector	Commercial	8~12		4:1	0.8	3:1	5:1	0.4:1
	Intermediate	6~9			0.6	3.5:1	6:1	0.4:1
	Residential	4~6			0.4	4:1	8:1	0.4:1
Local	Commercial	6~9		6:1	0.6	6:1	10:1	0.4:1
	Intermediate	5~7			0.5	6:1	10:1	0.4:1
	Residential	3~4			0.3	6:1	10:1	0.4:1
Alleys	Commercial	4~6		6:1	0.4	6:1	10:1	0.4:1
	Intermediate	3~4			0.3	6:1	10:1	0.4:1
	Residential	2~3			0.2	6:1	10:1	0.4:1
Sidewalks	Commercial	10~14		3:1	Use illuminance requirements			
	Intermediate	6~9		4:1				
	Residential	3~4		6:1				
Pedestrian / Bike Lanes		15~22		3:1				
AASHTO 2005 Lighting Guide (16)								
Interstate and Other Freeways	Commercial	6~12	2	3:1 or 4:1	0.4~1.0	3.5:1	6:1	0.3:1
	Intermediate	6~10	2	3:1 or 4:1	0.4~0.8	3.5:1	6:1	0.3:1
	Residential	6~8	2	3:1 or 4:1	0.4~0.6	3.5:1	6:1	0.3:1
Principle Arterial	Commercial	12~17	As uniformity ratio allows	3:1	1.2	3:1	5:1	0.3:1
	Intermediate	9~13			0.9	3:1	5:1	0.3:1
	Residential	6~9			0.6	3.5:1	6:1	0.3:1
Minor Arterial	Commercial	10~15		4:1	1.2	3:1	5:1	0.3:1
	Intermediate	8~11			0.9	3:1	5:1	0.3:1
	Residential	5~7			0.6	3.5:1	6:1	0.3:1
Collector	Commercial	8~12		4:1	0.8	3:1	5:1	0.4:1
	Intermediate	6~9			0.6	3.5:1	6:1	0.4:1
	Residential	4~6			0.4	4:1	8:1	0.4:1
Local	Commercial	6~9		6:1	0.6	6:1	10:1	0.4:1
	Intermediate	5~7			0.5	6:1	10:1	0.4:1
	Residential	3~4			0.3	6:1	10:1	0.4:1
Alleys	Commercial	4~6		6:1	0.4	6:1	10:1	0.4:1
	Intermediate	3~4			0.3	6:1	10:1	0.4:1
	Residential	2~3			0.2	6:1	10:1	0.4:1
Sidewalks	Commercial	10~14		3:1	Use illuminance requirements			
	Intermediate	6~9		4:1				
	Residential	3~4		6:1				
Pedestrian / Bike Lanes		15~22		3:1				

* The required minimum level of average maintained horizontal illuminance varies by pavement types, with the lowest values for Portland cement concrete surface and the highest values for rough asphalt surface

** The veiling luminance ratio is the ratio of veiling luminance $L_{v(max)}$ to the average maintained luminance L_{avg}.

To meet the required light level, lighting equipment should be properly selected and installed. Decision variables for equipment selections and installation may be lighting costs, vehicular and pedestrian volume, type of roadway, roadway geometry, and type of lighting equipment. Roadway lighting assemblies installed on Texas roadways include conventional luminaire poles and high mast poles. The two types of lighting units differ in luminaire size, mounting height, and spacing. Typical conventional light poles have lower wattage lamps (single arm or double arm 150W, 250W, or 400W high pressure sodium [HPS] lamps), lower mounting height (50 ft or lower), and shorter spacing (180~250 ft), whereas high mast assemblies use higher wattage lamps (12 400-watt HPS lamps), higher mounting height (100 ft or higher), and longer spacing (500 ft or greater).

Selection between conventional and high mast units should consider several factors: installation and maintenance costs, traffic volume, and possibility of lighting pollution. Conventional lighting often requires less installation cost on non-interchange roadway segments, while high mast lighting is less expensive for interchange areas because of reduced complexity of conduits and conductors and requirements for fewer lighting fixtures and poles. Maintaining high mast lighting also costs less because it involves less extensive traffic control (signs, cones, and lane closures, etc.). The TxDOT 2003 Illumination Manual recommends that high mast lighting be considered for complete interchange lighting and for tangent segments of freeways with initial ADT of 70,000 or greater. However, high mast lighting should not be applied in substantially developed residential area to avoid lighting trespass. If it must be used, special high mast design should be considered.

Lighting poles may be placed between curb and right-of-way line, called house side mounting, or on medians, called median mounting. Although the TxDOT 2003 Illumination Manual does not specify the location of high mast poles, they are typically house side mounted. They may also be installed on wide medians when the width is great enough to treat each direction of main lanes as a separate roadway. Placement of conventional lighting poles depends on the type of poles (either non-breakaway or breakaway), clear zone requirement, or hazard of falling poles to surrounding roadway users, vehicles, or property. Normally, breakaway poles are preferred over non-breakaway poles because they shear easily on impact and are less likely to damage impacting vehicles or to cause injury to occupants. Non-breakaway poles are usually house side mounted and should not be median mounted if unprotected. TxDOT requires protection for non-breakaway poles if they are mounted inside the clear zone; otherwise they must be placed outside the clear zone and as close to the right-of-way line as possible. Usually, unprotected poles located inside the clear zone should be breakaway. Table 4 summarizes TxDOT's general rules about placement of breakaway poles.

Table 4. TxDOT Guidance for Pole Placement of Conventional Lighting.

Location	**Placement Rules (1)**
House side mounting	Should be 15 ft from lane edge and have a clearance of 2/5 mounting height behind the poles for interstate highway Should be at least 2.5 ft from lane edge for other highways
Median mounting	For medians of 30 ft or wider: • Should not be closer than 2/5 of the mounting height from either main lane edge For medians of 30 ft or narrower: • Not suggested unless for city street with curbed medians, speed limit of 45 mph or less, and low risk of falling poles to pedestrians • Should be at least 2.5 ft from any curb face, and the pole height should not exceed 30 ft and mast arm lengths should not exceed 4 ft • Should be at least one mounting height back from the end of the median at intersections

Continuous Lighting Warrants and Criteria in Other States and Countries

The research team also investigated continuous lighting warrants and criteria in other states and countries in an attempt to see if lighting installation and operation have been managed using hourly criteria.

Continuous Lighting Warrants in Other States and Countries

Like TxDOT, most states in the US and many other countries adopt the individual criteria consistent with the AASHTO lighting guides (*16, 17*) for continuous lighting. A few states in the US, such as Mississippi, use the comprehensive rating criteria proposed by the NCHRP 152 report (*18*) for intersection spot lighting, and some other countries, such as Canada, adopt the comprehensive rating system for both continuous and spot lighting warrants (*9*).

Table 5 and Table 6 summarize the continuous lighting warrants adopted by different states in the US. Not all states specify continuous lighting in their lighting guidelines, e.g., California has high standards for visibility of traffic control devices and does not warrant specifically continuous lighting. Instead, safety lighting is required by undesirable geometrics or high traffic volume (*19*). Some states such as Kansas do not provide clear criterion thresholds to warrant lighting and rely on engineering judgment for continuous lighting (*20*). Oregon DOT does not provide lighting for new construction inside city limits on state highways, but no criterion is specified for the definition of new construction (*21*). Nighttime hourly traffic volume is used as one of the warranting elements in Washington for continuous lighting (*22*), and in New Jersey (*20*) and Minnesota (*23*) for intersection spot lighting. Some states also indicate a concern of energy and environment issues in their lighting related documents, such as California, New Mexico, Texas, Colorado, Arizona (*24*), Maryland (*25*), Florida (*26*), etc. A few states still use the NCHRP 152 report as the major reference to warrant lighting on some types of roads, e.g., Mississippi uses the NCHRP 152 report for non-access control roads and intersections (*27*), and West Virginia adopts the NCHRP 152 report for existing roadway lighting (*28*).

Table 5. Continuous Lighting Warrants Consistent with AASHTO Lighting Guides.

Individual Criteria	Warrants from State DOTs Other than TxDOT (*20*)
Traffic Volume	Missouri: 30,000 vpd & near cities Minnesota: 40,000 vpd New York: 75,000 vpd
Roadway Related Factors	New York: ≥ 2 interchanges with average spacing ≤ 0.5 mi
	Missouri: ≥ 2 miles freeway segment passing through areas with one of the following characteristics: • Lit street grid visible from the freeway • A series of developments, e.g., streets, residential and parking areas • Lit cross streets ≤ 0.5 mile apart • Width of freeway cross-section elements below desirable levels
Safety	Minnesota: night-to-day crash rate ratio ≥ 2.0 for freeway; higher than state average (*23*)

Table 6. Continuous Lighting Warrants Other than the AASHTO Lighting Guides.

State	Warrants
Arizona (*29*)	Lighting on freeway and conventional highway considers the following factors: • ADT of newly opened freeway (section, ramp, and crossroad) (for freeway only) • ≥ 3 interchanges with average spacing ≤ 3.0 mi (for freeway only) • ≥ 3 lanes in each direction (for freeway only) • Lit street grid visible from the freeway • Whether the cross streets lit up to 0.5 mi in each direction from the freeway • The area under consideration is urban • Night and day crash comparison in the past 3 years
California (*19*)	No freeway continuous lighting. Safety lighting should not be installed unless required by undesirable geometrics or high traffic volume; local street lighting within the limits of freeway project may be warranted based on local finance.
Delaware (*30*)	Lighting should be considered for the following conditions: • Percentage of nighttime crashes ≥ 40% and lighting may reduce crashes • Residential area with internal streets lit and ≥ 75 homes
Illinois (*31*) Montana (*32*)	Freeway lighting uses AASHTO guide; warrant rural highway lighting if one or more of the following conditions exist: • Complex geometry or section of highway with raised median • High conflict locations (vehicle-vehicle interactions: many driveways, significant commercial/residential development, high truck percentage) • Night-to-day crash ratio > state average, and study indicates lighting would reduce night crash • Local agency finds sufficient benefit and pays large part of the lighting costs

Table 6. Continuous Lighting Warrants Other than the AASHTO Lighting Guides (continued).

State	Warrants
Indiana (*33*)	Use a Highway Lighting Crash Warrant Worksheet to conduct benefit/cost analysis for roadway segments of 1.5 km (1 mi) or less for continuous lighting warrants.
Kansas (*20*, *34*)	Traffic volume, closely spaced interchange, night crashes, and unusual geometrics.
Mississippi (*18*)	Segments of through divided highways with median widths of less than 16 ft; all segments of through highway with six or more through travel lanes.
New York (22)	If one or more of the following conditions exist: • Night-to-day crash ratio ≥ 3.0 and total crash rate is at least 2 times > state average, provided 1 nighttime crash per intersection/yr has occurred on the segment of road over a 3 year period or an average of 6 or more nighttime crashes/mi/yr • Gap between continuously lit segments < 0.5 mi and % gap length to total length of 2 lit segments plus gap < 25% • Local government(s) desire installation of street or arterial lighting based on non-user benefits such as aesthetics, civic pride, crime reduction, and increased business activity
North Dakota (22)	Freeway lighting uses AASHTO guides and: • Completely lit interchanges are ≤ 1.5 mi apart along freeways • Local government finds sufficient benefit and pays 50% of the installation cost For rural roadway, if one or more of the following conditions exist: • Reconstruction of existing roadway will require removal of existing lighting system • Night-to-day crash rate ratio ≥ 2.0 and study of conditions indicates lighting may result in a significant reduction in night crash rate • Installation of lighting adds to safety and comfort of vehicular driver and pedestrians, and facilitates traffic flow and/or where local government finds sufficient benefit and pays 50% installation cost and 100% operation and maintenance costs
Oregon (*21*)	If both of the following conditions exist: • ≥ 30% of total crashes are at night • Night crash rate exceeds overall crash rate by more than 50% • Total crash rate > statewide average for similar roadway character
Oklahoma (*20*)	For non-freeway: • 6,000 vpd for 2-ln road, ≥ 12,000 vpd for 4-ln road • Night-to-day crash rate ratio ≥ 1.5 • Potential for crashes due to driveways, channelized islands, development, high % trucks and geometric deficiencies
Washington (22)	If all of the following conditions exist: • Highway segment is in a commercial area • Nighttime peak hour LOS is D or lower, or night-to-day crash rate ratio > 1.0 • Engineering study indicates lighting would improve nighttime driving conditions
West Virginia (*28*)	Use the AASHTO 1984 lighting guide for new construction and the NCHRP 152 report for existing roadway.

Outside of the US, both individual warrant criteria and comprehensive rating are adopted for continuous lighting. Canada is the major country using the comprehensive rating system that originates but slightly differs from the NCHRP 152 report. Table 7 lists the summary of the Canada warranting rating system for continuous lighting (TAC 2005 lighting guide) (9). Note that the individual rating points are multiplied by weight values that vary among rating elements and types of roadways to calculate the sum of each rating factor and then to reach the total points for a type of roadway. Lighting is warranted if the total points are 60 or higher.

Table 7. Continuous Lighting Warrants of Comprehensive Rating.

Rating Factor	Rating Elements	Roadway Type*	Criteria with Rating Points from 1 point to 5 points **
Geometrics	No. Lanes (ln)	F, E, L	4 ~ 8
	Lane Width (m)	F, E, L	> 3.6 ~ < 3.0
	Horizontal Curve Radius (m)	F, E, L	> 575 ~ < 3500 (F), > 175 ~ < 600 (E, L)
	Vertical Grade (%)	F, E, L	< 3 ~ > 7
	Shoulder Width (m)	F, E	> 3 ~ < 1.2
	Off Roadway Embankment Slopes	F, E	> 6:1 ~ < 3:1
	Sight Distance (m)	E, L	> 210 ~ < 60
	Interchange Frequency (No. per km)	F	> 6.5 ~ < 1.5
	Median Width (m)	F	> 12 ~ < 1.2
	Driveway and Entrance (/km)	L	< 20 ~ > 80
	Median Opening (/km)	L	< 2.5 or One-way ~ > 9.0 or none
	Parking	L	Prohibited ~ Both Sides
Operation	Level of Service (Night at any hour)	F	A ~ E or lower
	Intersection / Interchange Frequency (No. per km)	E	> 2.5 ~ < 1.0
	Turning Lanes	E	Right Only ~ Two way left turn lane
	Left Turn Lane	L	All Major Intersection or one way ~ Infrequent or two way left turn lane
	Median Width (m)	E, L	
	Operating or Posted Speed (km/h)	E, L	≤ 60 ~ ≥ 100 (E) ≤ 40 ~ ≥ 80 (L)
	Pedestrian Activity Level	E, L	Low ~ High
	Signalized Intersection (%)	L	100 ~ 50
Environment	% Development adjacent to road	F, E, L	Nil ~ > 75 (F), Nil ~ > 90 (E, L)
	Distance from Development to Roadway (m)	F, E, L	> 60 ~ < 15
	Area Classification	E, L	Rural ~ Downtown
	Ambient Lighting	E, L	Nil ~ Intense
	Raised Curb Median	E, L	None ~ At few intersections (≤ 50%)
Crashes	Night-to-Day Crash Ratio	F, E, L	< 1.0 ~ > 2.0

* F-Freeway, E-Expressway, L-Arterial, collector, and local roads

** Table content is a summary of lighting warrants contained in the Canada TAC 2005 lighting guide (9)

Table 8 lists a summary of individual lighting warrants adopted in Europe, Australia, and Asia. The Netherlands is one of the few countries using hourly traffic volume as one of the major warranting criteria for roadway lighting (*35*). China also suggests lighting management for energy saving according to hourly traffic volume in their lighting standards, but the standards do not provide specific volume levels (*13, 14*).

Table 8. Lighting Warranting Conditions for Other Countries.

Country	Continuous Lighting Warranting Conditions
Belgium (*35*)	The roadway segments between interchanges have luminance level lower than specified minimum level.
Switzerland (*35*)	Urban highways are in the neighborhood of lit urban roads or in areas with higher risks.
Finland (*35*)	Two-lane highway is lit if an adjacent, lit pedestrian way or lit bike path exists. Safety justification
France (*35*)	ADT > 50,000 vpd, or 25,000 vpd < ADT < 50,000 vpd with interchange spacing shorter than 5 km (3.1 mi)
Netherland (*35*)	Always light roadway when one of the following exists (1990 Warrants): • Four or more lanes • Two lane with 1,500 vphpl peak volume • One lane with 2,000 vphpl peak volume • One lane with 1,800 vphpl peak volume, if slow traffic present Also consider the following factors (1997 Supplements) • Far from scenic area • Lighting alternatives: e.g., glare screens, guidance lighting, switching or dimming the lights in late night, cost/benefit
Australia and New Zealand (*10*)	Non-Freeway: ADT > 5,000 vpd, Night-to-Day crash ratio > 1.3, number of lanes ≥ 2 lanes in one direction; Urban Freeway: ADT > 40,000 vpd, spacing < 2 km (1.25 mi) between lit segments
China (*13*)	All freeways, Some part of First-class highways, Major urban arterials, Roadways with raised medians.
Japan (*15*)	Lighting is applied to meet the luminance or illuminance level specified for the following conditions: • Main roads with medium to high speed • Conflict areas with low-speed mixed traffic • Other: pedestrians, bicycles, and parking ,etc.

Design Criteria in Other States and Countries

In most states in the US, the AASHTO lighting guides (*16, 17*) and the IESNA-RP-8 2000 lighting guide (*3*) are the major references of lighting design criteria. The NCHRP 152 report (*5*) included illuminance criteria, but provided no luminance design method. Table 9 lists a summary of average minimum maintained illuminance and/or luminance levels adopted by these lighting guides. This table also includes design criteria from the CIE 115-1995 lighting guide (*7*) for comparison, although it is not often referenced as the major source in many states. For lighting of non-pedestrian conflict areas, the AASHTO, IESNA, and NCHRP lighting guides have criterion levels close to each other, which are lower than the CIE requirements. All these lighting guides require higher luminance and illuminance levels for expressways and arterials than other roadways, such as freeways and local roads, because arterials alike often have more complex conflict conditions than freeways and relative higher speed limits than local roads.

Roadways with high pedestrian volumes also require high lighting levels because of the higher visibility needed for the pedestrian to see close objects and footway surface at night.

Table 9. Range of Design Criteria for Continuous Lighting in the US.

Roadway Type	AASHTO 2005 (*16*)		IESNA RP-8-2000 (*3*)		NCHRP 152 (*5*)	CIE 115-1995 (*7*)	
	E_{avg} (lux)	L_{avg} (cd/m^2)	E_{avg} (lux)	L_{avg} (cd/m^2)	E_{avg} (lux)	E_{avg} (lux)	L_{avg} (cd/m^2)
Freeway	6~12	0.6~1.0	4~9	0.4~0.6	6	20~50	1.0~2.0
Expressway*	n/a[1]	n/a	6~14	0.6~1.0	11~22		
Arterial	5~15	0.6~1.2	6~17	0.6~1.2		30~50	1.5~2.0
Collector	4~12	0.4~0.8	4~12	0.4~0.8	6~13	20~30	1.0~1.5
Local	3~9	0.3~0.6	3~9	0.3~0.6	4~10	10~15	0.5~0.75
Alley	2~6	0.2~0.4	n/a	n/a	2~6	n/a	n/a
Sidewalk	3~14	Use E_{ave}	n/a	n/a	2~10	10~15	Use E_{ave}
Walkway Bikeway	15~22		2~20** 0.6~10***	Use E_{ave}	5~22	1.5~20	

* Expressway criteria were available in the AASHTO 1984 lighting guide and have a range from 6 to 14 lux
** Average horizontal illuminance
*** Minimum vertical illuminance at 1.5 m above walkway/bikeway, measured in direction parallel to pedestrian flow

The illuminance criteria method is more frequently adopted as the major design approach than the luminance method in the US, and the STV method is seldom used in lighting design procedures. Table 10 lists the design methods adopted in the US.

Table 10. Lighting Design Method Adopted by Different States in the US.

Criteria	Illuminance (Major)	Illuminance (Major) and Luminance (Optional)		STV (Optional)
Guidelines	AASHTO 1984	AASHTO 2005	IESNA RP-8-2000	IESNA RP-8-2000
State	Connecticut, Idaho, Illinois, Iowa, Kentucky, Mississippi, New Jersey, New York, North Dakota, Oklahoma, Texas, West Virginia	Colorado, Delaware, Georgia, Maine, Minnesota, Montana, Oregon, Pennsylvania, Rhode Island, Virginia, Washington	Alabama, Colorado, Connecticut, Delaware, Georgia, Illinois, Kentucky, Maine, Maryland, Massachusetts, Missouri, Ohio, Texas, Virginia, Washington	Virginia, Colorado

Table 11 and Table 12 list the summary of design criteria adopted by countries around the world. European countries, Canada, and Japan use the luminance method as the major design criterion for motorways, and they adopt illuminance criteria for pedestrian and/or bicycle ways. European roadways are lit to levels more than twice as high as those in the US and with better uniformity. The reflection properties of pavement are an integral part of the lighting design process because of the adoption of the luminance design method. Belgian agency representatives suggest that roadways lit to levels between 1 cd/m^2 and 2 cd/m^2 produce good visibility (*35*). The Netherlands uses three luminance criteria at 0.2 cd/m^2, 1.0 cd/m^2, and 2 cd/m^2, respectively, for low, normal, and high lighting levels. China adopts both luminance and illuminance methods for lighting design (*35*). The US and Canada use generally lower luminance levels, higher uniformity ratios, and higher glare ratios than other countries such as European countries, China, and Japan.

Table 11. Range of Illuminance Criteria around the World.

Roadway Type	Average Maintained Illuminance (lux)*			Uniformity*	Glare*
	R1	R2 & R3	R4	E_{avg}/E_{min}	L_{Vmax}/L_{min}
Freeway	4.0~30.0	6.0~30.0	5.0~30.0	3.0~4.0	0.3~6.0
Expressway	9.0~30.0	9.0~30.0	8.0~30.0	2.5~4.0	0.3~5.0
Arterial	5.0~30.0	7.0~30.0	7.0~30.0	2.5~4.0	0.3~10.0
Collector	4.0~20.0	6.0~20.0	5.0~20.0	2.5~6.0	0.4~10.0
Local	2.0~10.0	2.0~10.0	2.0~10.0	3.0~6.0	0.4~15.0
Walkway	0.8~50.0			n/a	n/a
Bikeway	1.5~22.0			n/a	n/a

*The table content is a summary of illuminance criteria contained in various lighting guides (*3, 7, 9, 11, 15, 13, 16, 35*)

Table 12. Range of Luminance Criteria around the World.

Roadway Type	Average*	Uniformity Ratio*		Glare*
	L_{avg} (cd/m^2)	L_{avg} / L_{min}	L_{max} / L_{min}	L_{Vmax} / L_{min} or TI
Freeways	1.0~2.0	2.5	1.4~2.0	0.1~0.15*
Expressways	0.6~2.0	2.5~3.5	1.4~6.0	0.3 (or 0.1~0.15*)
Arterials	0.6~2.0	2.5~3.5	1.4~6.0	0.3 (or 0.1~0.15*)
Collectors	0.5~1.5	2.5~4.0	1.4~8.0	0.1~0.4
Locals	0.2~1.0	2.5~6.0	2.0~10.0	0.4 (or 0.15*)

*The table content is a summary of luminance criteria contained in various lighting guides (*3, 7, 9, 11, 15, 13, 16, 35*)

FREEWAY SAFETY AND CONTINUOUS LIGHTING

Factors affecting freeway nighttime traffic safety may include roadway geometry (number of lanes, lane width, shoulder width, roadway alignment, etc.), traffic volume, and lighting condition, plus other factors such as weather conditions and driver characteristics. Among these, roadway lighting is one of the most frequently studied factors for nighttime safety. A general belief is that proper roadway lighting is a countermeasure to reduce the risk of crashes. However, whether continuous lighting can reduce freeway crashes and to what extent it might is still controversial.

Impact of Freeway Continuous Lighting

Numerous research studies have reported the beneficial effect of installing or improving roadway lighting and the negative influence of removing or reducing roadway lighting. However, research on the impact of continuous lighting on freeway nighttime safety is limited.

Installing or Improving Freeway Continuous Lighting

Studies on the relationship between nighttime traffic safety and roadway lighting often use two methods: the before-and-after comparison and the cross-sectional comparison. A before-and-after study compares crash potentials at the same sites before and after the change of lighting conditions. A cross-sectional study compares the crash potentials at lit sites and unlit sites with similar geometry and traffic conditions. Crash potential is a general term of several safety measures of effectiveness (MOEs), such as crash frequency (number of crashes per mile or per site) and crash rate (number of crashes per number of vehicles per mile or per site). Evaluation of the safety impact of roadway lighting often compares the odds ratio, which is calculated as the night-to-day crash frequency ratio (or crash rate ratio) of lit sites to unlit sites. Considering daytime crash potentials in the odds ratio is to gain the same roadway geometric design condition while only lighting and traffic conditions vary. Research about effectiveness of providing or improving continuous lighting has used both types of methods and various MOEs.

Yates and Beatty (*36*) investigated 8,373 urban freeway segments between interchanges for the effect of continuous lighting, in which 8.9 percent of 4-lane freeways, 58 percent of 6-lane freeways, and all 8-lane freeways were identified with lighting. The researchers conducted a simple comparison of crash rates on lit and unlit freeways considering presence of lighting, lighting intensity, number of lanes, day and night hours, and average daily traffic volume. Results of the simple comparison showed that lit freeway segments had higher crash rates than unlit segments by number of lanes and by daily traffic volume per lane. Marked differences existed between the geometry of lit and unlit freeway segments. Compared with lit segments, unlit segments had 56 percent wider median, higher percent of coverage of delineators on the right side only and on both sides, and lower daily traffic volume per lane. However, these discrepancies were not used for the statistical analysis and thus not available to explain the difference in crash experiences on lit and unlit freeways. No relationship was found between lighting intensity and crash experiences because of the limited data.

Box (*37*) investigated 203 miles of lit and unlit urban freeways from six cities (Toronto, Denver, Chicago, Atlanta, Dallas, and Phoenix) to examine the relationship between lighting and freeway safety. Twenty-two lit routes were selected, and the criteria of selection included data availability for at least one year, minimum length of one mile, similarity in the number of lanes, interchange density, lighting conditions, adjacent land use, and traffic volume level. Nighttime traffic was estimated at about 25 percent of the ADT. Night-to-day crash rate ratios of total crashes were found to be 1.43 on lit freeways and 2.37 on unlit freeways, which corresponded to a theoretical 40 percent reduction. For fatal and injury crashes, the respective ratios for lit and unlit freeways were 1.69 and 3.53, corresponding to a theoretical 52-percent crash reduction. The results were statistically significant. The researcher also compared one lit segment and one unlit segment for more specific types of crashes and locations. He disaggregated crashes into rear-end, other vehicle, fixed object, and other off-road crashes at different locations (mainline, ramp entrance, ramp exit, and on ramp). The comparison used a chi-square test and a t-test. The result showed that lighting was associated with less rear-end crashes but not with crashes involving fixed objects. Ramp entrances had more crashes than ramp exits, with a higher percent of rear-end crashes.

Hilton (*38*) found that continuous lighting improved freeway safety in a before-and-after study using a chi-square test and a Poisson test. The study sites consisted of two freeway segments on IH 95 in Virginia, each of which was 8.57 miles long. One was a subject site with lighting on in the 6-month before period and off in the 6-month after period, and the other served as a control site without lighting in both study periods. The before-period had the same months (from December to May) as the after-period in two successive years from 1972 to 1974. The researcher used composite traffic count data with weekday and weekend variance adjusted and calculated the night-to-day crash rate ratios. While no significant difference in the night-to-day crash rate ratio showed at the control, the crash ratio in the lit period was lower than that in the unlit period at the subject site. Also, the crash reduction was higher in December through February than in March through May, which the researcher believed was because of shorter nighttime and thus low nighttime traffic volume in March through May.

Lamm et al. (*39*) evaluated the impact of changing lighting conditions on freeway safety using a before-and-after analysis of nine years (from 1972 to 1981) of crash data on a suburban freeway in Germany. The study investigated three successive sections on the same suburban freeway (two curved sections, S1 and S2, and one tangent section, S3) and consisted of three periods (a before period, B, and two after periods, A1 and A2). The freeway sections had two main lanes and one emergency lane in each direction, with a 70-mph speed limit and an average nighttime hourly volume of at least 900 vph. In the one-year period B, all three sections were unlit. In the five-year period A1, S1 and S2 were lit from dusk to dawn, while S3 remained unlit. In the three-year period A2, S1 remained lit from dusk to dawn, and in S2 lights were turned off from 10:00 PM to 5:00 AM after which until dawn lighting was provided when daylight was not available. S3 remained unlit during period A2. The study found that the addition of continuous lighting on all three previously unlit suburban freeway sections significantly reduced crash rates in A1. However, in the case of partial lighting, i.e., when the lights were switched off between 10:00 PM and 5:30 AM in A2, crash rates were increased. The researchers noted that the rate of personal injury crashes steadily decreased since 1972, which was assumed because of the energy crisis of 1973–1974, speed limit changes, stricter drunk driving laws, seat belt laws, and mandatory safety-helmet laws.

Griffith (*40*) integrated crash, roadway, and traffic volume data from different sources to compare urban freeway safety with continuous lighting and with interchange-only lighting in the Minneapolis-St. Paul metropolitan area. Five years of crash and roadway characteristics data were obtained from the Highway Safety Information System (HSIS), and lighting information and 24-hour traffic counts data were from the Minnesota Department of Transportation (MnDOT). Two freeway sections were compared: 54.6 miles of continuously lit freeway sections and 35.5 miles of freeway sections with interchange-only lighting. Sections with continuous lighting had 1.2 interchanges per mile, while the other had 0.8 interchanges per mile. Traffic volumes were found similar on both types of sections. The researcher also assumed that other extraneous factors, such as weather, vehicle fleet, and driver characteristics, to be the same since the two sections were adjacent to one another. The Poisson test result showed that the total night-to-day crash-rate ratio for sections with interchange-only lighting was 12 percent higher than the continuously lit sections. For the non-interchange areas, sections with interchange-only had 18 percent higher night-to-day crash ratio than the continuously lit sections. On average, the study estimated that installing lighting on freeway sections between interchanges would reduce nighttime crashes by 16 percent. Considering different crash severities on non-interchange areas, no significant difference was found in total injury and severe injury crashes between the two groups of freeway sections, and the only significant difference was in property damage only (PDO) crashes, which was 32 percent higher on the interchange-only lighting sections.

Bruneau et al. (*41*) compared night-to-day crash rate ratios under three lighting conditions of complete continuous lighting, interchange-only lighting, and no lighting on 4-lane rural freeways (a total number of 213 sections with a total length of 497.2 miles) in Quebec, Canada. The researchers categorized the data based on three levels of ADT (less than 20,000 vpd, from 20,000 to 40,000 vpd, and greater than 40,000 vpd). The number of interchanges on continuously lit freeways was two to three times higher than other lighting conditions. The results showed that continuous lighting reduced risk of overall nighttime accidents significantly, by 33 percent when compared to interchange-only lighting and by 49 percent when compared to complete darkness. Although continuous lighting did not reduce injuries and fatalities significantly, there was a significant reduction in PDO accidents, by 35 percent when compared to interchange-only lighting and by 43 percent when compared to darkness.

Donnell et al. (*42*) completed a comprehensive NCHRP project to evaluate the relationship between continuous lighting and crashes on four freeway sections in three states. The data set from Washington State contained two freeway sections with a total length of 64.84 miles and was used for two analyses: one considered sections influenced by continuous lighting, interchange lighting, and overpass lighting (with an average 1.22 interchanges per mile and 0.73 overpasses per mile); the other used a subset of data from the first analysis that excluded interchange and overpass locations. The two other analyses used one freeway section from Oregon and Virginia, respectively, and considered continuous freeway lighting as defined by the AASHTO 2005 lighting guide. The Oregon analysis had 680.6 miles of freeway (11 percent of sites were continuously lit) and was based on freeway segments investigated in the study by Monsere and Fischer (*43*). The Virginia data contained 113 miles of freeway (79 percent of sites were continuously lit).

The researchers developed negative binomial regression models for each analysis to predict daytime and nighttime crash frequencies and compared the predicted and the observed night-to-day crash frequency ratios. Overall, the observed night-to-day crash ratios overestimated the positive effect of lighting without controlling traffic volume and geometric design variables (except the Virginia analysis). The percent differences in predicted night-to-day crash ratios for segments with and without continuous lighting were 4.29 percent, −6.76 percent, and −6.64 percent using prediction models in the first Washington analysis, the Oregon analysis, and the Virginia analysis, respectively, whereas −15.31 percent, −18.98 percent, and −5.6 percent using observed data. In the second Washington analysis, effects of different locations of continuous lighting (median, right-side, and both-side) were examined for different scenarios (with and without interchanges and overpasses, urban and rural, and urban or rural). The median-only and the both-side lighting had a positive effect in reducing night-to-day crash ratios for the with interchanges and overpasses scenario: −10.36 percent and −32.58 percent predicted and observed percent differences for median-only lighting; and −15.07 percent and −56.82 percent predicted and observed percent differences for both-side lighting. The house-side-only lighting also had a positive effect for the without interchanges and overpasses scenario: −9.95 percent and −45.16 percent predicted and observed percent differences. The negative values in the percent difference of night-to-day crash ratios indicated that continuous lighting was associated with lower nighttime crash potentials compared to that without lighting.

Overall, the NCHRP study presented mixed results in determining effectiveness of continuous lighting on freeway safety. In the Washington analyses, when accounting for interchanges and overpasses, continuous freeway lighting was associated with a 4.29 percent increase in the night-to-day crash ratio, and the house-side-only lighting was predicted with a 0.3-percent increase in the night-to-day crash ratio, which indicated a negative effect of continuous lighting. In the Oregon and Virginia analyses, a 6.7-percent decrease and a 6.6-percent decrease in the night-to-day crash ratios were found through model prediction, which indicated a net benefit of continuous lighting. Also, the assumption that lighting would not be associated with daytime crashes was not supported by the modeling results, because the expected number of daytime crashes was significantly higher at continuously lit locations comparing to that without lighting. This indicated that other factors associated with the presence of lighting but not included in the statistical models may have played a role. The researchers concluded that the association between the presence of continuous lighting and reduction in night-to-day crash ratio could not be determined with statistical significance in their study.

Box (*37*) conducted a before-and-after study for the impact of improving lighting on two sections of a 5.3-mile 6-lane urban freeway. With the improvement of lighting, the night-to-day crash ratio changed from 3.0 to 1.3 on one section and from 3.1 to 2.0 on the other section. The respective reductions were estimated at 18 percent and 11 percent for all types of crashes, and reduction in injury and fatal crashes was 24 percent for both sections. However, the researcher noted that the results lacked statistical significance because of the small sample sizes.

Elvik et al. (*44*) completed a meta-analysis of a number of studies to examine the effect of roadway lighting on safety. According to the analysis of 49 studies on the effect of lighting previously unlit roadways, installing roadway lighting generally reduced fatal crashes by 60 percent and injury and PDO crashes by around 15 percent. These effects were for all types of roadways and are statistically significant, but no significant effects of roadway lighting were found for freeway safety. According to 25 studies on the effect of improving existing lighting, when the lighting level was increased to no more than two times the original levels, lighting improvement had limited effect on safety, and the best estimation in crash reduction was about 5 percent and was not statistically significant. When lighting level was improved to two to five times and more than five times, crash reduction was estimated to be about 10 percent and 30 percent, respectively. Again, the researchers did not provide conclusions about the impact of improving lighting on freeway safety.

Removing or Reducing Existing Freeway Lighting

Richards (*45*) conducted a before-and-after study in Austin, Texas, in the early 1970s to evaluate the effect of turning off continuous lighting on freeway safety. The lighting cutoff was in effect only on the main lanes of three freeway sections of southbound IH 35 through Austin, Texas, for a total of 7.2 miles. The study assumed 28 percent of ADT to be nighttime traffic for all the sections. Two years of before-period data and two years of after-period data were evaluated in this study. A significant increase of 47.1 percent in crash frequency was observed on the unlit section in the after period. Crash rates and severity also increased in the nighttime after period. Significant increases in rear-end and pedestrian-related crashes were observed. Though the city of Austin saved about $25,250 per year on energy costs and about $1,250 per year in maintenance cost, the cutback increased the crash costs by about $17,000 per year.

Monsere and Fischer (*43*) evaluated the impact of the lighting curfews on selected urban freeways for the Oregon Department of Transportation using the empirical Bayes (EB) method in a before-and-after study. Study locations and changes in lighting conditions were categorized into four groups: two sections (3.0 miles) of freeway from continuous lighting to one-direction-only lighting, two sections (2.5 miles) of freeway from continuous lighting to no lighting, 30 interchange sites from complete lighting to partial lighting, and 14 interchange sites with partial plus lighting to partial lighting. Partial plus lighting was used in this study to define interchanges that had more than partial lighting but not full lighting. Two groups of reference data were used for the EB analysis: 38 interchange sites with full and partial lighting, and 42 sites (53 miles) of urban freeway sections with and without continuous lighting. The analysis contained five-year data for the before period and four-year data for the after period. The study found that the reductions of lighting on freeway sections caused a 28.95 percent increase in total crashes and a 39.21 percent increase in injury crashes during the night. Note that the multivariate regression models used for EB estimations considered only segment length and traffic as the modeling variables. Where full interchange lighting was reduced to partial lighting and partial plus lighting was reduced to partial lighting, an increase of 2.46 percent in total night crashes was observed, along with a decrease of 12.16 percent in injury crashes. This was related to the decrease in injury day crashes as well. These changes in crashes were all tested to be statistically significant.

Elvik et al. (*44*) also reviewed nine studies that reported the impact of reducing existing lighting on safety in their meta analysis. The estimated increase was 17 percent in injury crashes and 27 percent in PDO crashes. These estimates were statistically significant. Note that these studies were not exclusively for freeways, and lighting level was considered to be halved by turning off every other lamp.

Janoff (*46, 47*) also evaluated the impact of different techniques of lighting reduction using methods other than crash analysis in two successive studies in the 1980s. In the first study (*46*), a small group of lighting experts from the Illuminating Engineering Society Roadway Lighting Committee rated six different lighting reduction methods. These methods were those being used across the US related to the oil embargo and those associated with (then) newer technology. The methods included: 1) all lights turned off after midnight, 2) every other lamp extinguished after midnight, 3) one side extinguished after midnight, 4) twin luminaires with one extinguished after midnight, 5) all luminaires dimmed a fixed amount after midnight, and 6) variable level lighting as a function of time, volume, visibility, etc. The ratings were based on potential effects on energy use, safety, other traffic operations, practicality, cost, and legal problems. On a scale of one to seven, extinguishing all lighting resulted in the highest rating of

6.8, and the volume-dependent system had the lowest rating of 5.2. Overall, simpler systems (all lights turned off after midnight) were preferred as they were less costly and more practical to implement with very high benefit/cost ratios. However, the more sophisticated systems (all luminaires dimmed a fixed amount) scored higher in safety and legal implications. The maximum difference in overall rating was only 10 percent, indicating a small difference.

Janoff (*47*) later evaluated the impact of reduction in lighting on freeway driver behaviors during periods of low traffic volume. The premise of the study was that the increase in crashes was due to the fact that lights were turned off for the entire nighttime period and not when traffic volume was low. The study used six alternative techniques of lighting reduction: full lighting, dimming to 30 percent light output, dimming to 50 percent light output, extinguishing every other luminaire, extinguishing luminaires on one side of the roadway, and no lighting. Three experiments designed to determine the effect of these techniques on driver behaviors were: 1) a pilot study to evaluate the impact of extreme techniques (turning all lighting on or off) at extreme geometric conditions (straight and level interchange ramps) on driver detection of a simulated roadway hazard (a 6-inch Styrofoam hemisphere with a 6-inch diameter skirt), 2) a controlled field study to evaluate the impact of six different lighting tactics at a single geometry on driver detection of the same simulated roadway hazard, and 3) an observational study to measure reactions (such as swerves or lane changes, braking and use of high-beam headlights) of motorists to the same simulated road hazard under three conditions of reduced lighting (full lighting, 50 percent power uniform dimming, and no lighting). Data were collected on a fully lit multilane section (6 miles long) of IH 95 in Philadelphia and Bucks County (urban or suburban land use). The pilot study indicated that lighting should not be reduced on interchange ramps. The controlled field study results showed that the best mean detection distance was achieved under the full lighting condition with an orderly decrement in driver performance for all other lighting conditions. The reduction in driver performance was not statistically significant for various dimming techniques, but the difference in driver performance among those dimming techniques was statistically significant. The response pattern from the observational study followed the same trend as that seen in the detection distance results of the controlled field study (for the same lighting techniques).

Other Factors Affecting Nighttime Safety

Roadway geometric elements are the most fundamental factors affecting traffic safety. Higher crash potentials are usually associated with narrower lane width, narrower shoulder width, and narrower median width. Crashes tend to occur more often on curved roadway sections than on tangent sections. Freeway exit and entrance areas such as ramps and interchanges, where vehicles merge, diverge, and weave frequently, are also crash-prone locations (*2*).

Traffic volume is one of the most significant factors influencing traffic safety. Average Annual Daily Traffic (AADT) is the most frequently used variable in predicting annual crash potentials, but disaggregated traffic data are also used to analyze crash potentials in shorter time periods. Many studies using hourly crash counts and hourly traffic data have reported a U-shape relationship between total number of crashes and hourly volume (*48*, *49*, *50*, *51*). This relationship indicates that more crashes happen when traffic volumes are in the high and low ranges than in the medium range. However, as hourly volume increases, single-vehicle crashes often decrease, whereas multivehicle crashes often increase. Some studies using the v-over-c ratio (the ratio between hourly volume and roadway capacity) or the level of service (LOS, roadway performance rating based on v/c ratio ranges) and have found that crash rates increase as v/c ratio increases or LOS decreases from A to E (A is the best rating, and E is the worst rating) (*52*, *53*, *54*).

Time of day that is related to natural lighting conditions and/or traffic variation is another frequently used factor for traffic safety. Grouping time of day into day and night is deemed appropriate in modeling considering the difference in natural lighting conditions (*55*, *56*). Higher crash potentials have been observed during PM peak hours rather than AM peak hours on express roadways (*57*). Nighttime crash potentials have been observed to peak around 2:00 AM or 3:00 AM on urban freeways (*58*). Traffic safety also varies among days of the week. Under the same low volume range, higher night crash rates have been observed on weekends than on weekdays (*51*). Note that traffic and time of day are usually correlated, thus the temporally disaggregated study approach using hourly traffic volume is more appropriate to capture traffic variation for lighting curfews during part of the nighttime hours. However, none of the above disaggregated analyses are intended for lighting effectiveness.

Note that the above mentioned adverse factors on safety, e.g., narrow shoulder and median width, high ramp density, high nighttime traffic volume, and weekend peak nighttime traffic hour, are often associated with conditions that warrant continuous lighting. However, these factors are not often considered in the safety evaluation of continuous lighting due to the lack of comparable sites with and without continuous lighting or sufficient data in the before and after periods. This may explain the reason that research results on the impact of freeway continuous lighting are not satisfactory.

LIGHTING EFFECTIVENESS

Roadway lighting may affect driving behaviors in terms of nighttime driver characteristics and driving speed. Lighting may also have an impact on roadway capacity.

Impact of Roadway Lighting on Driver Characteristics

A 1999 before-and-after study conducted in Norway found that installation of road lighting affects the age and gender distribution of drivers (*59*). The results showed that men drove relatively more during darkness than women, and that older drivers (45 years and older) drove more at night after roadway lighting was installed. The increases in male and female older drivers at night were about 2 percent and 13 percent, respectively.

This Norway study also reported that roadway lighting reduced average driver concentration. The researchers measured driver concentration coarsely by video registration of vehicle lateral position on a 200 m (656 ft) straight roadway section before and after roadway lighting installation during day and night for 515 free-flow vehicles. They placed longitudinal lines on the video screen which corresponded to 130 mm (5.1-inch) intervals on the roadway. They used the lines as references to record each incidence of a vehicle crossing a line and defined consecutive two lateral shifts (of one or more intervals) in opposite directions as a deviation from the straight course. The number of such deviations was used to indicate a lack of concentration. The study found increases of 11 percent and 59 percent in average number of changes in lateral positions during daytime and nighttime, respectively, after lighting installation. This more or less accorded with the result of their questionnaire survey results that 83 percent of 1,575 drivers responded that they would be more concentrated when driving without roadway lighting.

Impact of Roadway Lighting on Speed

Several studies reported an increase in driving speed because of roadway lighting. A study conducted in 1972 found that lighting was associated with an increase in the average nighttime speeds of passenger vehicles (by 2.1 mph) and commercial vehicles (by 1.1 mph) on three lower speed roads (with an average nighttime speed around 30 mph) (*60*). To examine the effect of lighting on high-speed roadways, this study collected free-flow speed data right before lighting installation and one year after lighting installation on two 2-lane highways with average nighttime speeds of 47 mph and 51 mph, respectively. The average speed of all vehicles on one highway increased by 4.98 mph and by 2.72 mph during night and day, respectively, which corresponded to an increase in 2.26 mph in relative speed change (RSC) (the change in difference between daytime and nighttime speeds). On the other highway, the RSC of commercial vehicles decreased by 3.4 mph, and the RSC of passenger vehicles increased by 1.7 mph after lighting installation. There was also a tendency for the standard deviation of vehicle speeds to increase by about 1.2 mph on both highways, because of which, the researcher cautioned the possible association with crash rate.

The aforementioned Norway study also investigated the driver-stated speed and the observed actual speed before and after lighting installation (*59*). The survey results showed that 59 percent of 1,440 drivers who responded would drive faster with roadway lighting, and 75 percent of 1,577 drivers stated that they would drive slower without roadway lighting. This indicated that about 67 percent of drivers would potentially increase their driving speed at night with the presence of roadway lighting. The observed driving speed on the experimental section (with lighting) increased by 5 percent on the straight section and 0.7 percent on the curve section, respectively, when compared to the control section (without lighting). This was explained by the fact that roadway lighting was more effective on a tangent section, where lighting increased considerably the visible distance, while on curves, the visible distance was not increased very much by road lighting.

Impact of Roadway Lighting on Capacity

One of the often claimed benefits of roadway lighting is that it spreads traffic throughout the 24 hours and consequently increases the capacity (*60*). As reviewed in the 1972 study by Cornwell (*60*), highway lighting increased 5 percent of capacity in the nearside lane and

3 percent of capacity in the far-side lane. A more recent study in the Netherlands in 1998 found from the literature that daytime roadway capacity is 5 percent greater than nighttime capacity with or without roadway lighting (*61*). This 1998 Netherlands study also estimated that the capacity of two directions of the same roadway section assuming the capacity shifts are fully a result of speed changes. To meet this assumption, the researchers used a fixed critical density value for capacity estimation before and after lighting installation. To calibrate the Greenshields model of the flow-density model, the researchers observed traffic passage for various 5-minute periods during workdays and adopted a critical density of 50 pcu/km. The results showed that daytime capacity was about 7 percent greater than nighttime capacity; the daytime capacity did not change significantly after lighting installation, but the nighttime capacity increased by 2.5 percent after lighting; both the significance of lighting's impact on capacity and the relative difference between capacities under daylight and artificial lighting were found to be insensitive to the assumed critical density values.

PRACTICE OF ROADWAY LIGHTING

Current practice is usually lighting the roadway throughout the hours of darkness with the same illuminance and/or luminance level justified by warranting conditions and proper design criteria, which is called normal lighting, according to the CIE 115-2010 lighting guide (*8*). However, energy consumption resulted from such constant lighting, especially continuous lighting, could be costly and unnecessary when traffic volume drops to low levels late at night. Lighting pollution is becoming another issue. Therefore, many traffic agencies are considering applying advanced techniques and developing new policies for more effective roadway lighting, such as lighting curfews and adaptive lighting.

Lighting Curfews

As described by the TxDOT 2003 Illumination Manual and the AASHTO 2005 lighting guide, curfews for lighting involve the use of advanced controls to turn off or dim parts of the lighting system as justified by reduced traffic volume, favorable weather, and other local conditions (*1*, *16*). The term *lighting curfew* is used to describe the concept of reducing or eliminating lighting during part of the nighttime hours. The research team investigated lighting curfew practices in the US and other countries through email surveys and literature reviews.

Lighting Curfews in the United States

Table 13 summarizes the results of email surveys of various state DOTs in the US regarding their current practices of lighting curfews. Among the 41 state DOTs that responded, 24 states are currently not considering developing a specific lighting curfew policy; eight states have expressed an interest in potentially developing a curfew policy; eight states are currently conducting a project for further policymaking about reducing lighting; and only one state has proposed a policy for lighting curfews.

Table 13. Survey Summary of State DOTs Opinions about Lighting Curfew Policy.

Response Type	State	Note
States having a lighting curfew related policy	Maryland	"House Bill 709" requires turning off highway lighting from midnight until 6:00 AM; however, Maryland DOT opposes such Bill due to safety concerns and the high cost of controlling sign lighting and highway lighting separately.
States considering developing a lighting curfews policy	Connecticut, Delaware, Maine, New Hampshire, Kentucky, New Mexico, Rhode Island, Texas, Vermont	Delaware: LED research proposal for roadway lighting Maine: "Lights-off" procedure in 2009 with thresholds of 600 vph for mainline and 300 vph on the ramps. New Hampshire: considering shutting off a number of high mast lighting, not related to curfew. NH State utilities included provisions for part time rates in the tariff structure. Kentucky: passed a resolution asking considerations for lighting curfews on rural, low-volume interchanges. New Mexico: considering using LED lighting for dimming Rhode Island: have a plan to turn off lighting during 12:00 AM to 5:00 AM Sun. through Thur. and 2:00 to 5:00 AM on Fri. and Sat. Texas: ongoing research project considers turning off some continuous lighting during late night hours and might use LED lamps. Vermont: don't have many interchanges or large intersections that require much lighting. Consultant contracts do the lighting design.
States showing some concern about lighting curfew policy	California, Idaho, Illinois, Nevada, New York, Oregon, Wyoming	New York: considering turning off all or most of parkway lighting for budget reasons. There is very little highway lighting on state highways based on safety needs. Wyoming: local night skies concerns prompted the action of using remotely controlled lighting for road closure operations and or incident management. They have been eliminating all sign lighting.
Comments from states not planning on lighting curfews	Alberta, Florida, Pennsylvania	Alberta: believe roadway lighting is necessary for safety even when traffic volume drops due to fewer vehicles providing geometry cues to drivers. Florida: public had suggested lighting curfews to reduce lighting glow, but DOT responded to justify lighting expenditures based on nighttime traffic and nighttime crash rate for unlit roadways. Pennsylvania: concern about tort liability and believe LED lighting is not efficient enough to be practical.

The Connecticut DOT keeps a majority of its 18,000 roadway lights on from dusk until 6:00 AM. It is estimated that at least one half, and perhaps three-quarters, of the streetlights do not serve a public safety need in the late night or early morning hours, when pedestrian traffic is nonexistent and vehicular traffic volume is tremendously reduced. The DOT has considered establishing a new tariff for partial night street lighting. The proposed plan is to turn off roadway lights after 11:00 PM or midnight and is expected to reduce energy consumption greatly (*62*, *63*).

Maryland is the only state where the legislature has proposed a bill that requires turning off lighting from midnight to 6:00 AM. However, Maryland DOT opposed the bill. On one hand, the DOT has already applied very conservative lighting warrants that lighting is only installed at locations where it provides a substantial safety benefit. They have reduced highway lighting to partial interchange lighting without continuous lighting and may possibly reduce bridge lighting where no safety issues exist. Additionally, turning off roadway lighting on most highways would also require turning off sign lighting due to the simultaneous control, but sign lighting is important for roadway safety. Maintaining sign illumination while dimming or turning off highway lighting involves extensive costs for rewiring and reconfiguring. The reduction in overnight lighting may raise safety issues, which increase costs even more. Nevertheless, the DOT expressed interest in turning off lighting at an alternate nighttime hour, for example 3:00 AM, and the DOT has two pilot projects ongoing to examine the feasibility of such lighting curfews (*64*).

Rhode Island DOT currently has a detailed plan for lighting curfews and is conducting a study for further policymaking. The DOT has selected eight trial roadways for a three-month study phase for lighting curfews from midnight to 5:00 AM on Sunday through Thursday and 2:00 AM to 5:00 AM on Friday and Saturday. These are periods when hourly traffic volume is around 500 vph in both directions. The DOT will conduct a before-and-after safety analysis of the trial roadways. Currently the Rhode Island DOT is paying $1,947,510.94 per year for lighting along access roadways, other secondary state highways, and park-and-ride lots. The plan expects that the reduced operating time will result in a 36 percent reduction in lighting hours that corresponds to a savings of approximately $600,000 per year. Additional methods facilitating lighting curfews include issuing press releases to announce curfew information and placing variable message signs and possibly static signs to inform drivers about the curfews (*65*).

Lighting Curfews in Other Countries

Some European countries, such as England, the Netherlands, Finland, Switzerland, and France, also have similar practices on lighting curfews. Lighting curfews in most of these countries are mainly for saving energy, but in some countries, such as England, lighting curfews in terms of part-night lighting are also to reduce carbon emissions. There are research projects going on for more flexible and efficient lighting controls in some countries, such as the Netherlands, Finland, and China. These lighting methods will be detailed in a later section. Table 14 shows a brief summary of lighting curfews in these countries.

Table 14. Lighting Curfews in Other Countries.

Country	Lighting Curfew Practice
England	The part-night lighting operation first began around early 2009. There are such part-night street lighting plans ongoing in districts of Gloucestershire County, Leicestershire County, and Wokingham District. Streetlights in residential areas are usually switched off between midnight and 5:30 AM after a risk assessment. Gloucestershire County also launched a street light dimming scheme by dimming high wattage bulbs by 35 percent between 10:00 PM and 5:30 AM (*66*).
The Netherlands	Some luminaires were simply turned off in the 1970s and there was moderate increase in crashes within tolerance. In the 1980s, they lowered lighting levels from the CIE recommended 2 cd/m^2 to 1 cd/m^2 on roadways where the warranting volume levels (see Table 8) were not met, while retaining the same recommended uniformity ratios (*35*).
Finland	A 20-year analysis of lighting-system costs showed that electric energy is two-thirds of the total cost. Some Finnish roadways have high/low-style controls, and light levels are lowered. The motoring public has not complained (*35*).
France	It is not unusual to dim the lighting to save energy between 10:00 PM and 6:00 AM. One-third of French towns decrease lighting at night, and 8 percent of the networks are dimmed at night (*35*).
Switzerland	The Swiss Energy Administration has a standard, not a law, on the lighting density limit (watts/m^2) and the amount of annual energy consumption (kwh/yr) that might affect the design lighting levels. To meet the requirements, some lighting is reduced typically from 11:00 PM to 5:00 AM (*35*).

Before implementing part-night lighting in Gloucestershire County, England, a risk assessment is conducted to check if a candidate location has the following exemption criteria for safety concerns (*66*):

- On main traffic routes, pedestrian crossings, subways, enclosed footpaths and alleyways or areas where there are potential hazards on the highway such as speed humps.
- On roads with a historical nighttime injury crash record higher than above-average levels.
- In areas with an above-average record of crimes.
- In areas with CCTV or local authority/police surveillance equipment.

- In areas where 24-hour operational emergency services operate, including hospitals or nursing homes.

After conducting the risk assessment, Gloucestershire County determined that lights are turned off from midnight until 4:15 AM GMT and from 1:00 AM until 5:15 AM during the British Summer Time (BST). A major component of the part-night lighting operation is the use of the photocell technique. A photocell changes resistance depending on the amount of light to which it is exposed. It uses daylight changes to determine time of day by calculating solar midnight as the middle of the night. Photocells used in this county work with time clocks and are set to switch off a set number of hours before midnight and to come back on a set number of hours after midnight. Programming of the photocells considered two issues, i.e., annual daylight variation throughout the year and the changes between GMT and BST. Because of various types of time clocks and photocells used, there is a variance in on/off switching times throughout the part-night lighting area (*67*).

Future Lighting Practices

The need to increase power conservation has brought on significant research and product development in the realm of roadway lighting. Aside from lighting curfews, *adaptive lighting* (or *dynamic lighting*) is another strategy of lighting operation for more flexible consumption of power energy. Also, more and more traffic agencies are considering using light-emitting diode (LED) lights for roadway lighting.

Adaptive Lighting

Adaptive lighting (also called dynamic lighting) emphasizes the concept of "varying lighting levels to suit activity levels" (*68*) and is different from lighting curfews. Though the definition of lighting curfews given by the AASHTO 2005 lighting guide does not exclude the method of dimming lighting level, most of the current practices of lighting curfews are simply switching off part or all of the lights for certain night hours. As a counterpart of normal lighting, adaptive lighting adapts (usually reduces) the normal level of average luminance or illuminance as allowed by certain conditions (*8*). The CIE 115-2010 lighting guide points out that using dimming techniques to reduce the light output from every lamp by the same amount will not affect luminance or illuminance uniformity, or the object contrast, but the threshold contrast increases. Reducing the average lighting level by switching off some luminaires can hardly fulfill the quality requirements (*8*).

Many countries have been doing research about adaptive lighting for two decades. The Netherlands installed a dynamic roadway lighting system in 1995. The lighting system used electronically controlled dimmable high pressure sodium (HPS) ballasts and was capable of adjusting any of three lighting levels: 0.2 cd/m^2 for low traffic density late at night, 1.0 cd/m^2 for normal or high traffic density, and 2.0 cd/m^2 for exceptional conditions such as fog, or a combination of rain, high traffic density, and crashes. After studying such an adaptive lighting system on a 14 km (8.7-mile) 6-lane highway, Dutch experts concluded that the high lighting level of 2.0 cd/m^2 was not justified due to the high cost and marginal or immeasurable safety benefits (*35*). The *Manual of Dynamic Motorway Lighting* adopts the normal lighting level when traffic density exceeds 1,100 vphpl and suggests lighting be dimmed by 80 percent when traffic is lower than 800 vphpl (*69*). The installation of dynamic lighting costs about 10 percent more than conventional lighting, but operating the system costs less than conventional lighting.

In England, Lancashire County Council (LCC) adopted a policy in 1998 that required all traffic route schemes to incorporate the capability of dimming lighting levels. LCC examined the lighting design criteria and required that lighting levels be reduced by approximately 50 percent at most when traffic volume decreased considerably compared to peak hour traffic volume (Table 15). A new lighting control system capable of dimming lighting levels by 70 percent using high frequency electronic ballast for HPS lamps was implemented on a 7-mile 2-lane roadway segment (on M65 from Burnley to Colne). Researchers measured drivers' electrical activity (EMG) of the orbicularis muscle, an indicator of the ocular stress, and found that EMG decreased by 14 percent and 23 percent when lighting level was set at 70 percent and 50 percent, respectively. This adaptive lighting system was estimated to save 24 percent energy consumption (about $23,000) annually and to reduce CO_2 emission levels by 52.9 percent (*70*).

Table 15. Road Lighting Levels in UK before and after Adaptive Lighting Strategy.

	Carriageway				**Hard Shoulder**			**Slip Roads**			
	L_{avg}	U_0	U_{L1}	U_{L2}	L_{avg}	U_0	U_{L1}	L_{avg}	U_0	U_{L1}	U_{L2}
Before	2.64	0.49	0.85	0.88	1.17	0.76	0.88	2.08	0.46	0.88	0.79
After	1.49	0.62	0.82	0.85	0.83	0.73	0.89	1.45	0.62	0.73	0.77
Vehicles per Hour			>3000		3000~1500					<1500	
Lighting Level			100%		75%					50%	

In Finland, an adaptive lighting experiment began in 2000 on a 3.5 km (2.2-mile) 2-lane roadway segment (from Oinola to Saukkola) with 9,000 ADT. The system used a continuous integration of traffic volume and weather conditions to determine the speed limits and roadway lighting levels. By using dimmers, the control system tried to keep the luminance of the roadway constant by varying the lumen output of each luminaire. The meters could also determine which luminaires were not functioning properly (*35*).

France conducted an experiment on a test track that was 400 m (1,312 ft) long and 7 m (23 ft) wide to examine the impact of dimming roadway lighting on driver visibility. The lights were installed at 8 m (26 ft) mounting height, 30 m (98 ft) spacing, and 20-degree tilt angle, which produced an average illuminance level of 31.5 lux, an average luminance level of 2.45 cd/m^2, an overall luminance uniformity of 0.6, a longitudinal luminance uniformity of 0.7, and a threshold increment of 4.88 percent. The tests were made for 100, 75, 50, and 25 percent of the luminous flux of the lamps. The study calculated the visibility level as the ratio of the difference between the luminance of the object and its background to the increment threshold of luminance. The study concluded that dimming lighting did not result in a great influence to the driver visibility until dimming to the 50 percent level; uniformity level was more important than average luminance level; and the minimum acceptable visibility level was about 4.5 (*71*).

In 2004, China installed 1,350 lamps out of 8,000 total luminaires for the first stage of a remotely controlled dimmable road lighting system. The proposed centrally controlled dimming system used patent-pending power electronics to provide variable AC voltage for controlling the brightness of the electromagnetic ballast high intensity discharge (HID) luminaires in existing lighting poles. Such system is able to provide a dimming range from 100 percent to 60 percent of lamp power. It does not require major rewiring and can protect over-voltage and prolong the lifetime of the lamps. On the experimental roadway segment, the lighting level was operated at 80 percent from 6:20 PM to midnight and 70 percent from midnight to 5:00 AM, as opposed to the normal full lighting level of 100 percent throughout all the dark hours. After 9 months of operation, there was a 27 percent overall energy savings without increase in crime rate or crash rate, and there was no complaint from residents (*72*).

The CIE 115-2010 lighting guide has introduced a design procedure for adaptive lighting. There are six lighting classes (from M1 to M6) for vehicular traffic based on road surface luminance, five lighting classes (from C1 to C5) for conflict areas, and six lighting classes (from P1 to P6) for pedestrian and low-speed traffic areas. The guide provides a set of tables to select the appropriate adapted lighting class or classes for different hours of darkness when the value of selection parameters is significantly different. Such parameters for vehicular traffic and conflict areas include speed, traffic volume and composition, roadway separation, intersection density, parked vehicles, ambient luminance, and visual guidance or traffic control. For pedestrian and low-speed traffic areas, the parameters also include facial recognition. For each type of lighting area, a sum of weighting values, V_{ws}, is calculated based on those selection parameters, and the final number of light class is determined by $(6 – V_{ws})$. The adapted lighting level or levels should be the average luminance or illuminance from a class or classes in the same table from which the normal lighting class has been selected (*8*). The 2010 draft of the Illuminating Engineering Society of North America (IESNA) RP-8 lighting guide also considers introducing adaptive lighting as a component for roadway lighting.

LED Roadway Lighting

Traditionally, there are two general types of electrical light sources: filament lamps and arc-discharge lamps. Filament lamps used in roadway lighting include incandescent and tungsten-halogen lamps; and arc-discharge lamps in roadway lighting include fluorescent and high intensity discharge lamps. The HID family is composed of mercury vapor, metal halide, HPS, and low pressure sodium (LPS) lamps. An emerging type of roadway light source is the LED luminaire. An LED luminaire is a collection of multiple diodes to produce high lumens while using moderate voltage. LED luminaires offer long service life and high energy efficiency, but their initial costs are higher than those of fluorescent lamps. Table 16 shows a summary of these roadway light sources (*6*, *73*).

Table 16. Summary of Roadway Light Sources.

Luminaire Type	Lumens	Wattage Range	Average Life (hr)	Maintenance Output at End of Life	Optical Control	Initial Cost	Operation. Cost
Incandescent	655–15,300	58–860	1,500–12,000	82–86%	Excellent	Low	High
Tungsten-Halogen	6,000–33,000	300–1,500	2,000	93%	Excellent Vertical, Poor Horizontal	Moderate	High
Fluorescent	4,200–15,500	60–212	10,000–12,000	68%	Poor	Moderate	Moderate
Mercury Clear	7,700–57,500	175–1,000	24,000+	62–82%	Fair	Moderate	Moderate
Metal halide	14,000–125,000	175–1,500	7,500–15,000	50–73%	Good	High	Low
HPS	5,800-140,000	70–1,000	20,000–24,000	73%	Good	High	Low
LPS	4,650–33,000	35–180	18,000	100%	Poor	High	Low
LED	3,400–8,610	63–210	50,000+	70%	Good	High	Low

Currently, the most frequently used roadway lighting source is HPS, but many traffic agencies are looking into LED luminaires. In the US, the states of California, Delaware, New Mexico, and Texas are considering using LED luminaires as street lights. Other countries such as the Netherlands, France, and China are also doing research to evaluate LED roadway lighting.

In 2009, the US Department of Energy (DOE) supported a demonstration project in Portland, Oregon, for LED roadway lighting. The City of Portland replaced eight HPS luminaires at Lijia Loop with eight LED luminaires. The illuminance level of LED luminaires was about 55 percent of that of HPS, but it still met the Portland lighting standard. The energy savings of using LED lighting was about 53 percent and the resident responses to the use of LED roadway lighting were positive overall. The payback period was estimated to be about 7.6 years (*74*).

In 2006, researchers at Taiwan University, China, conducted an economic analysis for LED roadway lighting. They developed their own LED lighting fixture and built a 200 m (656 ft) campus roadway lit by LED fixures (150-watt LED of 8,000 lumens at a 5.2 m (17 ft) height) for an energy savings analysis of LED lighting. The results showed that LED lighting can save 35.4 percent and 65.0 percent in energy consumption compared to sodium lamp and mercury lamp in brand new performance, respectively. They also conducted an economic analysis based on a hypothetical 10 km (6.2-mile) 2-lane highway with 30 m (98.4-ft) spacing of light poles. The total installation cost was estimated as $30.91 million for solar-powered LED lighting, $18.82 million for conventional mercury lighting, and $22.48 million for grid powered LED lighting. The payback period for the excess investment of LED lighting was estimated to be 1.2 years for LED using grid power and 3.3 years for LED using solar power, respectively (*75*).

Environmental Issues

A worldwide propaganda campaign is being promoted on the need to reduce electrical energy consumption because of global climate change. All efforts made for lighting curfews or adaptive lighting ensure that only the appropriate and necessary level of lighting is provided for any situation at any point in time (*8*). Other than energy consumption, light pollution and its impact on wildlife are two major environmental issues for roadway lighting.

Light pollution has increasingly become a major concern as an environmental impact of transportation facilities. It has been estimated that 35 percent to 50 percent of light pollution is caused by roadway lighting. Light pollution includes light trespass, glare, and urban sky glow. Light trespass is the effect of light that strays from its intended purpose. Glare, the unwanted source luminance, can be categorized into blinding glare, disability glare, and discomfort glare. Urban sky glow is the result of stray light being scattered in the atmosphere brightening the natural sky background level (*76*). The International Dark-Sky Association (IDA), formed in 1988, has made efforts to create public awareness for the prevention of sky glow. IDA assists lawmakers in creating lighting ordinances and works with manufacturers to create environmentally friendly outdoor lighting and to maintain "starry spaces for future generations" (*77*). IDA addresses issues of stray lighting, energy wastes of excessive nighttime lighting, and disturbance from unnatural night lighting to animals, humans, and ecosystems.

An ordinance from San Diego County, California, places a limit on stray light at 0.21 lux (equivalent to bright moonlight) on the horizontal and vertical planes at a point that is 1.5 m inside an owners' property line. An ordinance from Skokie, Illinois, classifies light falling on residences from a roadway lighting system in excess of 3 lux as a public nuisance (*77*).

Bright roadway lighting could reduce contrast sensitivity and color perception and could also result in disability glare, which causes drivers to look away from the lighting. Older drivers have a harder time in dealing with the disability glare due to the decreased ability to quickly adjust their eyes to different levels of lighting. IDA believes that shielded lower wattage lighting will reduce the frequency of disability glare (*78*). IDA also notes that just replacing higher wattage bulbs with lower wattage bulbs does not necessarily relieve the glare caused by a light source. Based the IDA light pollution brochure, the *California Motor Vehicle Code* limits the measured luminance of a light source, within 10 degrees of a driver's line of sight to be not more than 1,000 times the minimum measured ambient luminance in the field of view (*78*).

To address sky glow, some jurisdictions, particularly those around observatories such as Tucson, Arizona, have enacted ordinances requiring the use of full-cutoff luminaires and glare shields for roadway lighting. Calgary Alberta, Canada, switched its drop-lens streetlights to full cutoff fixtures and, with a reduction in lighting wattage, will realize a cost savings of around $1.7 million each year. The conversion costs will be made up in energy cost savings. The shielded lights typically need less wattage to be effective and can remove the glare caused by unshielded lights (*79*).

The CIE 115-2010 lighting guide recommends lighting curfews and adaptive lighting be applied to reduce the obtrusive lighting from roadway lights to within tolerable limits for residents during any period of the night (*8*). IESNA also has a recommendation on light trespass. Table 17 summarizes the maximum illumination levels IESNA recommends for different lighting zones (*80*).

Table 17. IESNA 2000 Maximum Luminance Levels to Avoid Light Trespass.

	Zone 1	**Zone E2**	**Zone E3**	**Zone E4**
Illuminance Limit (lux)	1	3	8	15
Luminance Limit (cd/m^2)	108	323	861	1615

In 2007, the IDA developed a program that rated US DOTs on their roadway lighting efforts for quality night lighting on highways. The states of California, New Mexico, Texas, Colorado, and Arizona are the top five states that have good roadway lighting design criteria. The article on the program states that "they (the aforementioned five states), in varying degrees, recognize and state the importance of full cutoff/fully shielded fixtures in their roadway lighting specifications; the best are in states that have dark sky legislation; the most progressive embrace the dark sky philosophy, which is reflected in clearly written warrants and roadway lighting specifications, complete and clear presentation of lighting levels, and state a concern not to over light when lighting is deemed necessary" (*81*).

The effects of ecological light pollution are widespread. Roadway lighting may disrupt species' navigational abilities (known as disorientation), attract and expose certain species to high predation and result in high mortality rate, and modify some species' natural behaviors by disrupting the precision of life-sensitive cycles (*82*).The IDA has found studies that suggest artificial light causes sleep disorders in humans due to a disruption in circadian rhythms and a reduction in the amount of melatonin, which is created in response to darkness. A well-known example of streetlight-related disorientation occurs among hatchling sea turtles. In Florida, hatchlings find their way to the sea by differentiating between dark, elevated areas and the bright, flat sea surface, but the coastal development had led to habitat degradation of sea turtles. The Florida DOT (FDOT) conducted a project in 2003 to help resolve the impacts of coastal roadway lighting on adjacent nesting beaches and to assist in revisions to the FDOT Roadway Lighting Standards to include sea turtle conservation measures. After identifying and assessing the problem areas, FDOT implemented some modifications to the existing lighting system, such as turning off the elevated HPS cobra head luminaires, replacing the lenses on pedestrian pole mounted luminaires for lower lumen output, and installing embedded LED pavement lighting. Overall, the roadway lighting illumination levels of the modified lighting system were generally within acceptable limits, the roadway users were very supportive of it, and crash trends were unaffected during the limited analysis period (*83*, *84*).

The impact of lighting attraction can be illustrated by the high mortality of fledglings around roadway lighting. Petrel and shearwater fledglings undertaking their first flight to sea are attracted to any type of light in the attempt to secure their first meal such as bioluminescent squid, and they will circle the lights until exhaustion sets in. Then grounding on the shore will expose them to starvation and predation. On Reunion Island in the Indian Ocean, streetlights and stadium lights were estimated as the major cause of 78 percent of groundings and were believed to result in up to 40 percent of the island's loss of these birds (*82*).

In the Netherlands, environmental studies conducted in the mid-1990s concluded that a lit roadway could be a barrier to wildlife movement, and a number of environmentalists suggested that night skies be kept dark. There were many sensitive areas in the northern part of the Netherlands that were classified as scenic areas. In these scenic areas, the Dutch applied multifaceted lighting approaches that included not installing lighting, installing dimmable lighting, and an active investigation into the use of lighting as a guidance system (*35*). Their *Manual of Motorway Dynamic Lighting* suggests a switch-off plan for roadway lighting in and adjacent to nature areas, i.e., simply turning off lighting when traffic volume level is below 800 vphpl as opposed to still having lights on at 20 percent of normal level outside nature areas (*69*).

In an attempt to reduce deer-vehicle crash occurrence, Colorado installed fixed illuminations on roadways with high deer crossing rates. A study found that deer crossing locations did not change much after highway lighting installation, and a greater proportion of deer crossed in the highway lighting area after the lighting installation and when lights were on than before the lighting installation and when lights were off. But the roadway lighting did not result in significant changes in the crossing-per-crash ratio (*85*).

Security

A number of studies around the world (such as in the US, UK, Japan, and France) have reported that lighting improvement can reduce the number of acts of crime and harassment. Most of these studies measured the crime rates before and after upgrading the lighting, or interviewed and recorded local residents' opinions about the effectiveness of the upgrading. The CIE 115-2010 lighting guide reviewed these studies and summarized the following findings about the effect of roadway lighting on security (*8*):

- Newly installed or upgraded lighting can result in displacement of crime to an adjoining area or an overall reduction without displacement.
- Good lighting can reduce the fear of crime and thus increase the sense of security.
- The increased sense of security creates a social control, either formal or informal.
- The lighting or its improvement can have an impact on urban security.
- Facial recognition should be considered for lighting locations where the fear of crime is a concern.

In 2002, an Australian study reviewed the relationship between outdoor lighting and crime and found no significant evidence that lighting could prevent or reduce crime. The study thoroughly reviewed research conducted between 1977 and 1997 in the US and concluded that the effects of lighting on crime were unknown. The researcher argued the following points of views for studies claiming significant impacts of lighting on security (*86*, *87*):

- The British government had been widely installing brighter lighting to prevent crime, but the effect was questioned by the 28 percent increase in crime rate in the year ending April 2002.
- For studies claiming lighting affects both daytime crime and nighttime crime, distinction should be made between direct effects and indirect effects.
- Studies presenting nighttime crime data only did not guarantee only direct effects, because direct and indirect effects often appeared to be mixed indiscriminately in analyses of changes accompanying the lighting treatment.
- Ignorance of the photometric changes of the lighting treatments could result in imprecise estimation, and other factors might be attributable for the change of crime rate.
- There may be systematic bias in experiments with industry funding as they may choose areas with substantially high crime rates where lighting treatments tend to be beneficial. Pooling available results to define precise relationship between lighting increments and changes in crime does not eliminate such bias and, thus, may not be reliable.
- Excessive outdoor lighting appeared to facilitate some of the social factors that lead to crime.

The British Standards Institution produced a revised code of practice for road lighting, between 1987 and 1990. Part 3 of the 10 parts, Code of Practice for Lighting for Subsidiary Roads and Associated Pedestrian Areas, published in 1989, prescribed different illuminance levels in terms of local crime rates among other things (Table 18) (*88*).

Table 18. British Recommendation of Illumination Level for Crime Consideration.

Roadway Characteristics	Average	Minimum
High pedestrian/vehicle use or a high crime risk	10 lux	5 lux
Moderate pedestrian/vehicle use or an average to low crime risk	6 lux	2.5 lux
Little pedestrian/vehicle use and a very low crime risk	3.5 lux	1 lux

CHAPTER 3: RESEARCH ACTIVITIES

In conducting this project, the research team performed several activities to collect the data needed to develop the lighting curfew guidelines. These activities included visits to field locations to evaluate lighting conditions, a safety analysis of the impacts of turning off freeway lighting during late-night hours, a visibility assessment of freeway conditions in areas with and without freeway lighting, and a benefit/cost analysis of the energy savings associated with implementing a lighting curfew on freeways.

EVALUATION OF FIELD CONDITIONS

To gather information that was used to select locations for the safety analysis and the visibility evaluation, the research team contacted TxDOT districts to identify various aspects of their lighting practices. The research team also traveled to selected locations to identify general lighting characteristics.

Survey of TxDOT Districts

In October and November 2010, the research team developed a survey to send to selected TxDOT districts to identify the types of lighting at locations for which the team had permanent count station data. The purpose of the survey was to identify potential sites for the safety analysis study and visibility evaluation in later tasks. A spreadsheet-based survey was developed and sent to the districts through the TxDOT Traffic Operations Division. The request was sent to the following districts: Austin, Bryan, Corpus Christi, Dallas, Houston, Lufkin, San Angelo, Tyler, Waco, and Yoakum. Responses were received from all but two districts; these two districts were included in the site visits so that the information could be obtained by visual inspection.

Site Visits for Roadway Lighting Information

Having gathered information about general lighting characteristics in several neighboring districts from the survey, the research team conducted some preliminary safety and visibility analysis activities in order to gain an appreciation of the types of data that would be needed for the detailed analysis. Members of the research team then traveled to three districts and drove the freeways to identify the type of lighting on the freeways, locations that did not have lighting, and potential specific study sites for the safety analysis and the visibility evaluation.

Site visits were conducted in Houston (March 20, 2011), Austin (June 20, 2011), and Dallas (July 7, 2011). The site visits focused exclusively on freeways based on the decision in the panel meeting to evaluate freeways. The information below indicates the freeways that were traveled in each city and the limits of the travel.

- Houston, March 20, 2011.
    - US 290 (Hempstead Freeway): from Hempstead to IH 610.
    - IH 610 (North Loop): from US 290 to IH 45.
    - IH 45 (North Freeway): from IH 610 to SH 242.
    - US 59 (Eastex Freeway): from SH 242 to IH 610.
    - IH 610 (North Loop): from US 59 to IH 10.
    - IH 10 (East Freeway): from IH 610 to S. Lynchburg Road.
    - SH 225 (LaPorte Freeway): from Independence Parkway to IH 610.
    - IH 610 (East Loop): from SH 225 to Clinton Drive.
    - IH 610 (South Loop): from SH 225 to IH 610 (West Loop).
    - SH 288: from US 59 to Airline-Ft. Bend Road.
    - US 59 (Southwest Freeway): from IH 610 to Sam Houston Tollway.
    - IH 610 (West Loop): from IH 610 (South Loop) to US 290.
- Austin, June 20, 2011.
    - SH 71: from SH 130 to US 183.
    - US 183: from SH 71 to SH 360.
    - IH 35: from SH 29 to FM 2001.
    - LP 1: from US 290 to US 183.
    - US 290: from IH 35 to SH 95.
- Dallas: July 7, 2011.
    - IH 45: from West Belt Line Road to IH 30.
    - IH 30: from IH 45 to IH 35E.
    - IH 35E: from IH 20 to SH 12.
    - SH 12: from IH 35E to IH 635.
    - IH 635: from SH 12 to IH 20.

- US 75: from downtown to SH 5.
- US 175: from IH 45 to IH 20.
- IH 20: from US 175 to IH 35W
- SH 408: from IH 30 to SH 12.

SAFETY ANALYSIS FOR ROADWAY LIGHTING

The main purpose of safety analysis in this research was to determine the traffic threshold condition for lighting curfews. In this task, the research team conducted extensive data collection to gather lighting information, geometrics, and crash data for freeways with and without continuous lighting. Then, the research team calculated and compared the hourly crash frequency and crash rate on lit and unlit sites under various scenarios, which included general and screened sites, different days of the week, and different volume levels.

Data Collection

Data collected for the safety analysis portion of the project included lighting condition information, geometric data, annual and hourly traffic data, and crash data. Continuous lighting segments along freeways were identified by visiting sites and searching Google Maps. Then, lighting information and the hourly traffic dataset were matched with the geometric dataset, which were then combined with the crash dataset.

Based on the results of the TxDOT district survey of lighting information and the field visits in Houston, Austin, and Dallas, the research team searched more detailed lighting information in Google Maps. Roadway segments with safety lighting at on-ramp and off-ramp areas or without any roadway lighting were considered as the non-continuous lighting (also called unlit) condition. A continuous lighting segment (also called a lit segment) was identified when the segment met the following three criteria:

- The roadway segment was equipped with the same type of roadway lighting fixture, that is, high mast lighting or conventional lighting mounted in the median or on the right edge.
- The roadway segment was at least 0.5 mile long.
- Both ends of the roadway section were at least 0.5 mile away from the center of any adjacent interchanges.

A lighting segment consisted of one or more roadway sections with consistent geometric characteristics. The TxDOT RHINO database (a database of geometric design characteristics) was used to obtain detailed freeway geometric information. The RHINO database contained six years of geometric data from 2003 to 2008. Each record in the database contained geometric information, such as number of lanes, lane width, median width, and shoulder width plus other information. A freeway section was pulled for analysis when its geometric characteristics met all of the following criteria.

- The section was located in an urban area.
- The section consisted of main lanes (to exclude frontage roads), and the length was at least 0.1 mile.
- The physical roadbed was coded by "Right Main-Lane" (to eliminate frontage road segments).
- The highway design type was coded as "freeway" without high-occupancy vehicle lanes, railways, or toll-roadways.
- The section had four or more lanes.

The combination of geometric and lighting information determined one study site. If a section had the same geometric design characteristics over the study period, while its lighting condition changed, then that section generated two study sites. The research team identified 430 sites from 22 freeways in the Houston, Austin, and Dallas Districts.

TxDOT Automatic Traffic Recorder (ATR), or the permanent count stations, was used to obtain the nighttime hourly volume on freeways. Each record of the RHINO geometric dataset also included an AADT value for a specific section, but hourly volume data were not available. Instead, the TxDOT ATRs data were used to obtain the nighttime hourly volumes for the freeway sections evaluated. Each ATR record provided the AADT and the annual average hourly volume for each hour of the day and day of the week at an exact freeway location. A "K factor" was defined as the hourly volume divided by the AADT from the ATR dataset. Since the number of ATRs was limited, the research team used the average K factors within the same district and the AADT from the RHINO dataset to approximately calculate the hourly volume at a specific location where no ATR existed. ATRs used to calculate the average K factors should be located on or close to freeway segments that were in urban areas. Toll-roadways were not included in the analysis. The ATR data defined a day as beginning at midnight, meaning that the late-night hours of one night are on a different day than the early-morning hours that immediately follow. For purposes of the safety analysis, the research team wanted to treat the entire nighttime period as occurring on the same day. To achieve this, the research team redefined the day to begin at 6:00 AM. Using this definition, the midnight to 6:00 AM traffic volumes were shifted so that they were included as part of the previous night's volumes. Table 19 illustrates this time shift for the traffic volumes. Weekday nights (nights defined as including the hours from 6:00 PM to 6:00 AM) included Sunday night through Thursday night, and weekend nights included Friday night and Saturday night.

Table 19. Change in Definition of Day for Early Morning Hours.

<table>
<tr><th>Time</th><th>General Lighting Condition</th><th>ATR Definition</th><th>Project Definition</th></tr>
<tr><td>6:00 PM – midnight</td><td>Nighttime</td><td>Previous day</td><td rowspan="2">Previous day</td></tr>
<tr><td>Midnight – 6:00 AM</td><td>Nighttime</td><td rowspan="4">Study day</td></tr>
<tr><td>6:00 AM – noon</td><td>Daytime</td><td rowspan="4">Study day</td></tr>
<tr><td>Noon – 6:00 PM</td><td>Daytime</td></tr>
<tr><td>6:00 PM – midnight</td><td>Nighttime</td></tr>
<tr><td>Midnight – 6:00 AM</td><td>Nighttime</td><td rowspan="2">Next day</td></tr>
<tr><td>6:00 AM – noon</td><td>Daytime</td><td>Next day</td></tr>
</table>

The TxDOT crash dataset contained information about the crash type, location, time of day, and day of week among others. Daylight saving times were used to determine the natural lighting condition when a crash happened. The duration from 30 minutes after sunset to 30 minutes before sunrise was considered as complete dark hours. PDO crashes were excluded because of the uncertainty in determining the crash cost, and only KABC (fatal [K], incapacitating injury [A], non-incapacitating injury [B], and possible injury [C]) crashes were kept in the dataset. The final dataset (from 2003 to 2008) contained a total of 13,922 crashes (11,167 crashes at lit sites and 2,785 crashes at unlit sites).

Exploratory Analysis of General Conditions

The exploratory analysis covered the general geometric and hourly traffic conditions, crash frequencies, and crash rates on lit and unlit freeway sites. The preliminary data processing showed that unlit sites were only available on freeways with no more than eight lanes in the final dataset, so the exploratory analysis only focused on 4-lane, 6-lane, and 8-lane freeways.

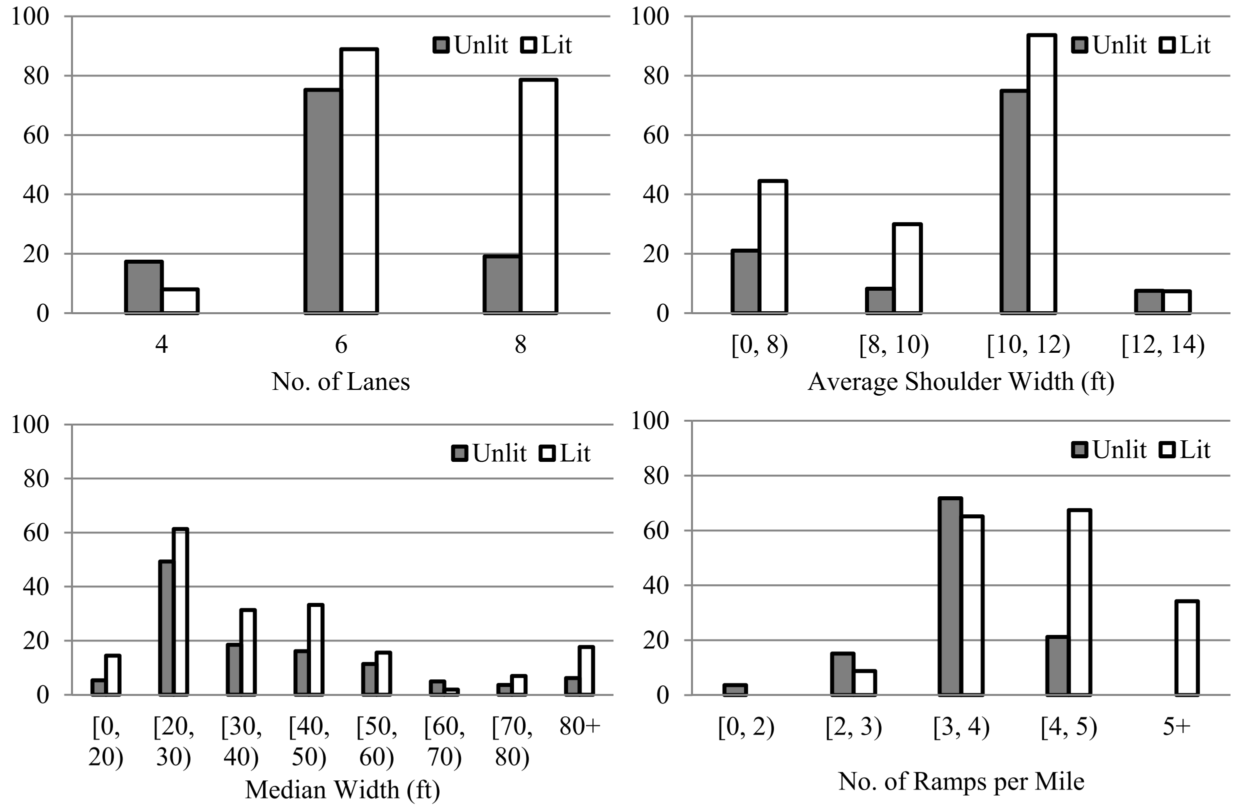
Geometric and Traffic Characteristics

Table 20 summarizes the variables associated with the geometric and traffic characteristics of the lit and unlit sites. They are summarized by the number of lanes. Continuous lighting installation was often associated with freeway sites with a larger number of lanes, narrower left shoulder, higher AADT, and higher nighttime hourly volume. Continuous lighting on 6-lane and 8-lane freeways was also associated with narrower average shoulder width and a greater number of ramps per mile.

Figure 1 and Figure 2 show more details about the geometric and traffic distributions between unlit and lit sites. Freeways with six lanes accounted for a large portion of the mileage for lit and unlit sites. The most common average shoulder width varied between 10 and 12 ft, while the median width between 20 and 30 ft was the most frequent value. A large percentage of the ramp density was between 3 and 4 ramps per mile, especially for unlit sections. About 85 percent of sites had hourly volumes less than 400 vphpl.

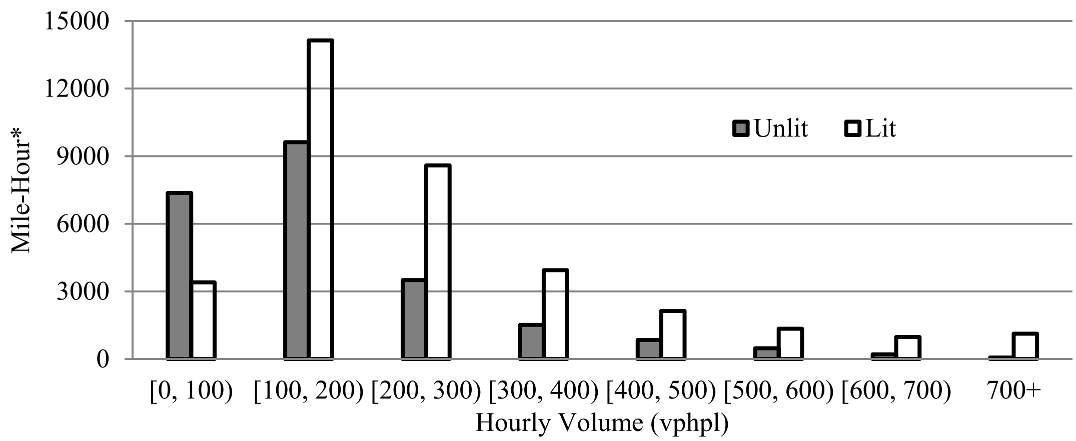
Table 20. Geometric and Traffic Conditions of the Study Sites.

Number of Lanes		4 Lanes		6 Lanes		8 Lanes	
Lighting Condition		Unlit	Lit	Unlit	Lit	Unlit	Lit
Total Length (mi)		17.35	8.05	75.20	88.89	19.15	78.60
No. of Sites		32	17	86	123	32	107
Section Length (mi)	Min	0.10	0.16	0.10	0.10	0.11	0.11
	Max	1.50	1.36	3.55	4.00	1.93	3.94
	Average	0.54	0.47	0.87	0.72	0.60	0.73
Right Shoulder Width (ft)	Min	4.00	8.00	8.00	0.00	8.00	6.00
	Max	12.00	10.00	12.00	12.00	12.00	12.00
	Average	7.94	9.18	10.53	9.72	11.50	10.37
Left Shoulder Width (ft)	Min	4.00	0.00	2.00	0.00	8.00	0.00
	Max	12.00	8.00	12.00	12.00	12.00	12.00
	Average	6.31	6.29	9.66	7.23	10.19	7.48
Average Shoulder Width (ft)	Min	4.00	5.00	6.00	2.00	10.00	4.00
	Max	12.00	8.00	12.00	11.00	11.00	12.00
	Average	7.13	7.74	10.10	8.47	10.84	8.93
Median Width (ft)	Min	32.00	12.00	16.00	8.00	20.00	4.00
	Max	74.00	70.00	264.00	112.00	50.00	140.00
	Average	48.81	36.65	34.10	38.76	43.56	37.37
Ramp Density (No. of Entrances and Exits per Mile)	Min	3.38	2.13	0.00	2.13	1.72	2.92
	Max	4.21	4.01	4.32	8.16	3.83	10.43
	Average	4.08	3.32	3.13	4.28	2.93	4.78
AADT (vpd)	Min	32650	50190	30360	46010	81440	43340
	Max	72950	165060	160870	201140	166770	287780
	Average	49788	104913	77814	121545	116608	170129
Nighttime Hourly Volume (vpdpln) (11:00 PM–6:00 AM)	Min	48	67	30	37	47	31
	Max	626	1419	1232	1198	632	1271
	Average	163	305	166	250	188	270



Note: y-axis is miles, the sum is for sites in the six-year dataset

Figure 1. Distribution of Variables per Number of Miles for Study on Lit and Unlit Sites.



* The mileage is summed over all sites in the six-year dataset for all average hourly volumes (11:00 PM–6:00 AM)

Figure 2. Distribution of Nighttime Hourly Volume at Unlit and Lit Sites.

Figure 3 shows the K factor values during the nighttime hours between 11:00 PM and 6:00 AM. On average, weekend (Friday and Saturday) nights had higher K factors than weekday (Sunday through Thursday) nights. Beginning from 1:00 AM, K factors were lower than 1 percent until 5:00 AM.

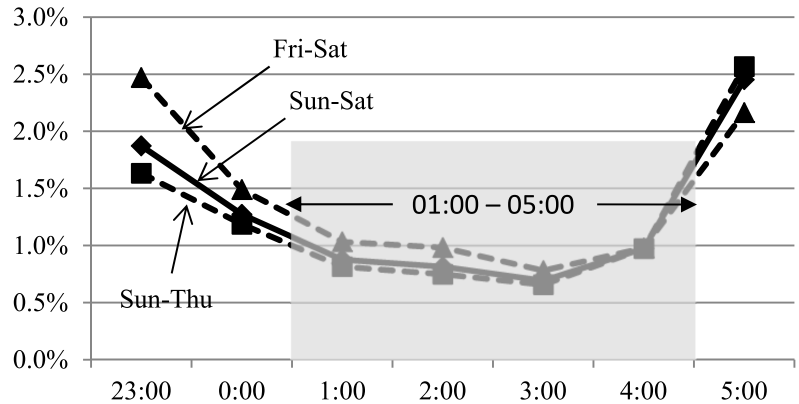


Figure 3. Change in K Factors throughout the Nighttime Hours.

Crash Characteristics

To compare the general safety conditions of unlit and lit sites, the research team examined average annual hourly crash frequency and crash rate using both spatially disaggregated and spatially aggregated data analysis. The hourly crash frequency and crash rate were calculated for individual sites in the disaggregated analysis. For the aggregated analysis, all sites having the same geometric and lighting conditions were grouped together. The equations below show how the values were calculated.

$$CF\_d = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{Y_i}\sum_{j=1}^{Y_i}\frac{n_{ijt}}{L_i}$$

$$CR\_d = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{Y_i}\sum_{j=1}^{Y_i}\frac{n_{ijt}}{1000L_iV_{ijt}}$$

$$CF\_a = \frac{1}{Y}\sum_{j=1}^{Y}\frac{\sum_{i=1}^{N_j}n_{ijt}}{\sum_{i=1}^{N_j}L_i}$$

$$CR\_a = \frac{1}{Y}\sum_{j=1}^{Y}\frac{\sum_{i=1}^{N_j}n_{ijt}}{1000V_{jt}\sum_{i=1}^{N_j}L_i}$$

Where CF_d and CR_d are the crash frequency (crashes/mi/yr-hr) and crash rate (crashes/mi/thou veh/yr-hr) for the disaggregated analysis, and CF_a and CR_a are the crash frequency and crash rate for the aggregated analysis. n_{ijt} is the annual number of crashes at site i during jth year and hour t, Y_i is the total years available for site i, N is the total number of sites, V_{ijt} is the hourly volume at site i in jth year hour t, N_j is the number of sites available in jth year, V_{jt} is the average of hourly volume in jth year and hour t, and Y is the total number of years.

Crash frequency and crash rate on sites with different numbers of lanes were calculated for nighttime hours for different days of the week. On average, lit freeways had higher crash frequency and crash rate than unlit sites. Figure 4 shows the results for 6-lane freeways.

At lit sites, the crash frequency on weekend nights was higher than weekday nights for both disaggregated and aggregated analyses, which corresponded to the fact that traffic on weekend nights was higher than weekday nights. However, the difference in crash rate between weekends and weekdays was smaller since traffic was considered as a measure of exposure. Both crash frequency and crash rate peaked at the hours between 2:00 AM and 3:00 AM and before 5:00 AM. In the hour from 5:00 AM to 6:00 AM, crash potentials on weekday nights greatly increased under most scenarios except the crash rate for the aggregated analysis. At unlit sites, the crash frequency on weekends and weekdays were close to each other, whereas the crash rate on weekdays was higher than the one observed during weekends for most of the nighttime period. Crash potentials still peaked at the hour from 2:00 AM to 3:00 AM for both types of analyses but also peaked at midnight in the disaggregated analysis. Generally, unlit sites had lower crash potentials than lit sites without controlling geometric characteristics.

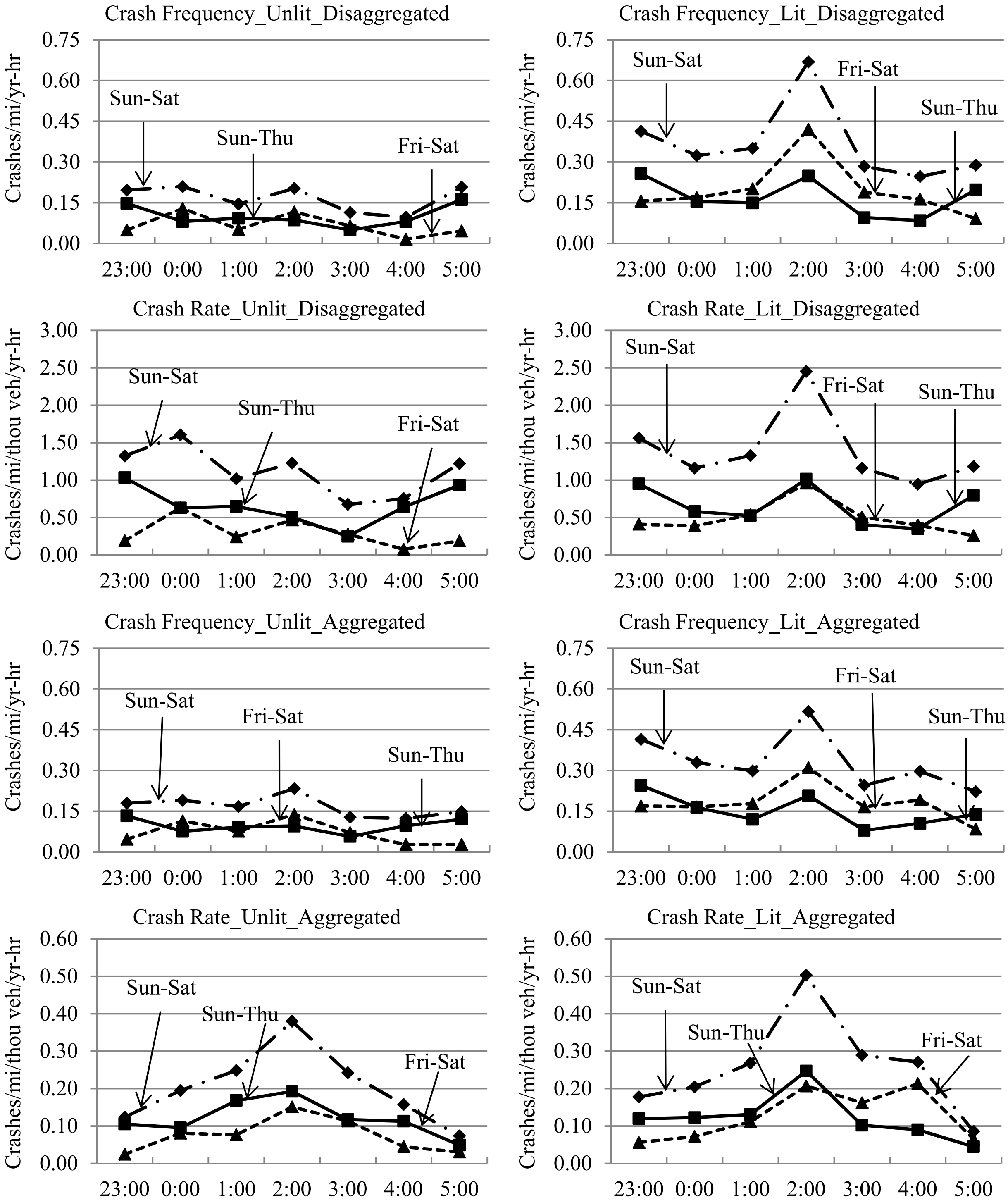


Figure 4. Hourly KABC Crash Frequency and Crash Rate on 6-Lane Freeways.

Threshold Analysis

To determine the potential traffic conditions for the lighting curfew, the research team screened out sites having similar geometric and traffic characteristics but different lighting conditions. The site screening process focused on 6-lane freeways since lit sites were not sufficient for 4-lane freeways and unlit sites were not sufficient for 8-lane freeways. From the exploratory analysis, 6-lane freeways with average shoulder width between 10 and 12 ft, median width between 20 and 30 ft, and ramp density between 3 and 4 ramps per mile had the most comparable amount of sites with and without lighting. Further comparison of the typical geometric characteristics between lit and unlit sites showed that when ramp density was between 3.0 and 3.5 ramps per mile or between 3.5 and 4.0 ramps per mile, the geometrics of lit and unlit sites were not significantly different from each other ($p<0.05$). The second group of sites did not contain enough sample size, so further traffic threshold analysis focused on the first group of sites. This group had a total of 43 sites (29 unlit sites and 14 lit sites), and the mileage was 38.17 miles (26.60 miles of unlit sites and 11.57 miles of lit sites). In the traffic threshold analysis, the research team further screened sites by the maximum hourly volume ranging from 100 vphpl to 400 vphpl with 100-vphpl increments. The spatially aggregated analysis was used for this assessment.

Since traffic on weekday nights was lower than weekend nights, the difference of crash potentials between lit and unlit sites was of interest. Table 21 shows the crash ratio of lit to unlit sites during nighttime hours from 11:00 PM to 5:00 AM on weekdays (Sunday through Thursday). Note that all sites had hourly volume greater than 100 vphpl from 11:00 PM to 1:00 AM and from 5:00 AM to 6:00 AM, and unlit sites had hourly volumes greater than 200 vphpl from 5:00 AM to 6:00 AM. So during these hours, the crash ratios of corresponding maximum hourly volumes were not available. The screened sites had hourly volumes no more than 300 vphpl after midnight and before 5:00 AM, the ratios of 300-vphpl and 400-vphpl maximum volumes were of the same values.

Table 21. Hourly Crash Ratio on Weekday Nights by Maximum Hourly Volume.

Hour Beginning Time	Crash Frequency Ratio (Lit to Unlit)				Crash Rate Ratio (Lit to Unlit)			
	100 vphpl	200 vphpl	300 vphpl	400 vphpl	100 vphpl	200 vphpl	300 vphpl	400 vphpl
11:00 PM	NA	0.372	0.554	0.516	NA	0.348	0.498	0.460
0:00 AM	NA	0.000	0.223	0.223	NA	0.000	0.155	0.155
1:00 AM	0.459	0.286	0.286	0.286	0.373	0.195	0.195	0.195
2:00 AM	0.772	1.404	1.404	1.404	0.634	1.055	1.055	1.055
3:00 AM	0.000	0.357	0.357	0.357	0.000	0.274	0.274	0.274
4:00 AM	3.630	1.049	0.931	0.931	3.407	1.226	1.136	1.136
5:00 AM	NA	NA	9.633	3.388	NA	NA	10.655	4.058

NA: traffic volume did not drop below 100 vphpl during the specified time.

Most hours had a ratio below one regardless of the maximum hourly volume, which indicated the hourly crash frequency and crash rate were higher on unlit sites than lit sites during most hours. Also, the crash ratio of lit and unlit sites was not constant throughout the nighttime hours. The ratio first peaked during the hour from 2:00 AM to 3:00 AM and dropped in the next hour and then started to rise again beginning from 4:00 AM. After 5:00 AM, the crash ratio became very high, which might have to do with the limited sample size.

Using the same screened lit sites, Figure 5 indicates the difference in hourly crash frequency and crash rate among lit sites with different maximum-volume values on different days of the week. Generally, crash frequency and crash rate had similar trends, and the curve of the 100-vphpl maximum volume level was apparently lower than other maximum-volume levels for all days of the week. The 100-vphpl curve started at 1:00 AM, which indicated that the screened sites had hourly volume greater than 100 vphpl before 1:00 AM. On weekday nights, all curves other than the 100-vphpl curve overlapped with each other from 1:00 AM to 5:00 AM. On weekend nights, the difference among curves became even smaller after midnight.

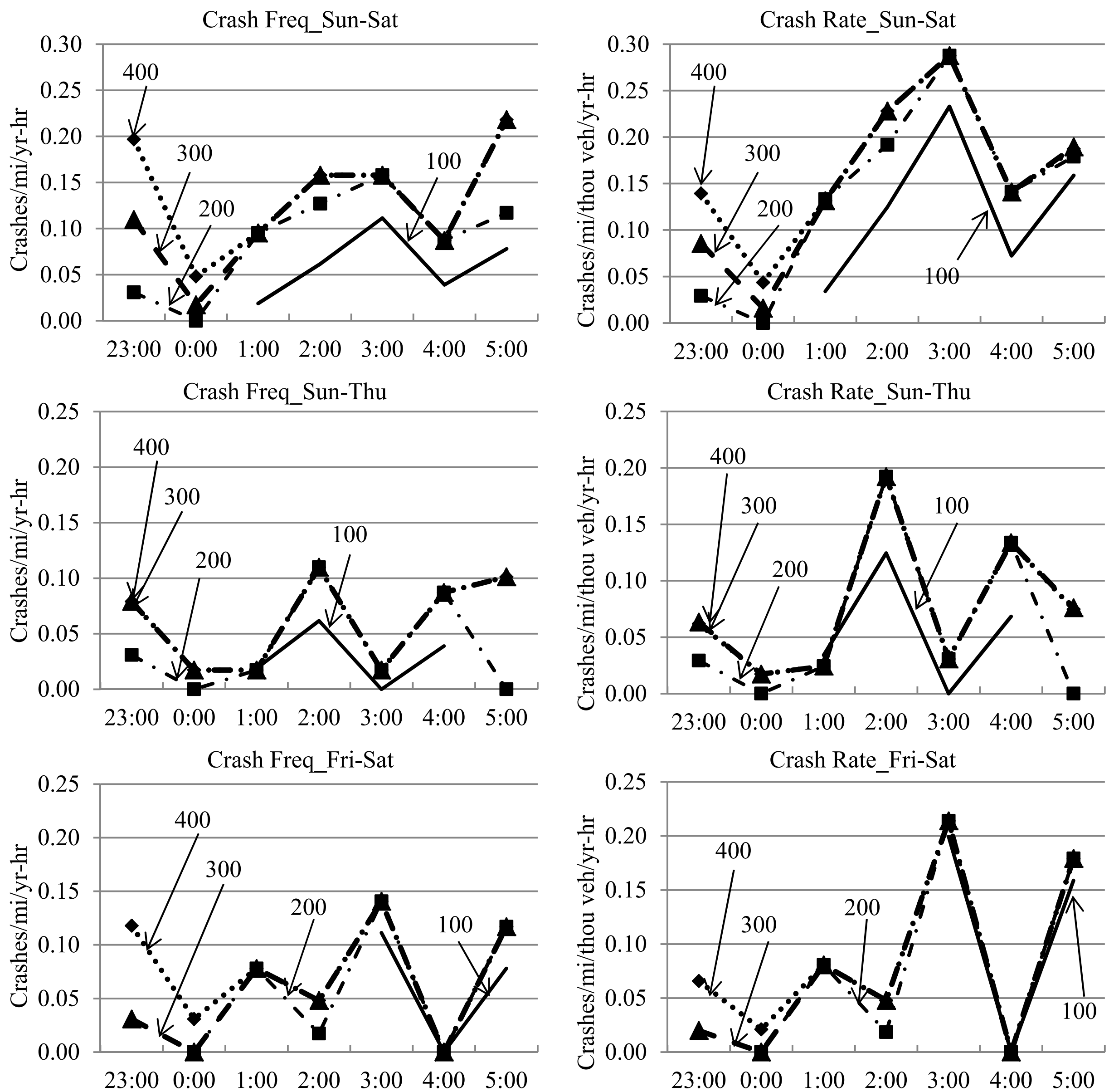


Figure 5. Hourly Crash Frequency and Crash Rate at 6-Lane Lit Sites by Max Volume.

Since from 1:00 AM to 5:00 AM crash potentials along nighttime hours were more consistent than other hours, average nighttime hourly crashes during the four hours from 1:00 AM to 5:00 AM were calculated. The results are shown in Table 22. Hourly crash frequency was lower on lit sites than unlit sites for all volume levels. The number of crashes at lit sites almost doubled when the maximum volume was increased from 100 vphpl to 200 vphpl.

Table 22. Average Crash Frequency and Crash Rate at 6-Lane Sites.

Safety Measure	Maximum Hourly Volume (vphpl)**	Sun-Sat		Sun-Thu		Fri-Sat	
		Unlit	Lit	Unlit	Lit	Unlit	Lit
Crash Frequency (crashes/mi/yr-hr)	100	0.059	0.058	0.045	0.030	0.023	0.056*
	200	0.140	0.117	0.067	0.058	0.072	0.059
	300	0.149	0.125	0.070	0.058	0.079	0.067
	400	0.149	0.125	0.070	0.058	0.079	0.067
Crash Rate (crashes/mi/10^3 veh/yr-hr)	100	0.136	0.116	0.107	0.057	0.047	0.100
	200	0.252	0.188	0.132	0.095	0.107	0.078
	300	0.262	0.197	0.134	0.095	0.114	0.086
	400	0.262	0.197	0.134	0.095	0.114	0.086

* On weekend nights, the sites of 100-vphpl maximum volume are only available from 3:00 AM to 5:00 AM
** The hourly volume is screened for hours between 1:00 AM and 5:00 AM

ROADWAY VISIBILITY ASSESSMENT

The goal of this research task was to evaluate field lighting conditions in terms of various light sources, comparison with the AASHTO guide requirements, and the change in lighting levels throughout the night. For this purpose, the research team conducted static measurements for luminance data when the data collection vehicle was parked on the pavement shoulder and dynamic measurements for illuminance data when the data collection vehicle was moving along the freeway under various lighting conditions during various hours of nighttime.

Data Collection

TTI has several different pieces of equipment that can be used for photometric research, and for the specific requirements of this study, the research team used the Radiant Imaging PM1600 series charged coupled diode (CCD) photometer and the T-10 Minolta illuminance meter (Figure 7). The CCD photometer provides an image of the roadway that can be used to assess the luminance of anything within the image, such as individual measurements of signs, pavement markings, and other objects and surfaces contained within the image. The CCD photometer has a wide dynamic range to measure the luminance of objects, and if necessary, the device can be aimed and the measurement field may be cropped in a manner that enables the device to more accurately measure very bright objects versus very dim objects. The ratio of the luminance of objects to the luminance of their respective backgrounds will be assessed from the images captured with the CCD photometer.

a) CCD Luminance Photometer b) T-10 Minolta Illuminance Meter

Figure 6. Equipment for Visibility Measurement.

The T-10 illuminance meter is a photometer designed to measure illuminance, or the light falling on an object. This device is cosine corrected to measure the entire contribution of light falling on an area perpendicular to the surface of the measuring head of the illuminance meter. Subsequently, if there are light contributions from a horizontal plane and a vertical plane to an object, those contributions can be isolated. For instance, the contribution of light from an overhead luminaire can be measured separate from the contribution of light from a headlight.

Light emitted from the majority of light sources, with the exception of lasers for example, does not emit as an individual beam, but at a variety of angles and intensities based on the light source and any associated optics. Subsequently, the majority of light sources will provide horizontal and vertical contributions of light, and so, horizontal and vertical illuminance measurements should be taken based on the needs of a particular study. While it is possible to measure the individual contributions from each light source with respect to horizontal and vertical illuminance, it would require isolating each light source "on" and all other sources "off," which would be impractical, if not impossible, under field conditions.

The research team equipped a field data collection vehicle with a CCD photometer and illuminance meters. The CCD photometer was installed inside the vehicle from the similar perspective of the driver. Figure 7 shows an image of the CCD photometer installed from the driver's perspective. The illuminance meter sensor head was installed on the roof outside of the vehicle. Three sensor heads were installed to gather illuminance data. The initial setup used to collect the dynamic measurements along the three corridors was: 1) aimed upward from the vehicle roof, 2) aimed longitudinally downstream from the vehicle roof, and 3) aimed longitudinally downstream from inside the vehicle. The vertical sensor collected light contribution from the near field luminaires that provide diffuse lighting of the pavement and nearby objects. The longitudinal sensors provided data to assess the amount of light directly reaching the driver through vehicle lighting and far field luminaires and other lighting sources.

Figure 7. CCD Photometer from Driver's Perspective.

The reason for having one interior and one exterior longitudinal sensor was to assess the impact of the windshield on reducing the ambient lighting entering the vehicle. These two sensors were oriented with an approximate 1 ft vertical offset and aligned laterally with each other with respect to the vehicle. The vertical offset may have impacted the results, but it was required to ensure that the incoming light was only affected by the angle of the windshield and not different window thickness or tinting. The researchers considered laterally offsetting and affixing them to the windshield to remove the vertical offset, but they believed that the risk of shadowing the sensor interior to the vehicle was of greater concern than the vertical offset.

The research team conducted a set of static and dynamic photometric measurements under dry nighttime conditions along state maintained TxDOT highways with and without overhead lighting. The research team collected luminance data with the CCD photometer along the study corridor, i.e., IH 35 in Austin when the data collection vehicle was parked on the pavement shoulder. The research team also collected illuminance data using three illuminance sensors when the data collection vehicle was moving along three different study corridors, i.e., IH 35 in Austin, IH 10 in San Antonio, and IH 10 in Houston, approximately every two hours starting around 10:00 PM and ending around 4:00 AM in July and August 2011. Each study corridor varied in length between 10 and 15 miles.

Luminance measurements were collected for two adjacent high-mast luminaires while the data collection vehicle was parked on the pavement shoulder. The study segments did not contain gores or overpasses and had shoulders that were at least 10 ft wide to accommodate the data collection vehicle. Measurements were collected from the outside shoulders of both directions of travel for the same set of luminaires, as the luminaires were only along one side of the road at a spacing of approximately 650 ft apart. A single set of illuminance readings along the study corridor was taken prior to taking luminance readings to record potential changes in the study conditions that may have occurred since collecting the first sets of illuminance data on a previous night. Once the illuminance measurements were completed, the research team measured the luminance of several low visibility targets (LVTs) and the luminance of the adjacent background surrounding each object. Unlike traditional STV measurements, the LVTs had three grayscale colors: white, gray, and black. The use of different grayscale colors were used to assess positive and negative contrast with respect to proximity of luminaires being measured. The research team recorded at least three successive CCD images of the LVTs with the vehicle headlights on and off, respectively.

For the study segments with luminaires, the research team measured the luminance of LVTs at five different longitudinal locations between a selected pair of luminaires. As shown in Figure 8, the LVTs were placed adjacent to the pavement edge and within the shoulder of the roadway. The five locations of LVT placement were at five equidistant points with two locations directly under the pair of luminaires and three others between the pair of luminaires. The resulting spacing between the LVTs was 162.5 ft. Based on visibility distance, only two LVTs could be viewed at a time, so the test vehicle was parked at three locations to measure the five LVTs. The research team first parked the test vehicle 120 ft prior to LVT 1, placed under the near luminaire, and took measurements for LVT 1 and LVT 2; then they moved the vehicle to 120 ft prior to LVT 3 and measured LVT 3 and LVT 4; then they parked the vehicle 120 ft prior to LVT 5 and measured the luminance of it.

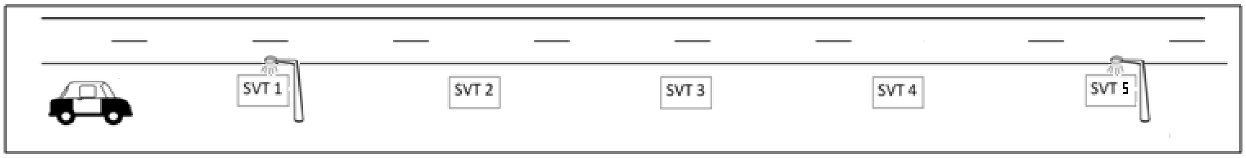


Figure 8. Luminance Measurement Layout.

As the luminance profile of the LVT was impacted by the headlamps of the test vehicle and the headlamps of other vehicles, the research team gathered measurements with and without the headlamps on and waited to take measurements until there were either no adjacent traffic or minimal adjacent traffic. At least three measurements were taken at each location to assess luminance changes between measurements in order to decide whether to take additional images. Out of over 50 measurements, there was only one measurement that appeared to have measureable light contamination from adjacent vehicles.

Luminance measurements were also collected along two dark segments of the roadway. Unlike the measurement with luminaires, only two LVTs were evaluated. The vehicle was placed 120 ft prior to the first LVT, and the second LVT was placed an additional 162.5 ft downstream. This setup matched the spacing used for viewing LVTs along the overhead illuminated segments.

For the illuminance measurements, illuminance readings were taken every second while traveling each study corridor at the start of each study interval. Each study corridor was measured in each direction from the inside and outside lanes for each study interval, which resulted in four sets of readings per interval. There were at least three study intervals for each study corridor completed. The readings were taken each second (1 Hertz), so the speed of the data collection vehicle was adjusted to ensure that at least five readings were taken between each pair of adjacent luminaires.

There were four different roadway lighting configurations evaluated during the dynamic measurement. Two of the lighting configurations used high mast lights, and two used conventional lights. Figure 9 depicts the examples of these lighting fixtures. The first lighting configuration was high mast lighting at 150 ft elevation above the pavement placed at 650 ft spacing only on one side of the highway. The other high mast lighting treatment was the alternating high mast lighting at 165 ft elevation above the pavement. The spacing between poles on one side (outside) of the roadway segment was 2,025 ft, and there were poles on the other side of the road midway between them, which made approximately 1,000 ft spacing between poles if both sides of the roadway segment were considered. One of the configurations of conventional lighting was a standard height (50-ft elevation between the luminaire and the pavement surface) median mounted double davit lighting with a pole spacing of between 280 and 290 ft. The last type of configuration was a single davit standard height lighting along the outside edge of the highway with 180-ft spacing.

a) High Mast
b) Median Mounted Double Davit
c) House Side Mounted Single Davit

Figure 9. Different Roadway Lighting Fixtures.

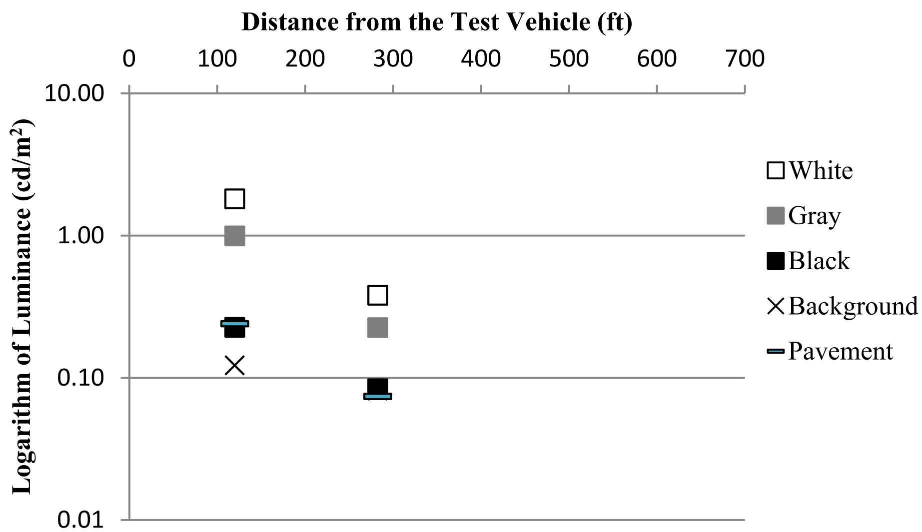
The analysis was conducted in two stages. First, the research team assessed the contribution of light to the roadway from overhead lighting, vehicle lighting, and off-axis commercial lighting with respect to time along each of the study corridors. This helped assess whether the lighting conditions differ throughout the evening, and what particular lighting contribution has the greatest impact on the nighttime driving environment. The second stage of the analysis was completed by assessing the visibility of the LVTs and the brake light with respect to time along each of the study corridors. The luminance of the study objects and the immediate surrounding environment within the CCD images was measured and the ratio of the object luminance versus the background luminance was calculated. Values near one mean lowest visibility. Values below one indicate a negative contrast visibility condition, and values above one indicate a positive contrast visibility condition. A negative contrast visibility condition only means that the object is dimmer than the background and not that the object is necessarily less visible. The static measurements of luminance data were used to assess how visibility was impacted by changes in the lighting environment. The dynamic measurements of illuminance data were used to assess the overall condition of the study corridor with respect to the static visibility measurements.

Luminance Measurements

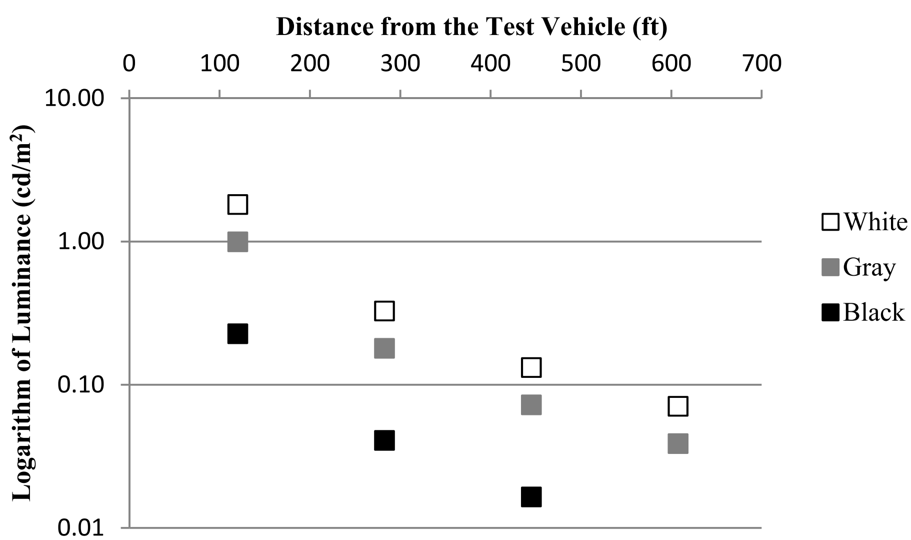
Luminance measurements were conducted on the IH 35 corridor in Austin. The research team first presents the results with respect to the impact of headlights on the nighttime measurements followed by the impact of high mast lighting for the given study corridor.

Impact of Headlights

Figure 10 shows the luminance values for two LVTs with respect to color, the background, and the pavement when no overhead lighting was present. The values are the average of the northbound and southbound measurements. It was not possible to use the LVTs to measure the impact of the headlights at a distance greater than approximately 300 ft in front of the vehicle (see Figure 10a). The research team used the property of how light falls off with respect to distance, known as the inverse square law, to estimate the luminance return from the LVTs beyond 300 ft. The revised graph, Figure 10b, includes only the LVT measurements, because the target could be controlled, while the background and pavement would vary with distance.



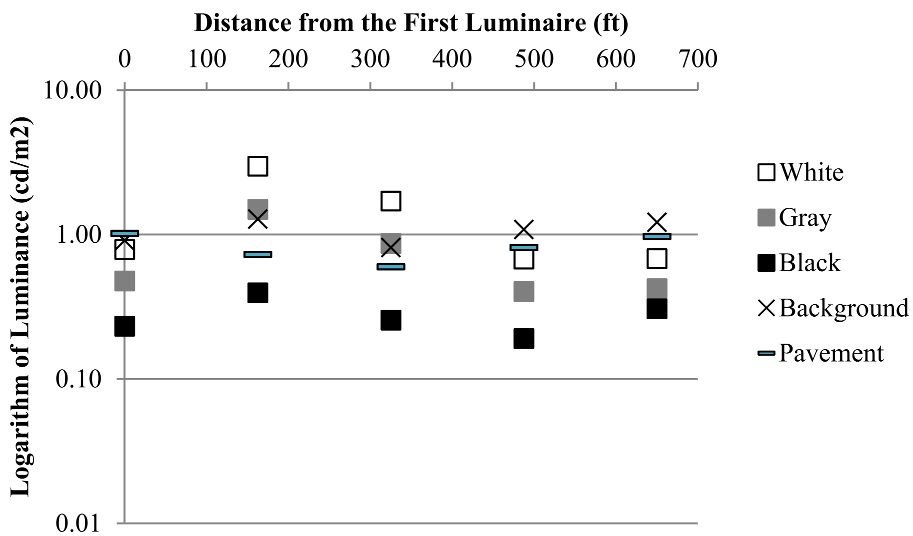
a) Measured Luminance (Average of Northbound and Southbound)



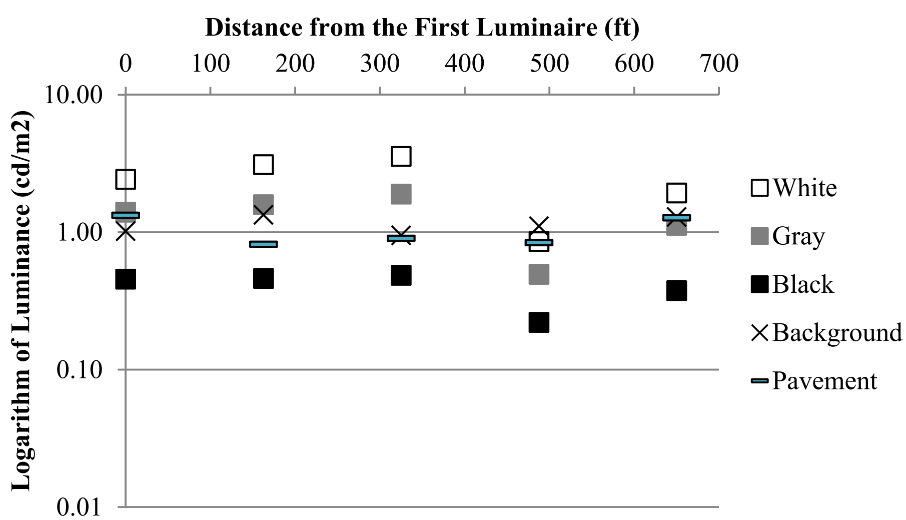
b) Estimated Luminance (Average of Northbound and Southbound)

Figure 10. Measured and Estimated Luminance with Headlights Only.

Figure 11 shows the LVTs along the northbound shoulder of the study corridor placed at five equidistant points with respect to two adjacent high mast luminaires installed along the northbound shoulder. Figure 11a contains the luminance values with the headlights off from the study vehicle, and when compared to Figure 11b, it can be seen that the headlights did increase the luminance levels.



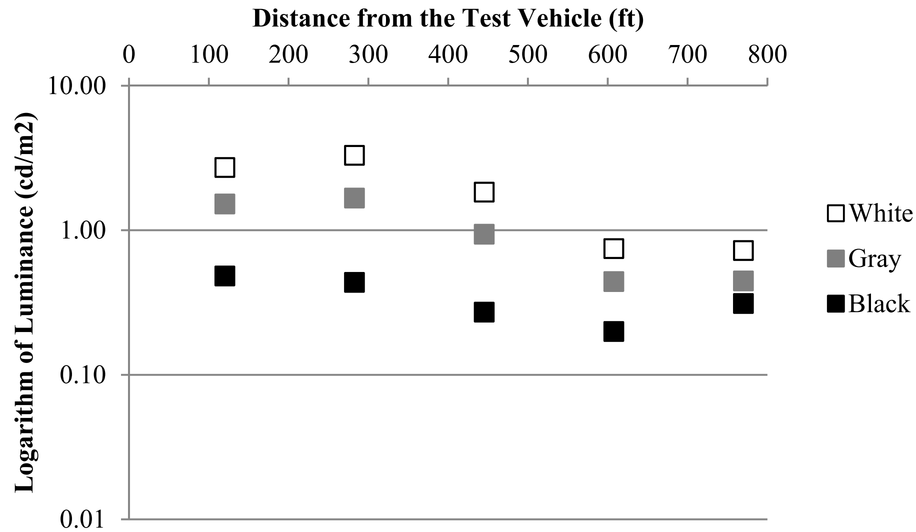
a) Luminance without Headlights



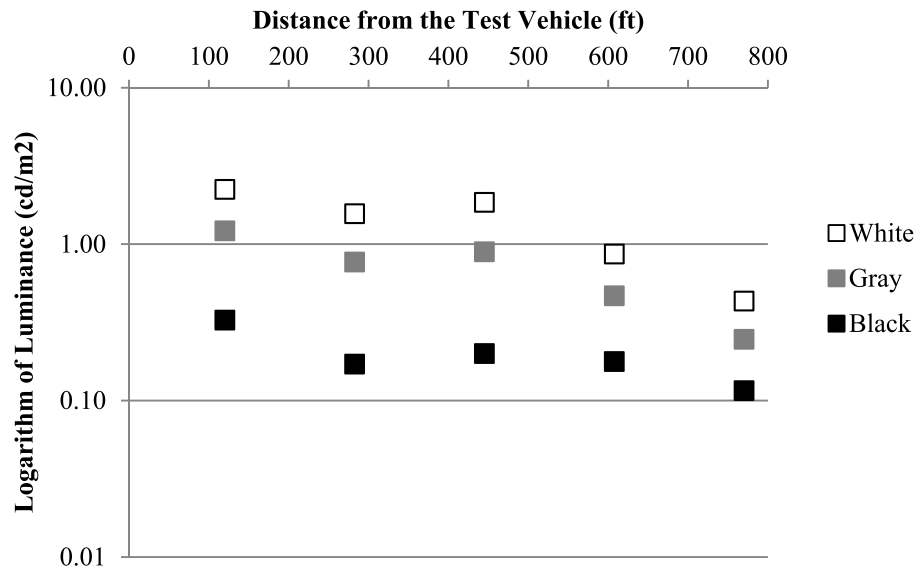
b) Luminance with Headlights

Figure 11. Luminance Measurements for High Mast Lighting (Northbound).

However, the study vehicle was placed at three different locations at 120 ft prior to the first, third, and fifth LVTs, so it cannot clearly be seen how the headlights would impact the LVT luminance levels. Subsequently, the research team applied the headlights distribution from Figure 10b to estimate the impact of the headlights on Figure 11b to create Figure 12. The correction was not applied to the background or the pavement.



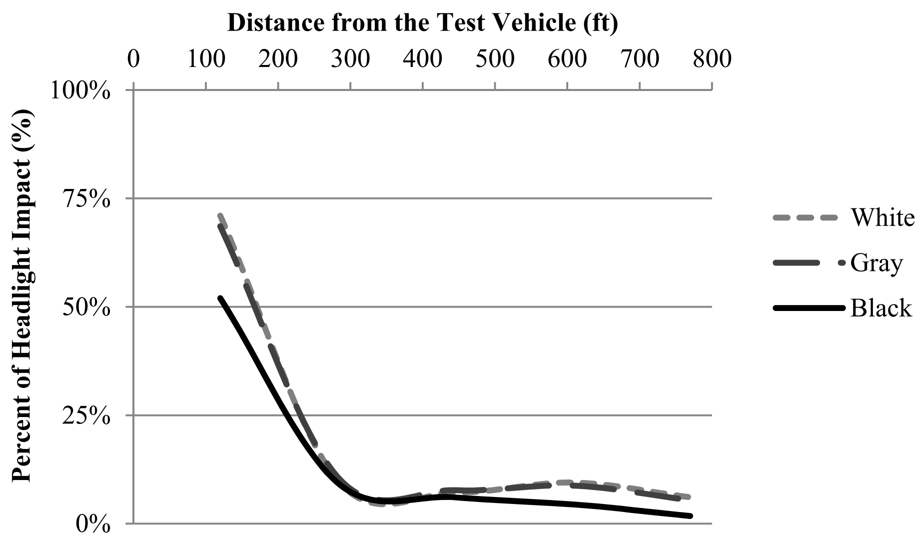
a) Northbound Luminance



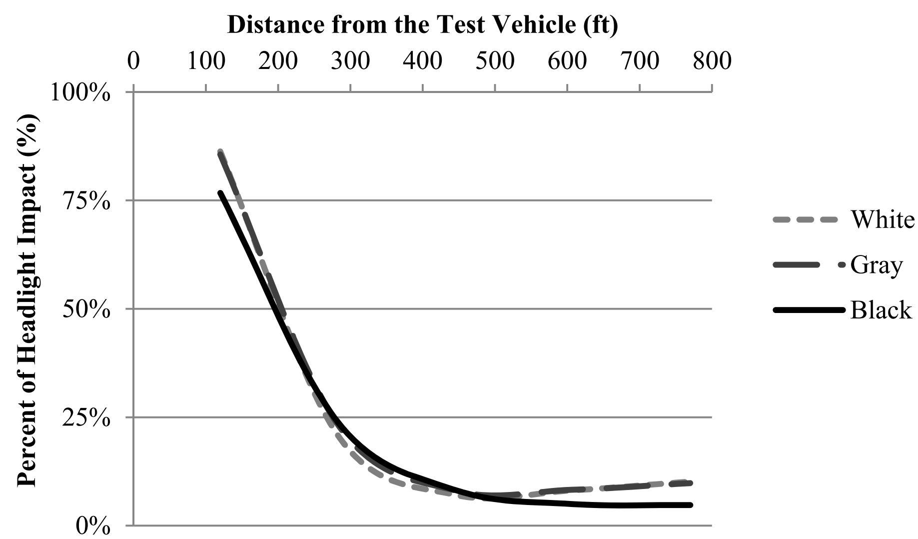
b) Southbound Luminance

Figure 12. Luminance for High Mast Lighting and Estimated Impact of Headlights.

The impact of headlights is also expressed as the percentage of contribution of headlights on total luminance when high mast lighting presents. Figure 13 shows that the contribution of headlights on luminance sharply decreases as distance increases until about 350 ft from the vehicle. The contributions of headlights on luminance of white and gray objects were very close to each other, while headlights had less contribution on luminance of the black object. Also, headlights had greater contribution to southbound luminance than northbound luminance because the luminaires were located on the northbound shoulder where higher percentage of luminance came from the luminaires.



a) Headlight Impact on Northbound Luminance

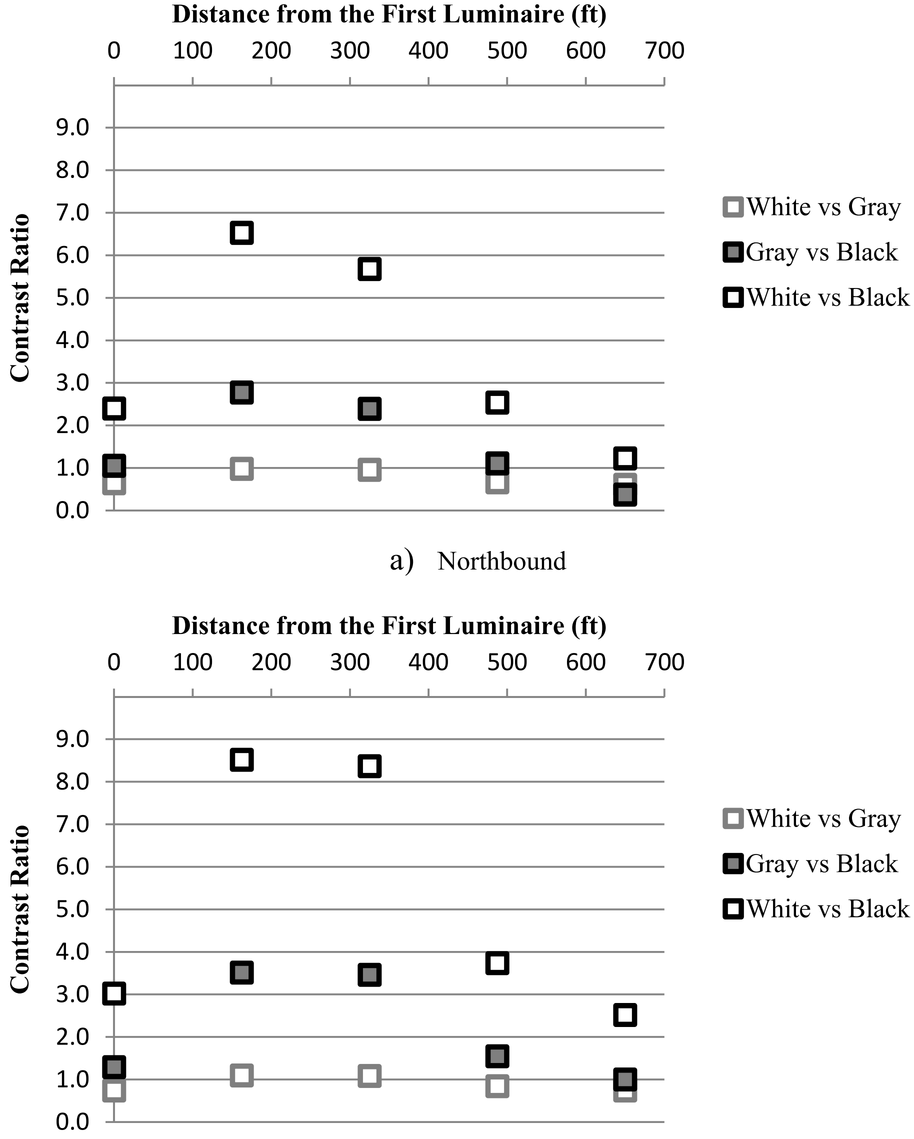


b) Headlight Impact on Southbound Luminance

Figure 13. Impact of Headlights on Luminance on Segments with High Mast Lighting.

Impact of High Mast Lighting

Figure 14 graphs various contrast ratios for lighting conditions with high mast lighting only. The majority of the ratios were above 1.0 with the lowest ratios for white versus gray and near the light sources.



a) Northbound

b) Southbound

Figure 14. High Mast Lighting Contrast Ratios without Headlights.

Illuminance Measurements

The illuminance data were collected in different cities. The majority of the sites were unique with respect to the ambient lighting conditions from the surrounding environment and the luminaire type and spacing. Table 23 shows the summary of site characteristics. The research team first analyzed the illuminance data from roadway segments with and without commercial lighting for various roadway lighting conditions and discussed the impact of commercial lighting; then they compared the measured illuminance levels with the AASHTO 2005 lighting guide; they also looked into how roadway illuminance changes as nighttime progresses when no roadway lighting or commercial lighting is present.

Table 23. Site Characteristics for Illuminance Measurements.

Location	Commercial Lighting	Roadway Lighting		
		Present	Description	Spacing (ft)
Austin	No	Yes	High mast, outside shoulder, one side only	650
Austin	Yes	Yes	Median mounted double davit	280
Austin	Yes	Yes	Outside shoulder single davit mounted	180
Austin	No	No	NA	NA
Austin	Yes	No	NA	NA
Houston	No	Yes	High mast, outside shoulder, alternating	2,025/1,000*
Houston	Yes	Yes	High mast, outside shoulder, alternating	2,025/1,000*
Houston	No	No	NA	NA
Houston	Yes	No	NA	NA
San Antonio	No	Yes	Median mounted double davit	290
San Antonio	Yes	Yes	Median mounted double davit	290
San Antonio	No	No	NA	NA
San Antonio	Yes	No	NA	NA

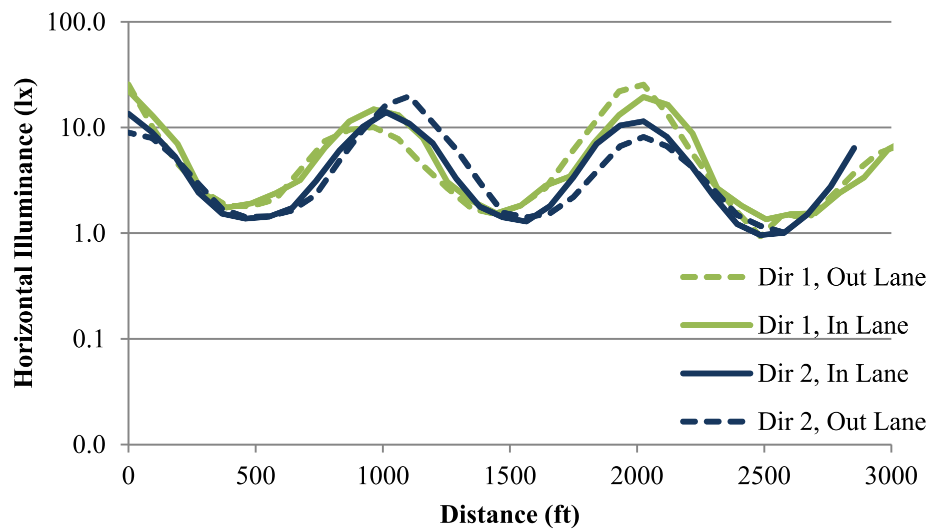
*The 2,025-ft spacing is between poles on the same side of the roadway, and the 1,000-ft spacing is between poles on opposite sides of the roadway

There are a few assumptions that were made when analyzing the data that are worth identifying. First, researchers assumed that horizontal illuminance data collected from the top of the instrumented field data collection vehicle could be used to approximate pavement illuminance, because it was not feasible to collect data in the driving lane at the pavement elevation safely without conducting nighttime lane closures. As a result, the horizontal illuminance values were used to estimate pavement illuminance with the use of the inverse square law associated with light, whereby the illuminance provided by a light source reduces by the inverse square of the distance travelled. In applying this property of light to discontinuous, but equally spaced, lighting sources, it was assumed that the light source was a continuous light source always at a fixed elevation above the pavement. This was a required assumption without gathering additional horizontal illuminance in the direction of each light source, which would have required a static measurement and one or more lane closures. There were other measurement approaches considered as well, but they also required static measurements.

When graphing the data, a few additional assumptions were made. Every illuminance data point was collected simultaneously with GPS data; however, the GPS data were lost. Subsequently, the research team used the average speed of the vehicle and the known spacing of the roadway lighting to approximate the distance along a roadway segment. With respect to the illuminance data, the data were collected at 1 Hz, but they were graphed as continuous data using linear interpolation between successive data points. Researchers believed that discontinuous points on a graph would have been more difficult to see trends and that the linear interpolation best approximated the data. With respect to graphing scale, researchers decided to use the same scale for all graphs regardless of the amount of data available or the range of the values to ensure that each graph could be compared to another graph. All illuminance data were graphed on a logarithmic scale because the human eye sees light intensity on a logarithmic scale.

Segments with Roadway Lighting Only

Figure 15 shows the estimated pavement illuminance along a highway segment in Houston with alternating high mast lights but without off-roadway commercial lighting. Some of the descriptive statistics are presented as well. Overall, direction 1 values were larger than those for direction 2, and the absolute maximum values were larger for the outside lanes versus the inside lanes, which can be explained by the sensors that were closest to the roadway lights in the outside lanes. The remaining statistics do not appear to explain the data as well as the graph, such as the absolute minimum values being lower for the outside lane—closer to the lights—than the inside lane.

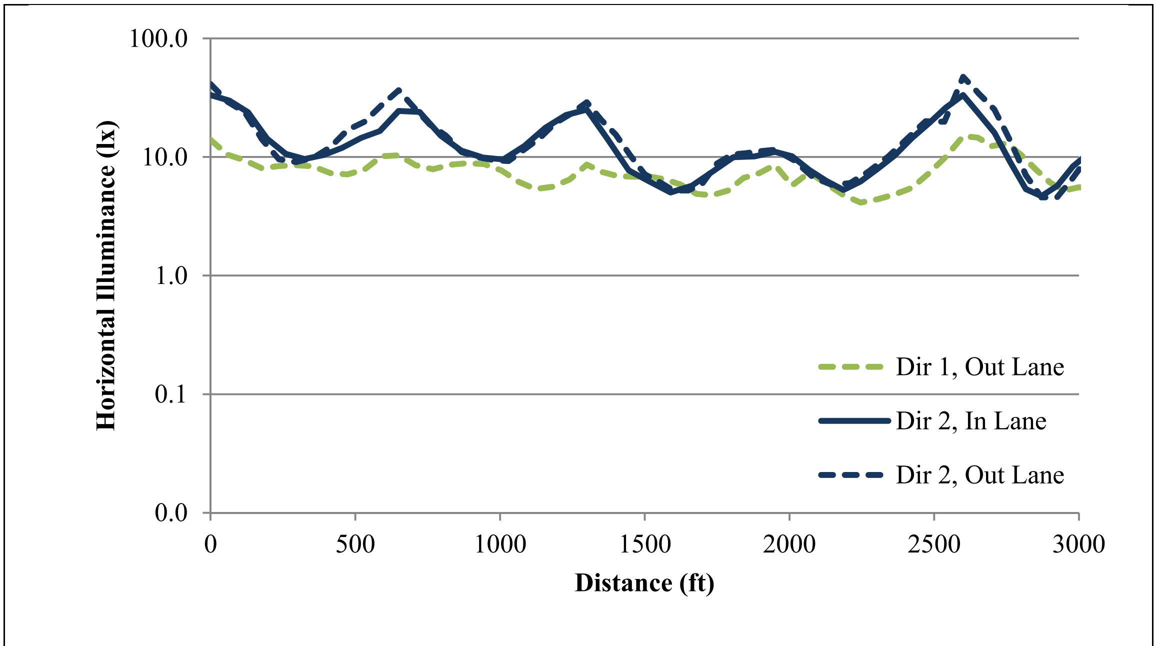


Direction	1		2	
Lane Position	Outside	Inside	Inside	Outside
Average (lux)	6.09	6.61	4.94	5.07
Absolute Maximum (lux)	25.56	22.31	13.99	19.80
Absolute Minimum (lux)	0.93	1.36	0.96	1.02
Average Maximum (lux)	13.23	16.28	12.99	12.29
Average Minimum (lux)	1.34	1.55	1.21	1.42

Figure 15. Illuminance for Alternating High Mast Lighting without Commercial Lighting.

When looking closer at the graph in Figure 15, it appears that the descriptive statistics are capturing the trends associated with alternating lighting. For instance, the second and third peaks show the alternating pattern with the outside lanes in direction 2 greater than outside lanes in direction 1, and then alternating in the next group of peaks. The data from the inside lanes also alternate where the inside lane data in one direction are greater than their respective outside lane data when the nearest light is on the opposite side of the roadway.

Based on the illuminance data collected in Austin for one-side-only high mast lighting without commercial lighting, Figure 16 shows the anticipated trends both in the graph and the descriptive statistics with the illuminance decreasing as the sensor moves away from the light source. With a lower lighting height and a closer spacing between lights, researchers expected and found that the majority of the values were higher than for the alternating high mast lighting.

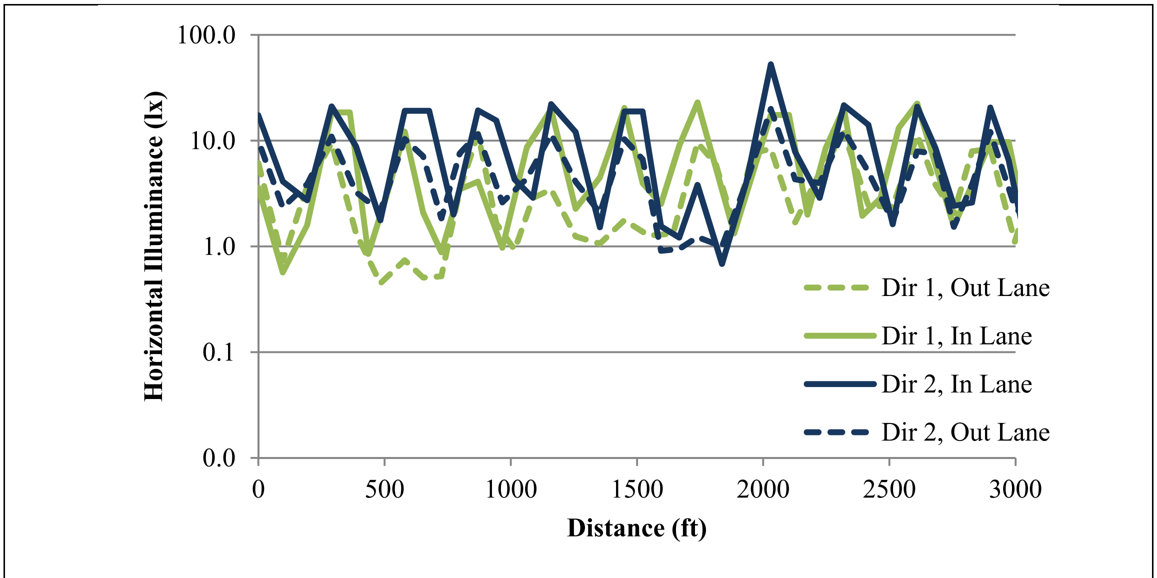


Direction	1		2	
Lane Position	Outside	Inside	Inside	Outside
Average (lux)	7.89	NA	14.09	16.01
Absolute Maximum (lux)	14.99	NA	33.96	47.43
Absolute Minimum (lux)	4.13	NA	4.68	4.57
Average Maximum (lux)	9.84	NA	26.38	33.40
Average Minimum (lux)	6.60	NA	6.32	6.15

NA: Data not available.

Figure 16. Illuminance for One-Side High Mast Lighting without Commercial Lighting.

Figure 17 contains data from San Antonio for a median mounted double davit lighting segment without commercial lighting. Again, the horizontal illuminance decreases as the sensor moves away from the light source with the data in the outside lane being below the values from the inside lanes.



Direction	1		2	
Lane Position	Outside	Inside	Inside	Outside
Average (lux)	4.77	8.71	10.28	5.52
Absolute Maximum (lux)	12.96	27.63	52.68	19.94
Absolute Minimum (lux)	0.45	0.57	0.68	0.91
Average Maximum (lux)	8.35	15.87	20.60	10.23
Average Minimum (lux)	1.47	1.68	1.85	1.89

Figure 17. Illuminance for Median Double Davit Lighting without Commercial Lighting.

Generally, the estimated pavement illuminance was higher as the sensor was closer to the light source when only roadway lighting was present. For all three types of roadway lighting evaluated, the travel lanes closer to the lighting source had higher average illuminance, absolute maximum illuminance, and average maximum illuminance.

When comparing the median mounted conventional lighting with one-side high mast lighting (Figure 17 vs. Figure 16), high mast lighting had generally higher average, maximum, and minimum illuminance values than conventional lighting for lanes closer to the luminaires, even given the fact that conventional lights had shorter spacing and lower pole height than high mast lights. This is believed to be the result of the higher wattage output and higher quantity of the lights used with the high mast lighting. Because of the higher spacing between poles in the staggered high mast configuration, however, alternating high mast lighting was not necessarily superior to the median mounted conventional lighting in terms of illuminance levels for lanes close to the luminaires.

Segments with Roadway Lighting and Commercial Lighting

Table 24 shows the statistics of the estimated pavement illuminance using data collected on a roadway segment in Houston with alternating high mast lighting and commercial lighting. Illuminance measurements showed similar patterns along the roadway to that of the roadway segment without commercial lighting (Figure 15). However, note that the minimum illuminance values of the outside lanes with commercial lighting were higher than that without commercial lighting, while this was not necessarily the case for the average and maximum values for both inside and outside lanes. One possible explanation for this is that the roadway segments in Houston where the illuminance data were collected were very wide, and the commercial lighting was far from the roadway, such that the impact on roadway illuminance levels was limited.

Table 24. Illuminance for Alternating High Mast Lighting with Commercial Lighting.

Direction	1		2	
Lane Position	**Outside**	**Inside**	**Inside**	**Outside**
Average (lux)	5.92	6.40	5.78	5.31
Absolute Maximum (lux)	23.20	23.56	20.33	23.92
Absolute Minimum (lux)	1.12	1.20	1.22	1.46
Average Maximum (lux)	13.46	13.63	13.30	9.31
Average Minimum (lux)	2.26	2.87	2.32	2.76

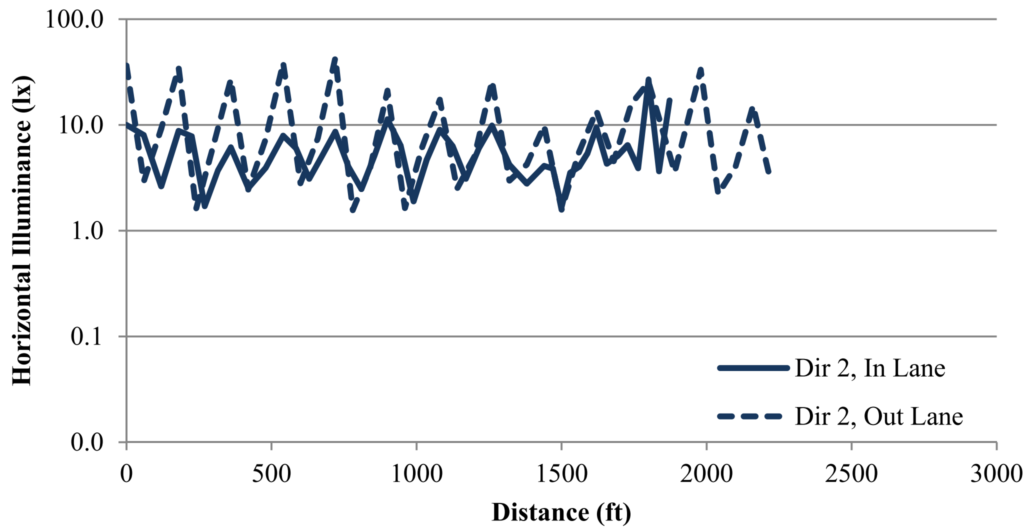
Table 25 shows the statistics of the estimated pavement illuminance based on data collected in Austin and San Antonio for roadway segments with median mounted double davit lighting and commercial lighting. Similarly, the inside lanes had higher illuminance than the outside lanes as they were closer to the roadway light source even though there was commercial lighting outside the roadway. The San Antonio segment had higher illuminance levels than the Austin segment.

Table 25. Illuminance for Median Double Davit Lighting with Commercial Lighting.

Direction	1		2	
Lane Position	**Outside**	**Inside**	**Inside**	**Outside**
Austin Data				
Average (lux)	6.89	NA	8.92	6.49
Absolute Maximum (lux)	16.57	NA	44.57	18.02
Absolute Minimum (lux)	2.21	NA	1.10	0.87
Average Maximum (lux)	13.25	NA	17.60	13.04
Average Minimum (lux)	2.64	NA	2.31	2.43
San Antonio Data				
Average (lux)	7.80	11.51	11.28	8.15
Absolute Maximum (lux)	20.96	34.74	34.21	20.50
Absolute Minimum (lux)	0.60	0.88	1.42	1.37
Average Maximum (lux)	15.14	24.18	22.61	16.19
Average Minimum (lux)	1.66	1.62	1.83	1.97

NA: Data not available.

Using the illuminance data collected in Austin for house-side conventional lighting with commercial lighting, Figure 18 shows the estimated pavement illuminance. The outside lanes that were closer to the light source had higher illuminance than the inside lane. The absolute maximum value of illuminance at the outside lane was almost twice as much as the inside lane value, and the average maximum value at the outside lane was almost three times as much as the inside lane value.



Direction	1		2	
Lane Position	**Outside**	**Inside**	**Inside**	**Outside**
Average (lux)	12.17	6.10	NA	NA
Absolute Maximum (lux)	43.00	26.85	NA	NA
Absolute Minimum (lux)	1.56	1.67	NA	NA
Average Maximum (lux)	26.29	9.87	NA	NA
Average Minimum (lux)	2.53	2.81	NA	NA

NA: Data not available.

Figure 18. Illuminance for House-Side Single Davit Lighting with Commercial Lighting.

Segments with Commercial Lighting Only

Table 26 shows the statistics of estimated pavement illuminance for roadway segments measured in each of the three cities where only commercial lighting was present. Considering the impact of headlights that varied by traffic volume and corresponding nighttime hours, the results listed in the table only represent the period of time shown for each of the three cities. Compared with the results when both roadway lighting and commercial lighting were present, the pavement illuminance values for segments with commercial lighting only were much lower.

Table 26. Horizontal Illuminance on Segments with Commercial Lighting Only.

Direction	1		2	
Lane Position	**Outside**	**Inside**	**Inside**	**Outside**
Austin Data (Data Collected 4:30 AM – 5:00 AM)				
Average (lux)	0.25	0.27	NA	0.15
Absolute Maximum (lux)	0.44	0.44	NA	0.32
Absolute Minimum (lux)	0.09	0.10	NA	0.00
Houston Data (Data Collected 2:30 AM – 3:00 AM)				
Average (lux)	NA	NA	0.56	0.67
Absolute Maximum (lux)	NA	NA	0.79	1.05
Absolute Minimum (lux)	NA	NA	0.33	0.28
San Antonio Data (Data Collected 11:30 PM – 12:30 AM)				
Average (lux)	0.30	0.28	0.29	0.28
Absolute Maximum (lux)	0.50	0.84	0.63	0.84
Absolute Minimum (lux)	0.15	0.00	0.04	0.00

NA: Data not available.

Segments without Roadway Lighting or Commercial Lighting

Table 27 shows the statistics of estimated pavement illuminance for roadway segments measured in each of the three cities where no lighting was present. Similar to Table 26, the results listed in the table only represent the period of time shown for each of the three cities. The illuminance levels were generally lower than that of roadway segments with only commercial lighting. However, the differences of illuminance between no lighting at all (Table 27) and commercial lighting only (Table 26) were smaller than that between commercial lighting only (Table 26) and roadway lighting plus commercial lighting (Table 24, Table 25, and Figure 18).

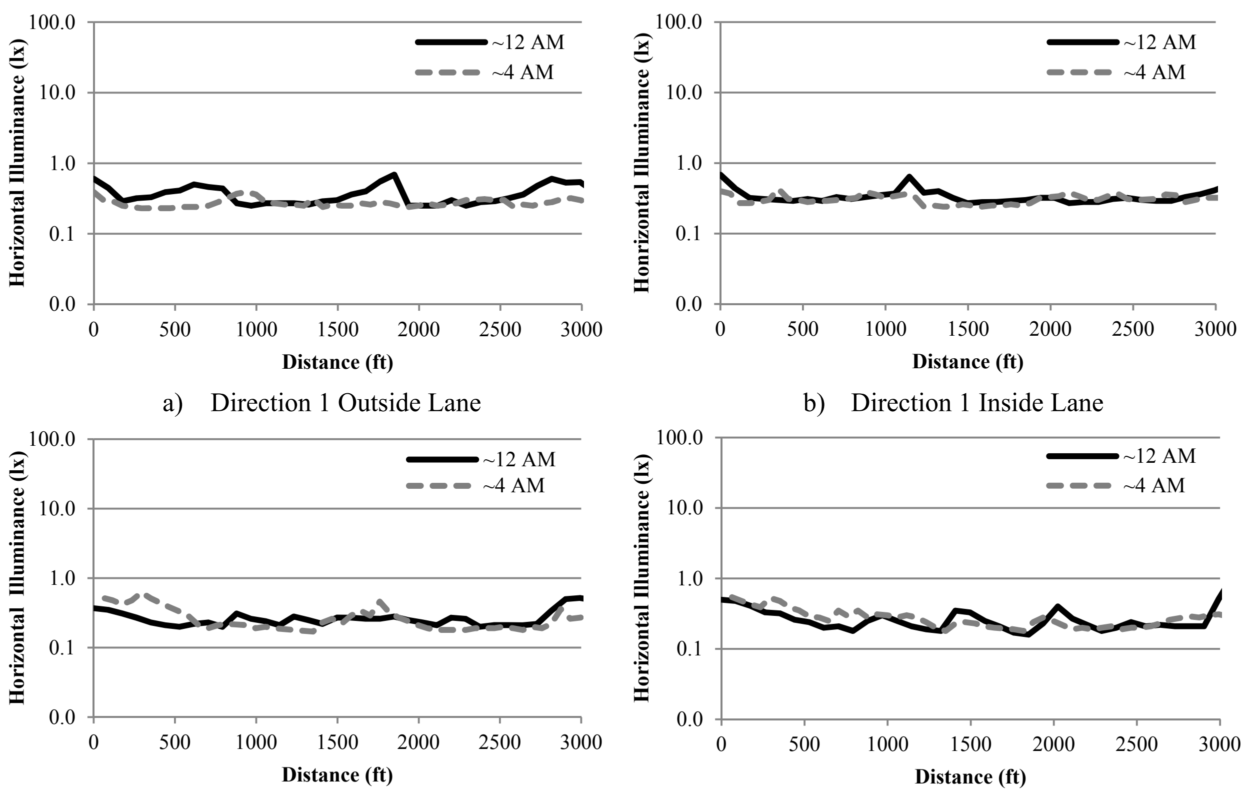
Table 27. Horizontal Illuminance on Segments without Lighting.

Direction	1		2	
Lane Position	**Outside**	**Inside**	**Inside**	**Outside**
Austin Data (Data Collected 4:30 AM – 5:00 AM)				
Average (lux)	0.17	0.18	NA	0.32
Absolute Maximum (lux)	0.37	0.29	NA	0.51
Absolute Minimum (lux)	0.02	0.03	NA	0.14
Houston Data (Data Collected 2:00 AM – 3:00 AM)				
Average (lux)	0.13	0.10	0.06	0.07
Absolute Maximum (lux)	0.25	0.24	0.16	0.27
Absolute Minimum (lux)	0.00	0.00	0.00	0.00
San Antonio Data (Data Collected 11:30 PM – 12:30 AM)				
Average (lux)	0.13	0.13	0.12	0.10
Absolute Maximum (lux)	0.22	0.35	0.35	0.32
Absolute Minimum (lux)	0.04	0.00	0.00	0.00

NA: Data not available.

The next point of interest was an investigation of whether the ambient lighting condition changed with respect to time of night. For this particular focus, the research team studied the horizontal illuminance from the driving scene. The measurements were recorded both from within the vehicle at the driver eye-height and from the top of the vehicle. Researchers took these measurements to show the impact of the glass in reducing the amount of light that reaches a driver.

Figure 19 shows the changes in horizontal illuminance along the roadway segments in San Antonio by directions and lane positions for two time periods. The result does not show a large difference between the time of night along the segment without roadway lighting or commercial lighting. The percent differences were calculated as well and listed in Table 28. There was a reduction in the amount of ambient lighting as the night progressed with the greatest reduction of 20 percent for direction 2. Also, direction 1 had a lower amount of reduction in the illuminance levels compared with direction 2. The difference by direction might be because traffic volumes significantly decreased coming into town (direction 1) while they did not appear to decrease leaving town (direction 2) throughout the night.



a) Direction 1 Outside Lane

b) Direction 1 Inside Lane

c) Direction 2 Outside Lane

d) Direction 2 Inside Lane

Figure 19. Horizontal Illuminance by Nighttime on Segments without Lighting.

Table 28. Illuminance by Nighttime on Segments without Lighting (San Antonio).

Direction	Lane	Average Horizontal Illuminance (lux) by Time of Night		Percent Change
		~12:00 AM	~4:00 AM	
1	Outside	0.26	0.26	0%
	Inside	0.30	0.29	−3%
2	Inside	0.39	0.33	−15%
	Outside	0.35	0.28	−20%

Table 29 shows the same analysis using data collected in Houston during three time periods. The table includes data from two different segments for direction 1 and one segment for direction 2, where segment 1 had higher illuminance levels than the other segments. The illuminance levels generally decreased as nighttime progressed (except the inside lane of direction 2 from about 12:30 AM to 1:45 AM and the outside lane of direction 2 from 1:45 AM to 3:00 AM). The overall percent of decrease in illuminance values from 12:30 AM to 3:00 AM ranged from 6 percent to 52 percent with the greatest decrease for segment 1 of direction 1. However, direction 2 had increased illuminance levels on the inside lane and the outside lane during the two testing periods, respectively, and had an overall percent of reduction in illuminance lower than that in direction 1. The change in lighting levels and the difference by roadway segment and by direction might be explained by the spatial and temporal changes in directional traffic volumes. The research team also noted that traffic volumes on the investigated segments in Houston were relatively higher than the other two cities during the time of data collection. This was part of the reason that the illuminance level in Houston was higher than that in San Antonio.

Table 29. Illuminance by Nighttime on Segments without Lighting (Houston).

Direction	Lane	Average Horizontal Illuminance (lux) by Time of Night			Percent Change		
		~12:30 AM	~1:45 AM	~3:00 AM	12:30 AM - 1:45 AM	1:45 AM - 3:00 AM	12:30 AM - 3:00 AM
1-1*	Outside	2.31	1.10	1.10	−52%	0%	−52%
	Inside	1.37	1.28	1.14	−7%	−11%	−17%
1-2*	Outside	0.49	0.44	0.35	−10%	−20%	−29%
	Inside	0.59	0.44	0.40	−25%	−9%	−32%
2	Inside	0.48	0.56	0.45	**17%**	−20%	−6%
	Outside	0.47	0.35	0.40	−26%	**14%**	−15%

* Two different segments in direction 1 are shown here

Impact of Commercial Lighting

The presence of commercial lighting did increase the illuminance level at some of the tested sites, and the extent of increase depended on roadway geometry and the location of the commercial lighting. For example, the roadway segments in Austin had fewer lanes, and commercial light sources located close to roadways, whereas the segments in Houston were wide and elevated higher than the adjacent land use where commercial light sources were located far away from the roadway. Therefore, commercial lighting had a higher impact on the Austin segments than on the Houston segments.

The research team compared in detail segments with and without commercial lighting when other conditions (roadway lighting, roadway geometry, etc.) were considered similar. The two sets of segments in San Antonio without roadway lighting and with median mounted double davit roadway lighting were selected for the comparison. Table 30 and Table 31 show the results. Overall, roadway segments with commercial lighting had higher illuminance compared to those without commercial lighting, no matter whether roadway lighting was present. For segments without roadway lighting, the presence of commercial lighting could result in horizontal illuminance that was over two times more than that without any lighting. For segments with median mounted double davit lighting, the difference in horizontal illuminance could be as high as 64 percent. On both sets of roadway segments, higher differences in horizontal illuminance were associated with outside lanes rather than inside lanes.

Table 30. Horizontal Illuminance on Segments without Roadway Lighting (San Antonio).

Direction	**1**				**2**			
Lane Position	**Outside**		**Inside**		**Inside**		**Outside**	
Commercial Lighting	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
Absolute Maximum (lux)	0.22	0.50	0.35	0.84	0.35	0.63	0.32	0.84
Absolute Minimum (lux)	0.04	0.15	0.00	0.00	0.00	0.04	0.00	0.00
Average (lux)	0.13	0.30	0.13	0.28	0.12	0.29	0.10	0.28
Difference in Average Illuminance (lux)	**0.17**		**0.15**		**0.17**		**0.18**	

Table 31. Horizontal Illuminance on Segments with Median Lighting (San Antonio).

Direction	**1**				**2**			
Lane Position	**Outside**		**Inside**		**Inside**		**Outside**	
Commercial Lighting	No	Yes	No	Yes	No	Yes	No	Yes
Absolute Maximum (lux)	12.96	20.96	27.63	34.74	52.68	34.21	19.94	20.50
Absolute Minimum (lux)	0.45	0.60	0.57	0.88	0.68	1.42	0.91	1.37
Average Maximum (lux)	8.35	15.14	15.87	24.18	20.60	22.61	10.23	16.19
Average Minimum (lux)	1.47	1.66	1.68	1.62	1.85	1.83	1.89	1.97
Average (lux)	4.77	7.80	8.71	11.51	10.28	11.28	5.52	8.15
Difference in Average Illuminance (lux)	**3.03**		**2.80**		**1.00**		**2.63**	

Comparison with the AASHTO Recommendation

The illuminance data collected for roadway segments with roadway lighting and/or commercial lighting were combined together and compared to the guidance provided in the AASHTO 2005 lighting guide (*16*). According to the AASHTO guide, the minimum allowed illuminance is 2 lux, and the uniformity ratio should be between 3:1 and 4:1. The average maintained illuminance should be between 6 to 12 lux and 6 to 8 lux, depending on the general land use (refer to Table 3). The segments with commercial lighting were categorized as commercial, and their illuminance measurements were compared to the average maintained illuminance of 6 to 12 lux. The segments without commercial lighting were considered residential and compared to 6 to 8 lux for average maintained illuminance.

The results from the field illuminance measurement are listed in Table 32. The research team found that the average maintained illuminance values are within expected values for all but one site, and at that location they were above the requirements. The greatest discrepancies were with the uniformity ratio, which resulted from the majority of the minimum illuminance values that were below the minimum of 2 lux.

Table 32. Comparison between Measured and Recommended Horizontal Illuminance.

Location	Commercial Lighting	Description	Illuminance (lux)		Uniformity Ratio
			Average	Minimum	
Austin	No	High mast, outside shoulder, one side only	12.56*	4.13	3.04
Austin	Yes	Median mounted double davit	7.36	0.81*	9.07*
Austin	Yes	Outside shoulder single davit mounted	8.81	1.56*	5.65*
Houston	No	High mast, outside shoulder, alternating	5.99	0.56*	10.65*
Houston	Yes	High mast, outside shoulder, alternating	5.91	1.12*	5.29*
San Antonio	No	Median mounted double davit	7.17	0.45*	16.05*
San Antonio	Yes	Median mounted double davit	9.59	0.60*	16.04*

*Indicates that this value exceeds the recommended values reported in the *AASHTO Roadway Lighting Design Guide*. As the values are reported in whole numbers for the average and minimum illuminance values, the values were rounded up prior to deciding whether the value met the criteria. This is why average illuminance values for Houston are considered within the recommended criteria.

One other point worth discussing is the amount of light that is reduced as the light enters the front windshield of the vehicle. It was recorded that the windshield of the study vehicle decreased the quantity of incoming light to the driver by more than 50 percent.

BENEFIT AND COST ANALYSIS

Development of lighting curfew guidelines needs to consider many factors. Turning off lights during part of the night hours may cause changes in crash occurrence and severity, electricity and maintenance costs, local crime rates, light pollution, plus other societal effects. Among these factors, the research team quantified the potential electricity savings and costs of increase in crashes for lighting curfews and conducted a benefit/cost analysis for lighting curfews on 6-lane lit freeways. However, the research team was unable at this time to quantify the potential benefit of environmental improvement or the potential cost of increased local crimes due to the limited research scope.

Electricity Savings

Electricity savings may vary depending upon the types of lighting fixtures turned off because of different bulbs and pole spacing. The estimation of electricity savings used the following equation:

$$ES = r \times P \times N \times h$$

Where ES is the electricity savings (\$/mi/yr-hr), r is the electricity cost rate, P is the total power output of per lighting fixture (kilowatt), N is the total number of lighting fixtures per mile, and h is the total number of hours for the lighting curfew per year.

According to TxDOT's monthly electric rate for roadway lighting, the average electricity cost rate was $0.125 per kilowatt hour. TxDOT's *Highway Illumination Manual* specified that the high mast lighting should have one assembly at a specific site for both directions of travel, and each assembly should contain 12 400-watt HPS bulbs. The typical spacing between high mast light poles was observed to be about 1000 ft. Conventional lighting could use either one 400-watt HPS bulb per light head at 250-ft spacing or one 250-watt HPS bulb per light head at 180-ft spacing at a specific site for one direction of travel. As such, Table 33 lists the results of electricity savings by lighting fixtures and curfew days of week. The per-hour lighting curfews on weekday nights could result in electricity savings ranging from $479 to $827 per mile per year.

Table 33. Electricity Savings by Lighting Fixtures and Days of Week.

Day of Week	High Mast Lighting	Conventional Lighting 400-watt Bulb	Conventional Lighting 250-watt Bulb
Sun–Sat	$1157/mi/yr-hr	$771/mi/yr-hr	$670/mi/yr-hr
Sun–Thu	$827/mi/yr-hr	$552/mi/yr-hr	$479/mi/yr-hr
Fri–Sat	$329/mi/yr-hr	$220/mi/yr-hr	$191/mi/yr-hr

Crash Costs

According to TxDOT (2008–2010) crash data, crash cost estimates used $1,200,000 per fatal (K) or incapacitating (A) crash and $82,000 per non-incapacitating injury (B) or possible injury (C) crash. Table 34 shows the percent of nighttime crashes by severity during the four hours from 1:00 AM to 5:00 AM. The percent of severe (K+A) crashes under the 100-vphpl maximum volume was much lower than other volume levels.

Table 34. Percent of KABC Crashes at 6-Lane Lit Sites between 1:00 AM and 5:00 AM.

Days of Week	Crash Severity*	Maximum Hourly Volume (vphpln)			
		100	200	300	400
Sun-Sat	K+A	8.20%	20.60%	19.30%	19.30%
	B+C	91.80%	79.40%	80.70%	80.70%
Sun-Thu	K+A	15.80%	20.80%	20.80%	20.80%
	B+C	84.20%	79.20%	79.20%	79.20%
Fri-Sat	K+A	0.00%	20.40%	18.00%	18.00%
	B+C	100.00%	79.60%	82.00%	82.00%

*K: fatal; A: incapacitating; B: non-incapacitating injury; and C: possible injury

Assuming that lighting curfews could increase nighttime crashes by 10 percent to 40 percent (*2*), the research team estimated the increase in crash frequency and crash cost during the four hours from 1:00 AM to 5:00 AM. Table 35 shows the results. The estimated crash costs of lighting curfews ranged from $776 to $7,297 per year if turning off lights for one hour between 1:00 AM and 5:00 AM on weekday nights.

Table 35. Estimated Increase in Crash Frequency and Crash Costs.

Days of Week	Percent Increase	Estimated Increase in Crash Frequency (Crashes/mi/yr-hr)				Estimated Increase in Crash Cost (($/mi/yr-hr)			
		100 vphpl	200 vphpl	300 vphpl	400 vphpl	100 vphpl	200 vphpl	300 vphpl	400 vphpl
Sun–Sat	10%	0.0058	0.00117	0.0125	0.0125	1,007	3,654	3,722	3,722
	20%	0.0116	0.0234	0.0250	0.0250	2,015	7,308	7,444	7,444
	30%	0.0174	0.0351	0.0375	0.0375	3,022	10,962	11,167	11,167
	40%	0.0232	0.0468	0.0500	0.0500	4,029	14,616	14,889	14,889
Sun–Thu	10%	0.0030	0.0058	0.0058	0.0058	776	1,824	1,824	1,824
	20%	0.0060	0.0116	0.0116	0.0116	1,552	3,649	3,649	3,649
	30%	0.0090	0.0174	0.0174	0.0174	2,328	5,473	5,473	5,473
	40%	0.0120	0.0232	0.0232	0.0232	3,104	7,297	7,297	7,297
Fri–Sat*	10%	0.0056	0.0059	0.0067	0.0067	459	1,829	1,898	1,898
	20%	0.0112	0.0118	0.0134	0.0134	918	3,659	3,795	3,795
	30%	0.0168	0.0177	0.0201	0.0201	1,378	5,488	5,693	5,693
	40%	0.0224	0.0236	0.0268	0.0268	1,837	7,318	7,591	7,591

* On weekend nights, the screened sites of 100-vphpl maximum volume are only available for the two hours from 3:00 AM to 5:00 AM

Comparing the crash cost and the electricity savings, turning off high mast lighting may have slightly higher electricity savings than crash costs. Table 36 shows the benefit/cost ratio and the difference between benefit and cost for turning off high mast lighting. If lighting curfews were implemented on weekday nights on lit sites with high mast lighting, slight net benefits would be expected. These extra savings could be achieved when the estimated increase in crashes was 10 percent or less, and when the freeway sites had a maximum volume of 100 vphpl.

Table 36. Benefit/Cost Analysis of Turning off High Mast Lighting.

Days of Week	Percent Increase	Estimated Benefit-to-Cost Ratio (per vphpl)				Difference between Benefit and Cost (($/mi/yr-hr)			
		100	200	300	400	100 vphpl	200 vphpl	300 vphpl	400 vphpl
Sun–Sat	10%	<u>1.149</u>	0.317	0.311	0.311	<u>150</u>	−2,497	−2,565	−2,565
	20%	0.574	0.158	0.155	0.155	−858	−6,151	−6,287	−6,287
	30%	0.383	0.106	0.104	0.104	−1,865	−9,805	−10,010	−10,010
	40%	0.287	0.079	0.078	0.078	−2,872	−13,459	−13,732	−13,732
Sun–Thu	10%	<u>1.066</u>	0.453	0.453	0.453	<u>51</u>	−997	−997	−997
	20%	0.533	0.227	0.227	0.227	−725	−2,822	−2,822	−2,822
	30%	0.355	0.151	0.151	0.151	−1,501	−4,646	−4,646	−4,646
	40%	0.266	0.113	0.113	0.113	−2,277	−6,470	−6,470	−6,470
Fri–Sat	10%	0.716	0.180	0.173	0.173	−130	−1,500	−1,569	−1,569
	20%	0.358	0.090	0.087	0.087	−589	−3,330	−3,466	−3,466
	30%	0.239	0.060	0.058	0.058	−1,049	−5,159	−5,364	−5,364
	40%	0.179	0.045	0.043	0.043	−1,508	−6,989	−7,262	−7,262

CHAPTER 4:
RESEARCH FINDINGS

Using the results from each research activity, the researchers developed a list of findings that are described by activity in this chapter.

FINDINGS FROM THE LITERATURE REVIEW

- Most lighting guidelines use ADT as the traffic volume threshold for warranting continuous lighting. A few guidelines use hourly traffic volume as one of the warrants criteria, which range from 1500 to 2000 vphpl.
- Proper roadway lighting is generally found to be beneficial for highway safety, but to what extent continuous lighting benefits freeway safety is inconclusive based on past research results.
- Installing roadway lighting could increase the number of older drivers and driving speed at night, but drivers tend to have better concentration on unlit roadways.
- Most lighting curfew practices in the US involve simply turning off the lights when traffic demand decreases to certain levels, whereas some European countries have been changing lighting levels to adapt to different traffic demands.
- Among the few states in the US having lighting curfew practices, their suggested hourly volume thresholds range from 500 to 600 vph. The hourly volume threshold suggested by European (mainly the Netherlands) lighting curfew practices is 800 vphpl to lower the lighting level.

FINDINGS FROM THE SAFETY ANALYSIS FOR ROADWAY LIGHTING

Based on the exploratory analysis and the threshold analysis of crashes and roadway and roadway lighting, lighting curfews could be feasible for sites having maximum hourly volume of 100 vphpl between 1:00 AM and 5:00 AM on weekday nights. Detailed supports of the conclusion are as follows:

- Weekday nights had lower K factors (hourly volume as the percent of AADT), than weekend nights. During the hours from 1:00 AM to 5:00 AM, the K factors on weekdays or average day of week were lower than 1 percent.

- On lit freeways, weekday nights had lower hourly crash frequency and crash rate than weekend nights. Nighttime hourly crash frequency and crash rate peaked at the hour of 2:00 AM to 3:00 AM. The trend was found in both disaggregated and aggregated data analysis.
- When controlling for similar geometric characteristics, the crash ratio of lit to unlit sites was below 1.0 for most nighttime hours and maximum volume values, which indicated that lit sites had fewer crashes than unlit sites. However, the crash ratio of lit and unlit sites was not constant throughout the nighttime hours, which indicated that estimates for lighting effectiveness in the literature using AADT were not appropriate to estimate increase in hourly crashes. Further analysis for a proper estimate is needed.
- Lit sites having a maximum hourly volume of 100 vphpl had lower crash frequency and crash rate on average day of week than other maximum hourly volume levels. The percent of severe crashes (fatal and incapacitating crashes) was also much lower when hourly volume was below 100 vphpl than other maximum volume levels.
- The estimated crash costs of lighting curfews ranged from $776/mi/yr-hr to $7,297/mi/yr-hr per year if turning off lights for one hour between 1:00 AM and 5:00 AM on weekday nights. The corresponding electricity savings was $827/mi/yr-hr if turning off high mast lighting. A net benefit could be achieved with an estimate for crash increase less than 10 percent if high mast lighting were turned off.

Note that the above results were based on the comparison of crashes on screened 6-lane sites (with ramp density between 3.0 and 3.5 ramps per mile, average shoulder width between 10 and 12 ft, and median width between 20 and 30 ft). The 100 vphpl maximum volume level was suggested as a threshold of lighting curfews for further field experiments. Table 37 lists the screened 6-lane sites with hourly volume no more than 100 vphpl at night for the field experiment. Note that the site screening process was based on history traffic dataset (from year 2003 to year 2008) and did not restrict other geometric characteristics, time of day, or day of week. So the screened sites had hourly volume less than 100 vphpl only for part night hours on some days of week. Further determination of site selection for field experiment should rely on careful field observation for geometric characteristics and up-to-date traffic count.

Table 37. 6-Lane Sites with Hourly Volume ≤ 100 vphpl during Some Part of Night.

District and Location	Freeway Name	Approximate Beginning Point	Approximate End Point
Austin	IH 35	Center Point Rd	S. IH 35 Turnaround Access
	IH 35	Parmer Ln	SH 45
	IH 35	SH 45	1.4 miles South of SH 130
	Loop 1	SH 360	W. Parmer Ln
	US 183	West of IH 35	East of Loop 1
	US 183	West of SH 360	West County line
Dallas	US 175	West of IH 20	1.7 miles West of SH 12
	US 175	East of SH 130	W. 2^{nd} Ave
Houston	SH 249	Northwest of Beltway 8	Cypresswood Dr
	SH 288	South of IH 610	North of Sam Houston Tollway

Note: Site screening is based on the historical traffic dataset (from year 2003 to year 2008) and does not restrict other geometric characteristics, time of day, or day of week.

FINDINGS FROM THE VISIBILITY STUDY

Based on the field visibility measurement and evaluation, the research team found that different roadway lighting configurations yielded different luminance or illuminance levels; headlights and commercial lighting could greatly affect roadway visibility under certain conditions; the average illuminance levels on most evaluated roadway segments met the requirements of the AASHTO 2005 lighting guide; and illuminance levels on unlit roadways without commercial lighting generally decreased.

Luminance Measurement

- Headlights could have great impact on roadway visibility, but the impact decreases sharply within a short distance from the headlights. Specific findings include:
  - When no overhead lighting was present, LVT luminance levels decreased as the distance from the headlights increased.
  - When overhead lighting was present, direct measurement showed that headlights increased the luminance levels.
  - When overhead lighting was present, corrected measurement indicates that LVT luminance levels generally decreased as the distance from the headlights increased, and the decrease was more apparent when the distance was greater than 450 ft.

- When high mast lighting was present, the contribution of headlights to luminance decreased sharply from about 70 percent at the luminaire (120 ft from the headlights) to about 10 percent at about 350 ft from the headlights.

- When high mast lighting was present with headlights off, the majority of the estimated LVT contrast ratios were above 1.0 with the lowest ratios for white versus gray and near the light sources.

Illuminance Measurement

- When roadway lighting but no commercial lighting was present, the measured illuminance decreased as the sensor moved away from the light source. Specific findings include:
    - Where one-side mounted or alternate-side mounted high mast lighting was provided, illuminance at the outside lane was higher than at the inside lane because of the near distance from the light sources.
    - Roadway segments with one-side mounted high mast lighting had higher illuminance values than that with alternating high mast lighting, because the one-side-only high mast lighting had lower luminaire height and closer pole spacing than alternating high mast lighting.
    - Where median mounted double davit lighting was installed, illuminance values for outside lanes were lower than inside lanes.
    - Median mounted double davit lighting had illuminance values of inside lanes that were higher than the alternating high mast lighting but lower than the one-side high mast lighting for the outside lane illuminance values.
- When both roadway lighting and commercial lighting were present, illuminance levels depended on the configuration of roadway lighting, the location of commercial lighting, the roadway geometry, etc.
    - Segments with median mounted conventional lighting had higher illuminance values on the inside lanes than outside lanes even when commercial lighting was present outside of the roadway.

- Where house-side mounted single davit lighting was present along with commercial lighting on the same side of the roadway, the maximum illuminance level on the outside lanes was much higher than on the inside lanes.
- In combination with the commercial lighting, the house-side mounted conventional lighting had the highest illuminance levels followed by median mounted lighting, and alternating high mast lighting had the lowest illuminance levels, for lanes closest to the roadway luminaires.

- Presence of commercial lighting could increase illuminance values on both inside and outside lanes, especially for roadway segments without roadway lighting.
- Overall, field illuminance levels generally decreased as nighttime progressed for roadway segments without roadway lighting or commercial lighting.
    - For the sites in San Antonio, the greatest reduction in lighting levels was 20 percent for the outside lane of the leaving town direction from midnight to 4:00 AM, and the coming into town direction had a lower amount of lighting reduction.
    - From the illuminance measurement in Houston, the amount of reduction in lighting levels differed by roadway segments in the same direction, by different travel directions, and by different nighttime periods.
- Comparing the field illuminance measurement with the AASHTO 2005 lighting guide:
    - Average maintained illuminance values met the AASHTO recommendation, but one site in Austin where one-side mounted high mast lighting was present without commercial lighting had a value higher than the AASHTO recommendation.
    - Most measured sites had minimum illuminance levels lower than the recommended minimum level of 2 lux.
    - Resulting from the low minimum illuminance, all but one site had measured uniformity ratios above 4:1 and ranged from 5.29:1 to 16.05:1, while the recommended ratio should be between 3:1 and 4:1.
- A vehicle's windshield can significantly reduce the amount of lighting entering the vehicle compartment. In the visibility study, the windshield reduced the amount of lighting coming to the driver by more than 50 percent.

FINDINGS FROM THE BENEFIT/COST ANALYSIS

The following items summarize the findings from the benefit and cost analysis:

- The potential benefits of lighting curfews include the electricity savings and reduced light pollution, and the potential costs of lighting curfews involve the increased crash costs and increased local crime rates. The research team was able to quantify the potential electricity savings and crash costs, while other benefits or costs were difficult to quantify because of the limited scope of the research project.
- The estimated crash costs of lighting curfews ranged from $776/mi/yr-hr to $7,297/mi/yr-hr for turning off lights for one hour between 1:00 AM and 5:00 AM on weekday nights. The corresponding electricity savings was $827/mi/yr-hr if turning off high mast lighting. Assuming crash increases no more than 10 percent, a net benefit could be achieved if high mast lighting were turned off.

CHAPTER 5:
PRELIMINARY GUIDELINES

Based on the research activities conducted as part of this research project and the findings described in the previous chapter, the research team recommends the following preliminary guidelines for implementing freeway lighting curfews on an experimental basis:

- A lighting curfew is defined as the turning off of road lighting during specific hours of the nighttime period.
- For purposes of these guidelines, the nighttime period is defined as the time between 6:00 PM and 6:00 AM. The day of the week is that associated with the day for the 6:00 PM hour. For example, 9:00 PM on Friday is part of Friday night and four hours later (2:00 AM) would also be considered Friday night.
- These preliminary guidelines apply only to continuous roadway lighting on freeways.
- A lighting curfew should not be implemented on Friday or Saturday nights.
- A lighting curfew should be considered for a segment of roadway when the traffic volume on the freeway averages 100 vphpl or less during each hour that the lighting curfew is implemented.
- For roadway segments meeting these criteria, the lighting curfew may be implemented between the hours of 2:00 AM and 5:00 AM.
- The following types of lighting should not be turned off during a lighting curfew:
    - Lighting that was installed on the basis of a safety study. This type of lighting also includes continuous lighting that was classified as safety lighting.
    - Interchange and ramp lighting.
    - Lighting at locations that present a major change in roadway geometry. Examples of major changes in roadway geometry include:
        - A lane reduction or addition.
        - A change in horizontal or vertical alignment that requires the posting of an advisory speed.
    - Lighting at locations where adjacent light sources may cause glare issues for the main lane traffic if a light curfew were implemented. Examples of such adjacent light sources include:
        - Commercial lighting that produces high illuminance levels on the main lane.

- Roadway lighting installed on adjacent roadways or cross streets.
- Headlights of vehicles traveling on adjacent or crossing roadways where nighttime traffic volumes are high.

- Lighting curfews should not be implemented during periods that exhibit the following conditions:
  - Special events in the vicinity of the roadway segment that increase traffic volumes during the normal time of the lighting curfew.
  - Periods where local or regional evacuations travel in the vicinity of the roadway segment.
  - Periods of unusual inclement weather that can be predicted in advance. Examples include above normal snowfall, extended periods of rainfall that result in flooding, and dense fog.

The occurrence of roadway crashes should be monitored during the experimental process. A lighting curfew should be canceled if there is a pattern of crashes occurring during the lighting curfew period. Crashes should also be monitored for the hours before and after the lighting curfew period so that consideration can be given to extending the curfew period based on the absence of crashes.

BASIS OF PRELIMINARY GUIDELINES

The guidelines presented in the preceding section were developed on the basis of several different factors as described below:

- Guidelines related to the traffic volume, day of week, and time of day are based on the results of the safety analysis described in Chapter 3. The safety analysis described in that chapter compared the cost of crashes to the electrical savings obtained by turning off lighting. Traffic data used in the safety analysis were not sufficient to provide driver characteristics analysis for different hours of the night. The research team cautions that a lighting curfew should not be implemented for hours when the percentage of unfamiliar drivers is high.
- The exclusions associated with the lighting curfew guidelines were developed on the basis of engineering judgment. Specific details related to the exclusions include:

- **Exclusion related to safety lighting:** Safety lighting is installed to address a specific issue that occurs during the nighttime period. The decision to install such lighting is typically based on a safety study. The research team felt that it would be contradictory to turn off this type of roadway lighting at any time of the night.
- **Exclusion related to interchanges and ramps:** These locations present some of the higher demand tasks required of freeway drivers. It is the research team's opinion that lighting should be provided in these areas to assist drivers in these higher demand locations.
- **Exclusions related to major changes in roadway geometry:** The crash data used in the safety analysis was not sufficiently detailed to provide the ability to analyze the safety impacts of geometric changes, specifically identifying the impacts of various severities of geometric changes. It is the research team's opinion that in the absence of safety data, the conservative approach is to retain roadway lighting at these locations.
- **Exclusions related to glare issues:** The visibility evaluation described in Chapter 3 found that commercial lighting and headlights could have a great impact on the main lane illuminance or luminance levels, especially when roadway lighting is not present. Although lighting data used in the visibility assessment were not sufficient to provide detailed curfew criteria for avoiding a glare effect, it is the research team's opinion that caution should be made when adjacent light sources may potentially cause glare problems because of a lighting curfew.
- **Exclusions related to unusual events:** The research team recognizes that there may be situations at individual roadway segments that experience unusual conditions due to a variety of factors. When such unusual conditions exist, the traffic volumes may increase or there may be a larger proportion of unfamiliar drivers than usual. The research team feels that the conservative approach is to retain roadway lighting under these conditions. Weather presents a particularly significant challenge for implementing a lighting curfew on an experimental basis. Conditions of heavy rainfall or fog may benefit from the presence of

roadway lighting, but it may be difficult to turn on roadway lighting during a curfew period if such weather occurs unexpectedly.

In developing the guidelines for the field experiment, the research team considered two distinct aspects of the lighting curfew issue: when to turn the lights off and when to turn them back on, if at all. The results of the safety analysis indicated that the crash rate per hour per lane became consistent with non-lit roadway segments about 2:00 AM. The research team does not recommend beginning a lighting curfew before this time without analysis of the safety impacts during the preceding hours. This period of time where the crash rate per hour per lane of lit segments was similar to that of unlit segments ends after 5:00 AM. The sunrise time in Austin, Texas, varies from an earliest of 6:20 AM in late March to 7:43 AM in late October. Texas law requires that vehicle headlights be used until one-half hour before sunrise, meaning that there is sufficient light for driving without assistance from roadway lighting or vehicle headlights to a period that ranges between 5:50 AM and 7:15 AM as shown in Figure 20. This would mean that there is a period of 50 minutes to 2.25 hours during which roadway may be needed. The research team recommends that the lighting be turned back on at 5:00 AM. Although there is a concern that turning HPS lighting back on for short periods of time may decrease the overall life of the HPS lamps, the growth in LEDs for roadway lighting should lessen the impacts of this concern as LED lighting becomes more prevalent.

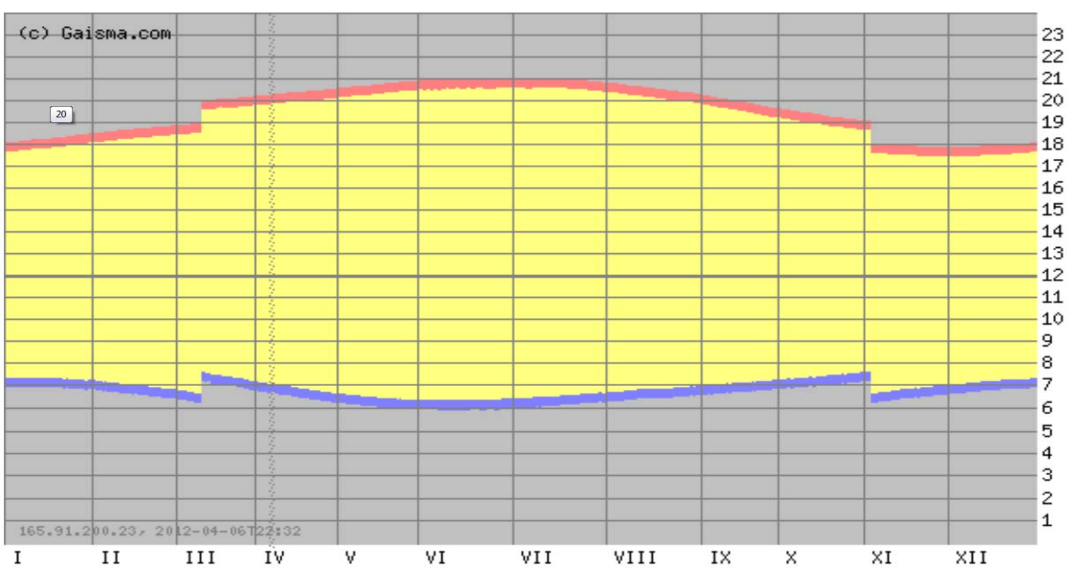


Figure 20. Sunrise/Sunset Times for Austin, Texas.

CHAPTER 6:
SUMMARY AND CONCLUSIONS

This project conducted numerous research activities in an effort to evaluate the impacts of turning off roadway lighting during selected hours of the late night and/or early morning period. The primary research efforts focused upon a safety analysis of crash records on freeways with various geometric and lighting characteristics during various hours of periods of darkness. Other research activities included a detailed review of the current practice and previous research efforts, evaluations of lighting conditions at selected sites on Texas freeways, and a benefit/cost assessment of the energy savings that could be realized by turning off the lighting.

The research effort resulted in a series of preliminary guidelines that serve as a starting point for implementing lighting curfews on Texas freeways. The key element of these guidelines is that a lighting curfew appears feasible when the traffic volume during the hours of the curfew is 100 vphpl or less. There are numerous constraints associated with implementing a lighting curfew, such as lighting that was installed as safety lighting or as the result of a safety study should not be included in a lighting curfew.

It was the original intent of this research to conduct a field study of the preliminary guidelines but this effort was not completed for a variety of reasons. One of the challenges of the field experiment was that the experimental site under consideration was wired in a manner that prohibited turning off main lane lighting but leaving the frontage road and interchange lighting on. This challenge is likely to exist at many other locations that would otherwise qualify for a lighting curfew and may limit the ability to implement a lighting curfew.

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