Evaluation of the Safety Performance of Continuous Mainline Roadway Lighting on Freeway Segments in Washington State

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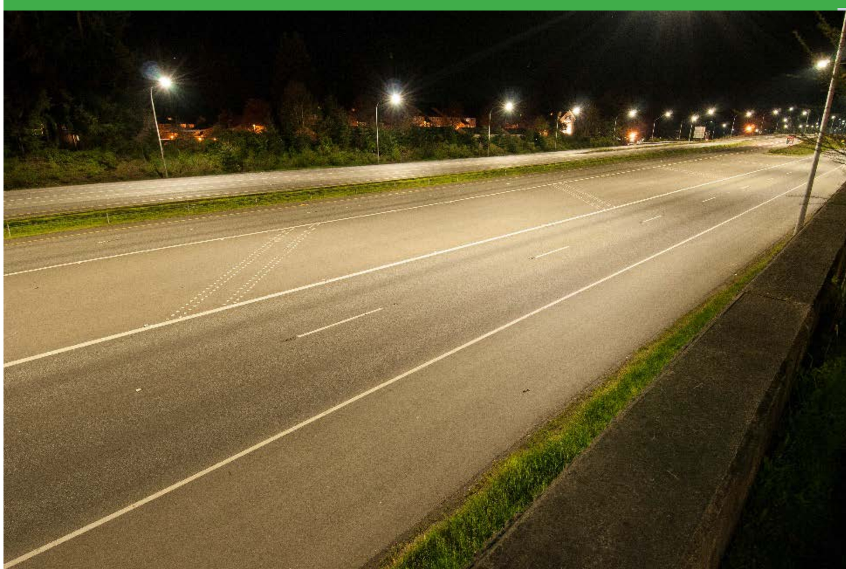

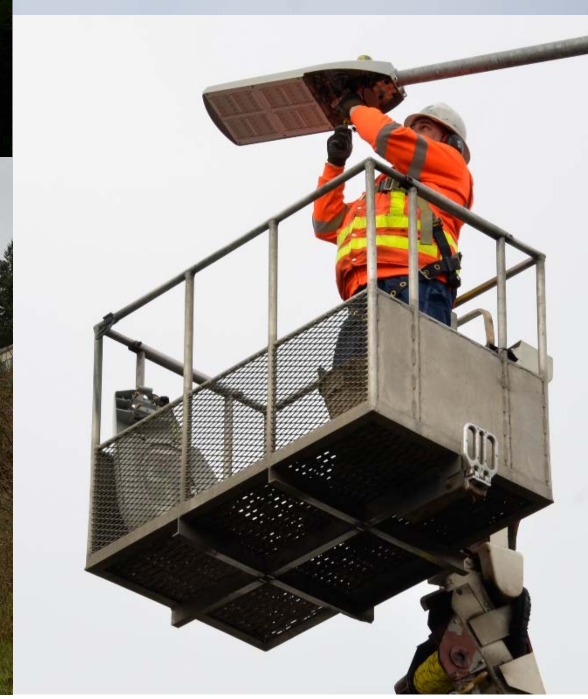

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WSDOT Research Report

Research Report
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EVALUATION OF THE SAFETY PERFORMANCE OF CONTINUOUS MAINLINE ROADWAY LIGHTING ON FREEWAY SEGMENTS IN WASHINGTON STATE

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16. ABSTRACT

Washington State Department of Transportation (WSDOT) evaluated continuous roadway lighting on mainline freeway segments in Washington State. An extensive literature review on the safety performance of roadway lighting was completed. As part of this research effort WSDOT developed multivariate random parameter (RP) models with specific lighting variables for continuous lighting on mainline freeway segments. Roadway lighting is often used as a countermeasure to address nighttime crashes and this research evaluates common assumption related to roadway lighting. The models developed for this research use crashes from the end of civil dusk twilight to the start of civil dawn twilight since lighting systems are of limited value outside these timeframes. Natural light conditions were estimated for crashes based on location and time of the crash event. Based on the RP results, the research team concludes that the contribution of continuous illumination to nighttime crash reduction is negligible. In addition to the findings on safety performance, a pilot LED project on US101 demonstrated that LED roadway lighting can significantly increase energy efficiency and environmental stewardship (e.g., reducing greenhouse gas emissions) while maintaining safety performance outcomes. The research team recommended modification to WSDOT design policy, including removal of the requirement of continuous mainline lighting and reduction of lighting where segment specific analysis indicates appropriate.

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EXHIBITS

LIST OF ACRONYMS

AID	FHWA Accelerated Innovation Deployment Demonstration
FHWA	Federal Highway Administration
HPS	High Pressure Sodium
HQ	Headquarters
HSM	AASHTO Highway Safety Manual
LED	Light Emitting Diode
LED	light-emitting diode
NOAA	National Oceanic and Atmospheric Administration
USNO	United States Naval Observatory
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This report provides an overview of recent research on WSDOT illumination reform activities. An extensive literature review of 300 research reports regarding roadway lighting and its impact on safety performance was previously completed. This document presents the development and findings from models using random parameter methods on continuous lighting design for mainline freeway segments, and concludes with a discussion regarding the implementation of the department's illumination reform from January 2013 through October 2015.

Roadway lighting is installed with the goal of nighttime crash reduction. Illumination reform at WSDOT is motivated by desire to optimize tradeoff decisions made during the design and operations of state highways. The ability to assess these tradeoffs has occurred as the science of highway safety has evolved rapidly in recent years, and these quantitative methods allow advances in understanding. The evolution of science based methods and recent findings by several researchers (Milton, Shankar and Mannering 2008, Bullough, Donnell and Rea 2012; Donnel, Porter and Shankar 2010; Gross and Donnell 2011; and Bullough, Donnell and Rea 2013) that all indicated a potential for new and enhanced understanding of the safety performance of continuous lighting and subsequently additional efficiency in its asset management and reduced environmental impacts. The 13% growth in illumination systems at WSDOT over 9 years is not sustainable **-** the annualized life cycle cost of this system is $13.5 million per year and with a current $5 million budget shortfall for annual replacement costs.

During the literature review the research team identified several deeply held beliefs about lighting. These deeply held beliefs have the potential to bias research methods, dataset development processes, and may affect professional acceptance about lighting impacts in relationship to nighttime crash reduction. The team critically evaluated and presents each of these beliefs for consideration:

- ***Belief 1: Roadway lighting reduces crashes during dawn and dusk (civil twilight)*** – crash reduction resulting from roadway lighting is unlikely during civil twilight because there is still limited target visibility at during civil twilight.
- ***Belief 2: All nighttime crashes can be 'fixed' with roadway lighting*** – only a subset of nighttime crashes may be 'correctable' with illumination since some twilight conditions are not impacted by the lighting systems.
- ***Belief 3: The ratio of daytime vs nighttime crash rates is a reliable and science-based method to estimate how many nighttime crashes to expect at a given location*** – the scientific basis for the rates and rate ratios are uncertain: it is likely that the rate ratios were appealing as a method to control for

site specific conditions when methods to incorporate site specific conditions into the analysis was not common.

- ***Belief 4: During congested conditions, adding roadway lighting reduces crashes*** – no scientific basis was found: advances in vehicle headlamp technology and the presence of large numbers of vehicles that provide lighting themselves may make nighttime congestion as a trigger for lighting a questionable approach. In addition, improvements in sign sheeting and lane marking materials have also occurred over the past few decades. It may also be that crash frequency (generally lower severity) increases during congested conditions and that these increases triggered recommendations for lighting in the past (it is important to note that nighttime congestion during the summer would be more likely to occur in daylight and that it is therefore unlikely that these crashes could be mitigated with lighting).
- ***Belief 5: Nighttime crash rate is a reliable and science-based method to identify locations for lighting*** – a crash rate is not a reliable method for identifying potential locations for lighting because it is based on the assumption that the relationship between crashes and traffic volumes are linear. Count models offer alternative methods to incorporate exposure into safety performance estimation.
- ***Belief 6: Only a few years of crash history are needed to identify locations where roadway lighting will reduce crashes*** – crashes are random, multivariate in nature and statistical methods are needed to account for natural variation of crashes over time while simultaneously accounting for other factors at the location that are likely to impact crash risk.
- ***Belief 7: Roadway lighting reduces crashes at the daytime (numerous studies included daytime crashes in the consideration of the benefits of lighting)*** – no scientific basis was found for the assumption that lighting would reduce crashes during daytime or during civil twilight. In fact, the presence of poles may increase crashes during higher volume daytime conditions.
- ***Belief 8: More uniform light is better –*** the scientific basis of this assumption is uncertain: work by Gibbons et al (2014) offers further insight on maximum uniformity levels.
- ***Belief 9: Roadway complexity is always a trigger for illumination*** – the scientific basis for this assumption is uncertain: roadway complexity may have daytime impacts as well (for which lighting will offer no mitigation) and the impact of lighting in complex roadway conditions given particular site conditions is still uncertain.

- ***Belief 10: The fixed object risk of roadway lighting is negligible*** – WSDOT determined that the cost of replacing lighting poles that are hit is large ($750,000 annually) and that the presence of poles creates crash risk.
- ***Belief 11: The impact of the roadway characteristics and conditions on safety performance*** – Elvik and Vaa (2004) assume that the roadway characteristics and conditions do not impact safety performance. Research for the first edition of the HSM indicates several characteristics of roadways that correlates with changes in safety performance and the relative impact of these characteristics differ across facility types (AASHTO 2010). When the safety performance of lighting is evaluated it is necessary therefore to control for the impact of roadway characteristics and conditions on safety performance.

Prior to the 1980s WSDOT eliminated lighting as part of a lighting reduction program and in the late 1990s continuous lighting was removed from parts of the interstate to reduce energy costs. WSDOT did not observe any adverse impacts on the safety performance of these facilities. From a modeling perspective the presence of these unlit segments are appealing because it creates variation in lighting conditions across similar location characteristics across the system. The research team used a mainline freeway segment dataset with crash data for 2010 through 2014 to estimate random parameter (RP) models with lighting variables such as median continuous, right side continuous, both side continuous, point lighting and no lighting values. It is important to note that the research did not cover point lighting locations but instead only evaluated the performance of continuous mainline illumination on limited access highways.

The approach by the research team to study continuous lighting on freeway segments differed from previous efforts that only used nighttime crashes as input. The models used multivariate random parameters models to allow segment by segment analysis.

Exhibit 1. Factors included in the random parameter models for continuous mainline lighting on freeways in Washington State

Geometry, volumes and urban/rural character	**Roadway lighting***
• Traffic volume • Number of lanes • Shoulder widths (left and right) • Horizontal curvature • Vertical curvature • Presence of interchange	• Median roadway lighting proportion • Right roadway lighting proportion • Both-side roadway lighting proportion • Point roadway lighting proportion • No roadway lighting proportion

* The lighting variables are measured as proportion by length values for interchange and non-interchange segments.

Most research prior to 2010 relied on nighttime-daytime crash rate ratios (including Elvik (1996) and Elvik and Vaa (2004)) to estimate the safety performance associated with roadway lighting. This approach was also used in work by Gibbons et al (2014) on adaptive lighting, Gibbons incorporated hourly estimated nighttime traffic volumes and controlled for daytime volumes to determine warrants for lighting based on crash rate ratios. Given that roadway lighting is used as a countermeasure to address nighttime crashes (measured from the end of civil dusk twilight to the start of civil dawn twilight), the research team decided to develop nighttime safety performance functions and only include nighttime crashes in the analysis. For the WSDOT project, staff focused on using advanced techniques to determine which crashes should be classified as nighttime crashes. National Oceanic and Atmospheric Administration (NOAA) developed an algorithm to calculate sunrise, sunset, and civil twilight times for any given location or a given date (NOAA 2015). The research team evaluated the differences between reported lighting conditions and the calculated lighting conditions, and concluded that a large number of crashes are generally misclassified as either dark conditions when it was clearly still daytime or daytime when it was clearly nighttime. The NOAA calculations provide a consistent manner in which crashes can be classified as nighttime crashes statewide on an ongoing basis.

The inclusion of daytime crashes into the evaluation of the safety performance of illumination is problematic. The reason that it is problematic is that the assumption is made that the conditions influencing the likelihood of a crash occurring, and the severity outcome given that a crash has occurred, are the same for either daytime or nighttime. Shin, Washington and Van Schalkwyk (2009) is one of many papers documenting differences in the distribution of single and multiple vehicle crashes between day and nighttime conditions. However, little is known about the differences in traffic, driver composition, passenger composition, and distribution of travel patterns over the course of a day and over a year and how these differences impact safety performance or severity outcomes.

Based on the random parameter modeling of continuous mainline lighting on freeways, the research team concludes that continuous illumination makes no measurable contribution to nighttime safety performance. Also, that the installation of continuous mainline lighting on freeways for safety performance is not warranted. Further, findings from the pilot LED project on US101 (Black Lake Blvd) indicate that LED roadway lighting can significantly increase energy efficiency, reduce greenhouse gas emissions and that the general public experienced the LED project as positive. Leading to the conclusion that illumination reform is a reasonable and practical way to improve the sustainability of the system while maintaining environmental stewardship.

The research team recommends that WSDOT discontinue installation of continuous mainline lighting on freeways as a required design element, and where appropriate consider illumination removal.

If funding is available and lighting reform remains a priority continue evaluation of illumination safety performance on the remainder of the highway system.

CHAPTER 1. INTRODUCTION

Purpose

This report summarizes the methodological approach and findings from a recent safety research effort undertaken by WSDOT. This report focuses on continuous lighting on the freeway system of Washington State. The detailed description of the dataset, modeling approach, and model outputs are covered in a journal article that is currently under development. This report also discusses completed, ongoing, and new activities in WSDOT's Illumination Reform.

Background to the Study

Agencies across the world have relied on roadway lighting as a safety countermeasure for many years. FHWA's 1996 Annual Report on Highway Safety Improvement Programs, lists illumination as the countermeasure with the highest safety benefit-cost ratio among other safety devices at 26.8 (shown in Exhibit 2) (FHWA 1996). Crash modification factors (CMFs) in the AASHTO Highway Safety Manual (2010) for roadway lighting are reportedly based on results from a meta-analysis by Elvik (1996) (referenced in Elvik and Vaa (2004) and described in Chapter 2). As scientific methods have advanced more recently researchers like Bullough, Donnell and Rea (2012), Donnel, Porter and Shankar (2010), Gross and Donnell (2011) and Bullough, Donnell and Rea (2013) have started questioning the magnitude of the likely impact of roadway lighting on safety performance.

HIGHWAY SAFETY IMPROVEMENTS WITH THE HIGHEST BENEFIT-COST RATIOS 1974-1995

Rank	Improvement Description	Benefit-Cost Ratio
1	Illumination	26.8
2	Upgrade Median Barrier	22.6
3	Traffic Signs	22.4
4	Relocated/Breakaway Utility Poles	17.7
5	Remove Obstacles	10.7
6	New Traffic Signals	8.5
7	Impact Attenuators	8
8	New Median Barrier	7.6
9	Upgrade Guardrail	7.5
10	Upgrade Traffic Signals	7.4
11	Upgrade Bridge Rail	6.9
12	Improve Sight Distance	6.1
13	Median for Traffic Separation	6.1
14	Groove Pavement for Skid	5.8
15	Improve Minor Stricture	5.3
16	Turning Lanes and Channelization	4.5
17	New RR Crossing Gates	3.4
18	New RR Crossing Flashing Lights	3.1
19	Pavement Markings and Delineation	3.1
20	New RR Crossing Lights & Gates	2.9

Exhibit 2. Highway Safety Improvements with the Highest Benefit-Cost Ratios (1974 – 1995), Source: 1996 Annual Report on Highway Safety Improvement Programs, FHWA-SA-96-040.

WSDOT recognized that with the evolution of science based methods the potential for new understanding in the area of lighting was significant. Further, WSDOT believed that the knowledge gained in the area of lighting could be used to create additional efficiency in its asset management program. This provides the motivation for this research effort.

WSDOT lighting assets

As of 2014, WSDOT had 3,100 lighting systems (Exhibit 3), with 400 of these installed since 2005. These systems include over 60,000 roadway lighting fixtures. The 60,000 fixtures include 48% cobra heads, 24% tunnel, 14% underdeck, 4% shoe boxes, 3% high mast, 3% pole tops and 2% sign lights (Source: SiMMS and WSDOT Roadside Features Inventory Program database).

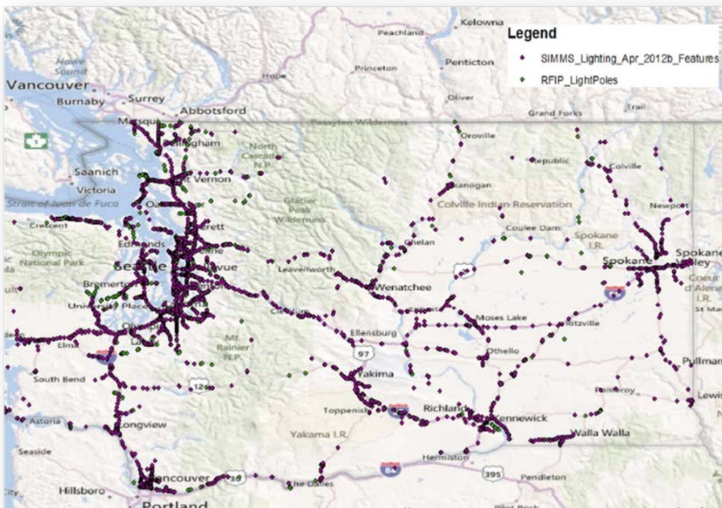

Exhibit 3. WSDOT Roadway Light Systems in 2014 (Source: SiMMS & WSDOT Roadside Features Inventory Program (RFIP) database)

An assessment of WSDOT expenditures in 2013 over a 13 year period showed that the annualized life cycle cost of the illumination systems owned by WSDOT is $13.5 million/year as shown in Exhibit 4. For the same time period, WSDOT has had a budget shortfall of $5 million for annual replacement costs of illumination. With current trends indicating rapid expansion of the lighting systems WSDOT owns, lighting assets are becoming an increasing concern.

Roadway lighting is presumed by many to offer safety performance benefits in most nighttime conditions and is also assumed to improve security of pedestrians. While these benefits are often found, not all locations benefit equally, and at some locations lighting may have an adverse effect. To effectively assess the benefits to cost tradeoffs against the environmental impact of lighting: carbon footprint, impacts on plant, animal and human life, and contribution to light pollution (night sky darkness) needs to be considered (Gibbons et al 2014). While more energy efficient fixtures can significantly reduce energy consumption, the capital costs of these fixtures are still high, requiring significant investment for conversion projects. Given the life cycle cost of roadway lighting and the associated environmental impact it is necessary for WSDOT to determine how to best use these assets to the benefit of the public.

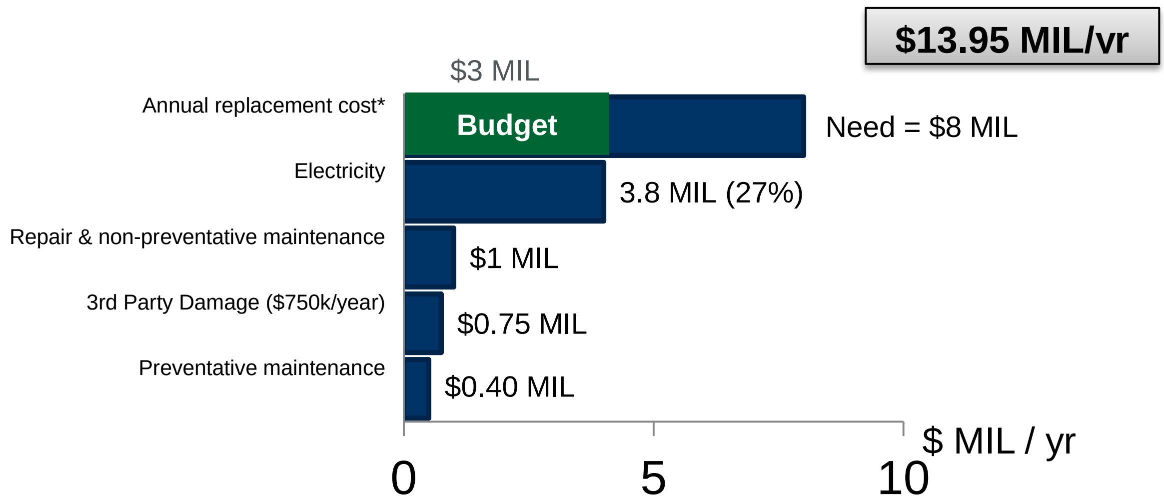

Exhibit 4. Annualized life cycle cost of the WSDOT illumination systems (2014)

WSDOT was the first state in the US to set a zero goal for traffic fatalities as outlined in its Target Zero Strategic Highway Safety Plan. In addition to Target Zero, WSDOT uses a practical solutions approach of least cost planning and practical design to developing solutions within its “Sustainable Safety” program. The combined effect of these efforts is that WSDOT approaches safety in a manner that prioritizes solutions by highest crash reduction benefit for the investments made. Safety, therefore, is a critical consideration when the department plans, designs, operates and maintains the roadway network. The Department has been quick to recognize that advances in the science of safety, as well as new statistical methods provide a unique opportunity to revisit the potential impact of roadway lighting on a segment by segment basis versus the past methods where all segments are treated the same. Using these new methods WSDOT is able to predict positive and negative correlation of lighting with crashes and estimate what the impact on safety performance would be based on location specific characteristics. This allows WSDOT to strategically invest in the system focusing on highest benefit locations while optimizing statewide benefits to our travelling public because excess lighting is not installed when benefits are limited.

Report Outline

Chapter 2 summarizes the findings from an extensive literature review of the safety performance of roadway lighting. Chapter 3 presents the motivation and findings from a predictive modeling effort on continuous lighting on mainline freeway segments. Chapter 4 briefly describes the activities of WSDOT staff as part of the department's illumination reform from January 2013 through October 2015. Chapter 5 presents conclusions and recommendations based on the findings from Chapters 2 and 3.

CHAPTER 2. LITERATURE REVIEW

Introduction

As part of the illumination research effort at WSDOT, the research team performed an extensive literature review. The review covered lighting based safety performance related research from 1948 through 2013 and an evaluation of the crash modification factors for lighting in the HSM (2010). The bibliography for the literature review is included as part of this report. This chapter provides a brief overview of the criteria applied for the evaluation of publications regarding the safety performance of roadway lighting and then discusses the basis for the lighting CMF used in the predictive method of the first edition of the Highway Safety Manual, and concludes by presenting findings from the literature review and evaluation.

Literature Evaluation

The literature review included over 300 papers and reports ranging from 1948 through 2015. This report includes the bibliography as Appendix A. The purpose of the literature review was to provide an understanding of the context, methods and relative value of the published research to WSDOT in terms of performance-based design and operations. Each publication was evaluated based on four components: experimental design, datasets, analysis method and usefulness for safety performance quantification. Exhibit 5 summarizes the evaluation criteria used for the review.

Exhibit 5. Evaluation criteria of literature

Component	**Questions**
Experimental design	• Site selection: were the sites similar in characteristics or different? What criteria were used? • Which crashes were included in the analysis? How were they identified?
Datasets	• Sample size: how many crashes were analyzed and what are the confidence levels for the results? • What site characteristics were collected and included in the analysis?
Analysis method	• Is the method science-based and valid for crash analysis? • Are the assumptions scientifically sound? • Does the method account for differences in roadway characteristics that we know have an impact on crash performance?
Usefulness for safety performance quantification	• Are the findings and assumptions from the research suitable to guide decision making regarding the safety performance of roadway lighting in specific conditions (given the context, traffic conditions, roadway characteristics, and crash history)?

Crash modification factors for lighting in the AASHTO Highway Safety Manual

Crash modification factors (CMFs) in the AASHTO Highway Safety Manual (2010) for roadway lighting are referenced as Elvik and Vaa (2004). After a thorough literature review WSDOT determined that the estimates are actually based on a table in the publication by Elvik and Vaa (2004) but from a study described in Elvik (1996).

The meta-analysis

Elvik's (1996) analysis included 37 studies; the focus of the meta-analysis was on adding lighting where the location was previously unlit. The studies were published between 1948 and 1989. In 81 percent of the cases the authors concluded that lighting improves safety performance and in 19 percent of the cases the authors found that "*safety has deteriorated*". Elvik research states that "*as far as statistical techniques for data analysis are concerned, most studies have relied on quite simple techniques, like estimating an odds ratio and testing it for statistical significance. More advanced multivariate analyses, in which the choice of statistical techniques is more important, are not found in this area*" (Elvik 1996). This comment is significant in that it indicates that there are significant opportunities for improvement of the CMF for performance based design and operations. Harkey et al (2008) reviewed Elvik's study and several other meta-analyses and rated the quality (level of predictive certainty) of intersection lighting CMFs as low and segment lighting CMFs as medium-low, confirming an opportunity for improvement.

Elvik (1996) concluded that the installation of roadway lighting reduces nighttime fatal crashes by 65%, nighttime injury crashes by 30%, and nighttime property damage only crashes by 15%. These percentages are slightly different when referenced in Elvik and Vaa (2004), as shown in Exhibit 6.

Exhibit 6. Effects of lighting on crashes (Source: Elvik and Vaa (2004), p.366, Table 1.18.1)

Accident severity	**Percentage change in the number of accidents**		
	Type of accident affected	**Best estimate**	**95% confidence interval**
Fatal accidents	Accidents in darkness	-64	(-74; -50)
Injury accidents	Accidents in darkness	-28	(-32;-25)
Property-damage-only accidents	Accidents in darkness	-17	(-21;-13)

An evaluation of the paper by Elvik (1996) raises several key questions: the validity of assumptions made in meta-analysis, likelihood of publication bias, and the impact of the roadway environment on roadway lighting safety performance.

i) Assumptions made in meta-analysis

Elvik recognizes in his 1996 paper that "*the safety effect of public lighting is likely to vary substantially from one case to another, depending, inter alia, on luminance levels, traffic environment and predominant type of accident at the location*". And yet, he assumes by using the meta-analysis method that the study results 'belong to a distribution having a well-defined mean value that should be reasonably well supported' (Elvik 1996). The studies included in the meta-analysis used the following ratio to quantify the impact of the addition of lighting:

$$Ratio = \frac{Nighttime\ crashes\ before\ (unlit) \big/ Nighttime\ crashes\ after\ (lit)}{Daytime\ crashes\ before\ (unlit) \big/ Daytime\ crashes\ after\ (lit)}$$

The use of daytime crashes as part of the analysis is questionable and one may argue that combining results across different environments (for example, urban, rural, freeway) make assumptions about similarities in safety performance that are now known to not exist. Elvik confirms that the studies used in the meta-analysis "*relied on quite simple techniques, like estimating an odds ratio and testing it for statistical significance*," and in Elvik and Vaa (2009), the authors acknowledge that "*most studies have methodological weaknesses"*.

ii) Publication Bias

Elvik mentions but dismisses publication bias ('*tendency not to publish results that are unwanted or believed not to be useful, for example, because they show an increase in accidents or because they are not statistically significant*' (Elvik 1996, p.114)). One may argue that current levels of support in favor of illumination as a safety countermeasure among safety professionals may be a strong enough deterrent for researchers not to publish their findings or to include findings of no correlation based on past practices when the results are contrary to current beliefs. Dominique Lord, the PI of the NCHRP 17-58 project for urban arterials confirmed that the research team found that lighting had no correlation with the safety performance on arterials with six lanes or more. Because of the researchers concern for lighting not being indicated as a significant variable, the research team requested that CMFs from the 1st edition be adopted for the new chapter in the 2nd Edition of the HSM (Lord, personal communications, October 2015). While this practice is controversial in the research community, it is also somewhat accepted to include variables found not be significant in models when there is a belief that the particular characteristic do correlate with safety performance even when the research results indicate to the contrary. This presents a dilemma as inclusion of the variables also perpetuates the validation and usage.

iii) Controlling for site conditions and characteristics

The meta-analysis did not control for site specific conditions. In their 2009 update of Elvik and Vaa (2004), the authors acknowledge that "*other factors than road lighting may have contributed to the differences in accident rates between lit and unlit roads*" (Elvik and Vaa 2009, p.275).

Highway Safety Manual Knowledge Base

During the development of the first edition of the HSM, NCHRP funded the development of a HSM Knowledge Base on crash modification factors for the first edition of the HSM (Bahar et al 2009). Exhibit 7 shows the results from the review of roadway lighting.

Exhibit 7. Summary estimates of the effects on accidents of public lighting (Source: Bahar et al, Exhibit 3-138, p.3-210 to 3-211)

Traffic environment	**Accident severity**	**Summary estimate of effect and standard error**	
		Summary estimate	**Standard error**
Summary estimates based on conventional meta-analysis			
All types of highway	All types, Fatal (18)	0.313	0.361
	All types, Injury (85)	0.717	0.056
	All types, PDO (19)	0.825	0.072
Rural highways	All types, Fatal (2)	0.265	0.720
	All types, Injury (19)	0.802	0.124
	All types, PDO (1)	0.696	0.426
Urban highways	All types, Fatal (13)	0.365	0.515
	All types, Injury (46)	0.685	0.073
	All types, PDO (16)	0.840	0.075
Freeways	All types, Fatal (3)	0.274	0.712
	All types, Injury (20)	0.728	0.121
	All types, PDO (2)	0.678	0.256
Summary estimates based on meta-regression analysis			
All types of highway	All types, Fatal	0.261	0.285
	All types, Injury	0.577	0.208
	All types, PDO	0.590	0.217
Rural highways	All types, Fatal	0.269	0.273
	All types, Injury	0.594	0.192
	All types, PDO	0.607	0.202
Urban highways	All types, Fatal	0.260	0.257
Summary estimates based on meta-regression analysis			
	All types, Injury	0.576	0.169
	All types, PDO	0.589	0.180
Freeways	All types, Fatal	0.253	0.269

Traffic environment	Accident severity	Summary estimate of effect and standard error	
		Summary estimate	Standard error
	All types, Injury	0.559	0.187
	All types, PDO	0.572	0.197

Additional meta-analysis by Harkey et al (2008) and expert panel input resulted in Exhibit 8. Note that the table below is a corrected version of the published table (Srinivasan 2015).

Exhibit 8. Highway Lighting AMFs as Presented by Harkey et al. (2008) (Corrected values)

Treatment	Setting Road type	Traffic Volume	Accident type Severity	AMF	Std. Error
Provide highway lighting	All settings All types	Unspecified	All types nighttime and all severities	0.80	n/a
			All types nighttime injury	0.71	n/a
			All types and all severities	0.94	n/a
			All types of injury	0.92	n/a
Base Condition: Absence of lighting.					

Appendix B presents a snapshot of illumination CMFs from the FHWA CMF Clearinghouse as of October 2013.

Lighting CMFs in the HSM

Exhibit 9 summarizes the illumination CMFs in the Highway Safety Manual. The research team was able to identify the origin of the CMF for the predictive methods for segments as part of Part C and the CMFs in Part D. Unfortunately, the team was unable to identify the source of the CMF for the predictive methods for intersections:

- Chapter 10 Project Report: Harwood et al (2000) did not include any lighting CMFs as part of proposed Chapter 10 content for the first edition of the HSM.
- Chapter 11 Project Report: Lord et al (2008) did not specify any proposed CMFs as part of proposed Chapter 11 content for the first edition of the HSM.
- Chapter 12 Project Report: the NCHRP project report for content for Chapter 12 of the first edition recommends a different equation for the CMF for lighting (Harwood et al 2007).

Exhibit 9. CMFs in the Highway Safety Manual (AASHTO 2010)

<table>
<tr><th>HSM Part/ Chapters</th><th>Estimate of the impact of lighting</th><th colspan="4">Source</th></tr>
<tr><td rowspan="3">Part C: Chapters 10, 11, 12 (Predictive method)</td><td>Facility type</td><td colspan="3">Formula</td><td></td></tr>
<tr><td>Segments</td><td colspan="3">Equation 10-21 on p.10-31, 11-15 on p.11-28, Equation 11-17 on p.11-31, and Equation 12-34 on p.12-42:
$CMF_{11r} = 1.0 - \left[\left(1 - 0.72 \times p_{inr} - 0.83 \times p_{pnr}\right) \times p_{nr}\right]$
Where
CMF_{11r} = crash modification factor for the effect of lighting on total crashes;
p_{inr} = proportion of total nighttime crashes for unlighted roadway segments that involve a fatality or injury;
p_{pnr} = proportion of total nighttime crashes for unlighted roadway segments that involve property damage only;
p_{nr} = proportion of total crashes for unlighted roadway segments that occur at night.</td><td>Elvik and Vaa (2004): Table 1.18.1 on p.366: using the CMF for injury accidents (0.72) and property damage only crashes (0.83).</td></tr>
<tr><td>Intersections</td><td colspan="3">Equation 10-24 on p.10-33, Equation 11-22 on p.11-35, Equation 12-36 on p.12-45:
$CMF_{4i} = 1.0 - 0.38 \times p_{nr}$
Where
CMF_{4i} = crash modification factor for the effect of lighting on total crashes; and
p_{ni} = proportion of total crashes for unlighted intersections that occur at night.</td><td>Referenced as sourced from Elvik and Vaa (2004) but the publication does not contain a CMF of 0.62</td></tr>
<tr><td rowspan="6">Part D: Chapter 13, Section 13.13.2.1 Provide Highway Lighting</td><td rowspan="6">All settings and road types (unspecified volumes)</td><td>Crash type (Severity)</td><td>CMF</td><td>Std. Error</td><td></td></tr>
<tr><td>All Types (Nighttime injury)</td><td>0.72</td><td>0.06</td><td>Elvik and Vaa (2004)</td></tr>
<tr><td>All Types (Nighttime non-injury)</td><td>0.83</td><td>0.07</td><td>Elvik and Vaa (2004)</td></tr>
<tr><td>All Types (Nighttime injury)</td><td>0.71</td><td>N/A</td><td>Harkey et al (2008)</td></tr>
<tr><td>All Types (Nighttime injury)</td><td>0.80</td><td>N/A</td><td>Harkey et al (2008)</td></tr>
<tr><td colspan="3">Base condition: Absence of lighting</td><td></td></tr>
</table>

Illumination research after publication of the HSM (2010)

Several studies about the safety performance of illumination were published after publication of the HSM. The bibliography of this report includes all known and publicly available publications on this topic.

Literature review conclusions: Deeply held beliefs

During the literature review we identified several deeply held beliefs about lighting. These deeply held beliefs have the potential to bias research methods, dataset development processes, and may affect professional acceptance about what lighting impacts and does not impact in relationship to nighttime crash reduction. The team critically evaluated each of these beliefs and presents each of these beliefs for consideration.

Belief 1: Roadway lighting reduces crashes during dawn and dusk (civil twilight) – crash reduction is unlikely during civil twilight because there is still limited target visibility at during civil twilight.

- ***Belief 2: All nighttime crashes can be 'fixed' with roadway lighting*** – only a subset of nighttime crashes may be 'correctable' with illumination since some twilight conditions are not impacted by the lighting systems.

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Belief 3: The ratio of daytime vs nighttime crash rates is a reliable and science-based method to estimate how many nighttime crashes to expect at a given location – the scientific basis for the rates and rate ratios are uncertain: it is likely that the rate ratio were appealing as a method to control for site specific conditions when methods to incorporate site specific conditions into the analysis was not common.

Belief 4: During congested conditions, adding roadway lighting reduces crashes – no scientific basis was found: advances in vehicle headlamp technology and the presence of large numbers of vehicles that provide lighting themselves may make nighttime congestion as a trigger for lighting a questionable approach. In addition, improvements in sign sheeting and lane marking materials have also occurred over the past few decades. It may also be that crash frequency (generally lower severity) increases during congested conditions and that these increases triggered recommendations for lighting in the past (it is important to note that nighttime congestion during the summer would be more likely to occur in daylight and that it is therefore unlikely that these crashes could be mitigated with lighting).

Belief 5: Nighttime crash rate is a reliable and science-based method to identify locations for lighting – a crash rate is not a reliable method for identifying potential locations for lighting because it is based on the assumption that the relationship between crashes and traffic volumes are linear. Count models offer alternative methods to incorporate exposure into safety performance estimation.

Belief 6: Only a few years of crash history are needed to identify locations where roadway lighting will reduce crashes – crashes are random, multivariate in nature and statistical methods are needed to account for natural variation of crashes over time while simultaneously accounting for other factors at the location that are likely to impact crash risk.

- ***Belief 7: Roadway lighting reduces crashes at the daytime (numerous studies included daytime crashes in the consideration of the benefits of lighting)*** – no scientific basis was found for the assumption that lighting would reduce crashes during daytime or during civil twilight. In fact, the presence of poles may increase crashes during higher volume daytime conditions.

Belief 8: More uniform light is better – the scientific basis of this assumption is uncertain: work by Gibbons et al (2014) offers further insight on maximum uniformity levels.

Belief 9: Roadway complexity is always a trigger for illumination – the scientific basis for this assumption is uncertain: roadway complexity may have daytime impacts as well (for which lighting will offer no mitigation) and the impact of lighting in complex roadway conditions given particular site conditions is still uncertain.

Belief 10: The fixed object risk of roadway lighting is negligible – WSDOT determined that the cost of replacing lighting poles that are hit is large ($750,000 annually) and that the presence of poles creates crash risk.

Belief 11: The impact of the roadway characteristics and conditions on safety performance – Elvik and Vaa (2004) assumes that the roadway characteristics and conditions do not impact safety performance. Research for the first edition of the HSM indicates several characteristics of roadways that correlates with changes in safety performance and the relative impact of these characteristics differ across facility types (AASHTO 2010). When the safety performance of lighting is evaluated it is necessary therefore to control for the impact of roadway characteristics and conditions on safety performance.

Chapter 3 gives a brief overview of WSDOT illumination reform activities and the motivation for the safety prediction modeling effort.

CHAPTER 3. ILLUMINATION REFORM AT WSDOT

Introduction

In 2012 WSDOT started illumination reform as part of the departmental commitment to sustainability. The reform is part of a larger effort at WSDOT to reduce carbon emissions. This effort is an important part of the WSDOT Sustainable Transportation Action Plan 2013-2015 (Updated 2015). This focus is also highlighted when the governor signed Executive Order 14-04, Washington Carbon Pollution Reduction and Clean Energy Action in 2014. Recognizing the potential benefits from reducing unnecessary energy consumption, roadway lighting is specifically called out as part of the next steps towards reducing the carbon footprint and increasing the use of clean energy in WA (Inslee 2014).

Two of the priority actions in the highway lighting component of the action plan were to: research options to increase the energy efficiency of highway lighting and flexibility in design requirements; and to develop safety predictive models to aid the department in identifying areas where illumination should be required and areas where illumination can be removed without adversely impacting system safety and mobility performance. Chapter 4 provides an overview of the first phase of safety predictive modeling performed to support illumination reform. The effort was undertaken with the understanding that advances in the science of safety offers opportunities to improve WSDOT's understanding of the safety performance of roadway lighting and to use this science-based approach to drive design policies.

LED Adaptive Lighting Pilot: US 101 – Olympia, WA

In 2013 the department deployed an adaptive LED lighting pilot project, shown in Exhibit 10. LED lighting offers 50% more energy efficient lighting and adaptive technologies allow for the dimming or shutting down of lighting to improve efficiency to approximately 74%. The deployment of adaptive lighting on SR 101 was evaluated by safety experts who determined that the lack crash history between 11PM and 5AM in the morning (shown in Exhibit 11) indicated that the location was appropriate for lighting modification.

Exhibit 10. Illustration of LED adaptive lighting pilot on US 101, Olympia, WA

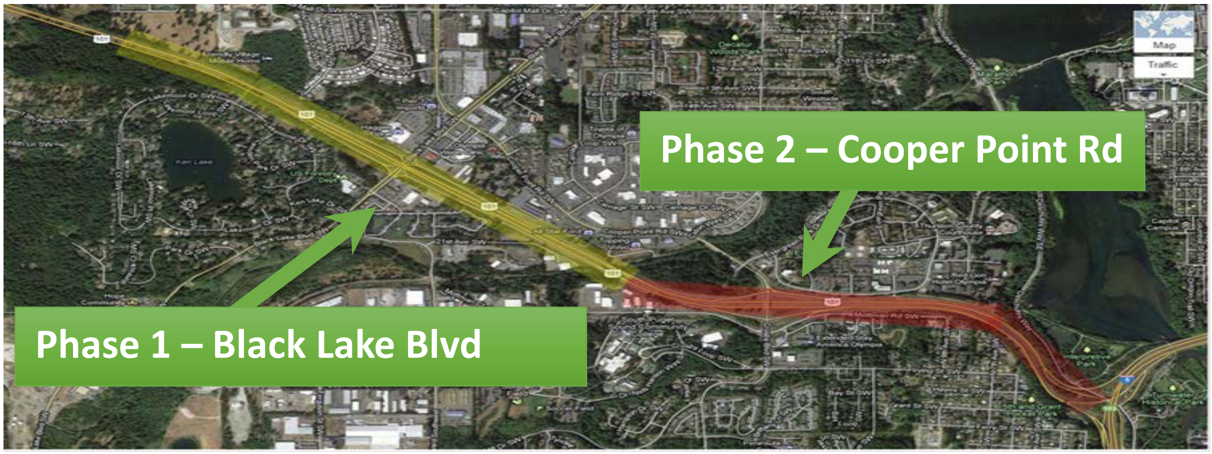
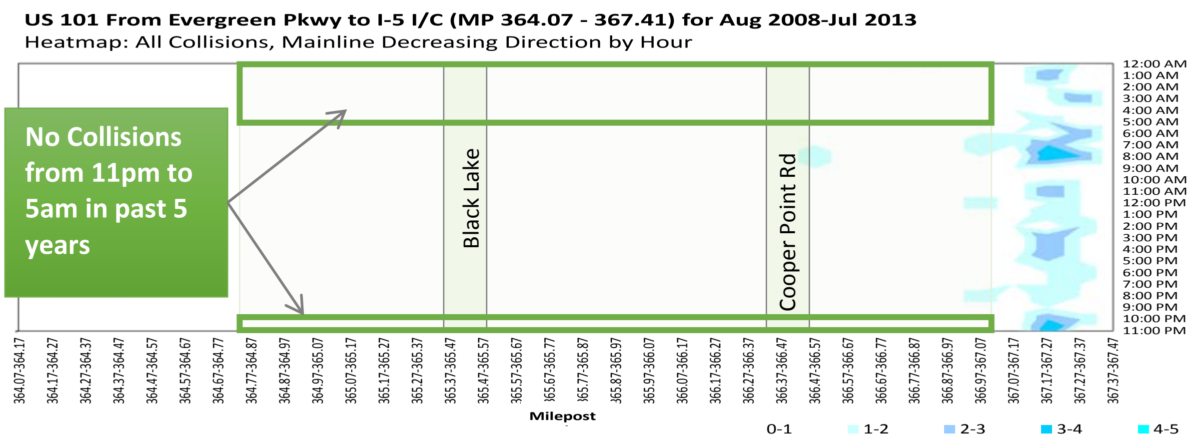


Exhibit 11. Example of crash history for the decreasing direction limits of the project (pre-pilot)



Under 23 U.S. Code § 409, safety data, reports, surveys, schedules, lists compiled or collected for the purpose of identifying, evaluating, or planning the safety enhancement of potential crash sites, hazardous roadway conditions, or railway-highway crossings are not be subject to discovery or admitted into evidence in a Federal or State court proceeding or considered for other purposes in any action for damages arising from any occurrence at a location mentioned or addressed in such reports, surveys, schedules, lists, or data.

SHRP 2 IAP Safety Pilot

During 2015 VTTI conducted a pilot research study of the impact of roadway lighting on nighttime crash performance and driver behavior. It was part of a series of pilot research projects funded by SHRP2 IAP Round 4. The focus of the project was to evaluate point lighting at on and off ramps on the interstate and to test proof of concept.

The research team included the following staff:

- WSDOT: Dr. Ida van Schalkwyk (manager & coordinator for the research team), and Dr. John Milton, P.E.;
- Prof. Venky Shankar, P.E. (PSU): Senior technical advisor; and
- VTTI: Dr. Ron Gibbons (PI) and a team of technical experts from VTTI.

The study concluded at the end of September 2015 and publication of the results is forthcoming.

New and ongoing activities

Introduction

By October 2015 WSDOT completed the following activities as part of its Illumination Reform:

- Completed the review of more than 300 publications on roadway lighting (overview included in Chapter 2 and the bibliography included as Appendix A).
- Completed the review of lighting design policies from multiple states and cities (WSDOT and UW staff, published as WSDOT WA-RD 847.1).
- Updated design policy in July 2014 impacting current systems & future projects.
- Completed the development of random parameter safety performance models for continuous mainline freeway segments (overview provided in Chapter 4).
- Made more than twenty presentations to international, national and state audiences (list of presentations presented in Appendix D).
- Completed the analysis of all WA interstate roadway lighting using research analytic methods, AASHTO Safety Analyst and the Highway Safety Manual.

WSDOT is planning, in the process of, or has completed 33 LED roadway lighting projects with 3,600 roadway lights (or 6% of WSDOTs inventory). During 2015 WSDOT was successful in obtaining grants, rebates and incentives to finance a LED replacement, removal of unnecessary illumination and adaptive lighting AID project. The remainder of this section will provide a brief overview of the project.

LED replacement, illumination removal and adaptive lighting AID project

In alignment with WSDOT's lighting reform program, the *LED replacement, illumination removal and adaptive lighting AID project* converts 1,924 roadway lights to high efficiency LED technology where the lighting is needed and removes 596 existing lights that are not providing benefit along corridors in North West and Olympic regions. WSDOTs success over the past 2 years by implementing state of the art analytic research methods to expand existing roadway lighting reform efforts culminates with this project. The $4 million project provides significant financial, maintenance and environmental efficiency savings through the use of innovative project delivery, financing and contracting tools. The project will be implemented through a performance contact that is financed through a combination of grants ($1,500,000), certificates of participation through the Office of the State Treasurer ($2 million), and utility rebates and incentives ($500,000). The project will leverage the energy savings which offsets 100% of the bond financing costs which are backed by a contractual 3rd party guarantee.

The project purpose aligns with Executive Order 1096.00, *WSDOT 2015-17: Agency Emphasis and Expectations*, which highlights the direction to reduce roadway lighting and implement adaptive control systems. Furthermore, this project highlights the Governor and Legislatures effort to implement energy efficiency grant and performance contracting programs through the Department of Commerce and Department of Enterprise Services while highlighting WSDOTs efforts regionally, nationally and internationally to lead roadway lighting reform by developing a risk-based approach to roadway lighting to create efficiency in roadway lighting decision making by considering the benefits and disadvantages of lighting to the fullest extent possible without significant impact to crashes and mobility.

Chapter 4 gives background to the safety predictive modeling of continuous mainline lighting on freeway segments, the data used, and presents findings from the modeling.

CHAPTER 4. SAFETY PERFORMANCE OF CONTINUOUS LIGHTING ON MAINLINE FREEWAY SEGMENTS IN WASHINGTON

Introduction

The literature review for the project revealed that most research prior to 2010 included primarily before-after studies where lighting was evaluated with:

a) naïve before-after study (not accounting for regression to the mean),

b) where lighting was evaluated but multiple countermeasures such as intersection and delineation improvements were made at the same time lighting was installed,

c) involved the use of crash rate methods that assumes a linear relationship between crashes and traffic volume, or

d) use daytime-nighttime ratios method that incorporates daytime crashes into the analysis.

More recently research started incorporating other factors that may impact crash risk and severity but most of these efforts still relied on night to daytime crash rate ratios. With the significant advances in computing power and advancement in analytical methods it is now possible to integrate data more easily. Researchers and agencies are able to use robust modeling to better understand how much lighting impacts crashes at nighttime and where lighting would be likely to improve safety performance at nighttime. Importantly, the new methods enhance the understanding of where lighting is likely to have an adverse impact on crashes, or where lighting can be removed without significant impacts to safety performance.

Background to the study

Narayan Venkataraman, a post-doctoral scholar at Penn State University developed a proprietary dataset with lighting configuration on all freeway mainline segments in Washington State. He used this dataset for the development of his dissertation, *Random parameter analysis of geometric effects on freeway crash occurrence*, towards the fulfillment of the requirements for his Ph.D. in Civil Engineering at the University of Iceland (published as Venkataraman, Ulfarsson, and Shankar 2013). As part of his research he successfully used random parameter negative binomial models to estimate safety performance on freeway segments. This represents a significant advancement in the area of safety prediction in that:

- The method controls for changes in cross-section, alignment, urban and rural character and different types of lighting simultaneously

- The method improves current safety performance function (SPF) performance by leveraging the negative binomial modeling structure and accounts for heterogeneity across the segments at the same time.

Venkataraman, Ulfarsson, and Shankar (2013) determined that point lighting proportions and proportions of continuous lighting were found to be random parameters. This means that lighting can have both positive and negative impacts on crash probabilities depending on the segment characteristics. This finding was of particular importance to WSDOT because the research method offers the opportunity to identify particular roadway design characteristics where illumination can be considered on a segment by segment basis and specific lighting recommendations, including the installation or removal of lighting can be made using scientific and data-driven processes.

To this end, Dr. Van Schalkwyk from WSDOT worked with Dr. Venkataraman and Prof. Shankar at Penn State University to develop random parameter models for evaluating the safety performance of continuous lighting on freeway mainline segments in Washington State.

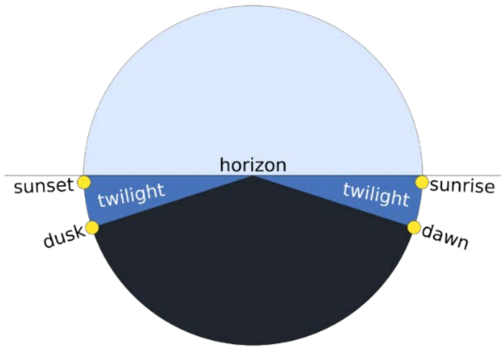
The remainder of this chapter provides an overview to the approach and findings from the study. A key element of the study was the dataset development using geographic location, time and date to determine individual lighting conditions at the time of the crash, so that the nighttime crashes were identified for inclusion in the illumination research excluded those that occurred during civil dawn, civil dusk, or daytime.

Nighttime crashes

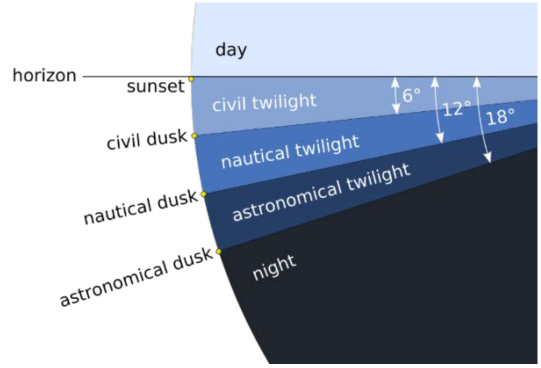
Illumination is used as a countermeasure for nighttime crashes. Roadway lighting has no demonstrated benefit during the daytime or during civil twilight: photocells are configured to switch on roadway lighting at the end of civil dusk twilight and switch it off at the start of civil dawn twilight. Exhibit 12 illustrates twilight in relation to sunset and sunrise and the different categories of twilight.

Civil dawn twilight starts when the geometric center of the sun is six degrees below the horizon and ends at sunrise. Similarly, civil dusk twilight starts at sunset and ends when the geometric center of the sun is six degrees below the horizon. During civil twilight the horizon is well defined and illumination from the sun is sufficient in clear weather to allow a human to distinguish objects (USNO 2011).

Exhibit 12. Twilight and civil twilight (Source: TW Carlson 2012)



a) *Twilight in relationship to sunset and sunrise*



b) Categories of twilight

Classification of nighttime crashes

Most research prior to 2010 relied on nighttime-daytime crash rate ratios (including Elvik (1996) and Elvik and Vaa (2004)) in the analysis. This approach was also used in work by Gibbons et al (2014) on adaptive lighting, Gibbons incorporated hourly estimated nighttime traffic volumes and controlled for daytime volumes to determine warrants for lighting based on crash rate ratios.

Because lighting is used as a countermeasure to address nighttime crashes, WSDOT decided to identify only those crashes on the freeway segment that occurred at nighttime and not those occurring in civil dawn or dusk (or daytime) for use in the model development.

The literature review revealed that nighttime crashes are generally identified in one of three ways (in some cases the researchers did not indicate how they classified nighttime crashes):

a) Using the reported lighting conditions from the crash report form (for example, Edwards 2015 and Isebrands et al 2010), or

b) Using a default 30 minutes after sunset as a start of nighttime and 30 minutes prior to sunrise as the end of nighttime and using a single location as a reference point for sunrise and sunset times (for example, Gibbons et al 2014), or

c) Using sunset and sunrise as the beginning and end of nighttime (for example, Donnell, Porter and Shankar, 2010).

For the WSDOT research project, staff focused on using a more advanced technique to determine which crashes should be classified as nighttime crashes. NOAA developed an algorithm to calculate sunrise, sunset, and civil twilight times for any given location or a given date (NOAA 2015). The research team evaluated the differences between reported lighting conditions and the calculated lighting conditions, and concluded that a large number of crashes are generally misclassified as either dark conditions when it was clearly still daytime or daytime when it was clearly nighttime. The NOAA calculations provide a consistent manner in which crashes can be classified as nighttime crashes statewide on an ongoing basis.

NOAA Calculation of Civil Twilight Time

This research project used the algorithms from the NOAA sunrise/sunset and Solar Position Calculators to develop SAS code for the estimation of civil dawn twilight time and civil dusk twilight time for each crash location and crash date. The SAS code is included as Appendix A to this report. The NOAA algorithm is based on Jean Meeus's astronomical algorithms (Meeus 1999). The algorithms are presented in Microsoft Excel spreadsheets. The SAS code includes trigonometry related code adapted from http://alaska.usgs.gov/science/biology/spatial/archive/filter_distributions/calc_dar3.sas.

Why excluding daytime crashes from the predictive modeling process is important

The inclusion of daytime crashes into the evaluation of the safety performance of illumination is problematic. The reason that it is problematic is that the assumption is made that the conditions influencing the likelihood of a crash occurring, and the severity outcome given that a crash has occurred, is the same in the daytime as it is in the nighttime. Shin, Washington and Van Schalkwyk (2009) is one of many papers documenting differences in the distribution of single and multiple vehicle crashes between day and nighttime conditions. However, little is known about the differences in traffic, driver composition, passenger composition, and distribution of travel patterns over the course of a day and over a year and how these differences impact safety performance or severity outcomes. Given that roadway lighting targets crashes occurring during darkness (measured from the end of civil dusk twilight to the start of civil dawn twilight), the research team decided to develop nighttime safety performance functions and only include nighttime crashes in the analysis. It is noted that, while roadway lighting poles create fixed objects that could potentially be hit during the day, very few of the utility pole crashes reported on mainline freeway segments in Washington were identified as lighting pole hits. From third party damage claims, WSDOT estimates these impacts to be more significant than the crash data indicates: totaling approximately $750,000 annually. Unfortunately without sufficient data, the inclusion of these crashes in the analysis is not possible.

The dataset

The freeway segment dataset developed by Venkataraman, Ulfarsson, and Shankar (2013) were supplemented with the nighttime crash assignments and updated traffic volumes for the period 2009 through 2013. The nighttime crash assignments were as follows:

- Use the location of each crash and the reported date to estimate the start and end time of nighttime using the NOAA algorithms, and assign a nighttime indicator to each crash based on the reported time of the crash.
- Isolate the dusk-to-dawn crash totals for the period 2009-2013 by direction on the entire freeway system.
- Isolate dusk-to-dawn totals by severity: total fatal crashes, total serious injury crashes, total evident injury crashes, total possible injury crashes and total property damage only crashes.

The freeway segment dataset is a directional segment level dataset for all limited access highways in Washington State. Exhibit 13 summarizes the factors included in the random parameter models for continuous mainline lighting of freeways.

Exhibit 13. Factors included in the random parameter models for continuous mainline lighting on freeways in Washington State

Geometry, volumes and urban/rural character	**Roadway lighting***
• Traffic volume • Number of lanes • Shoulder widths (left and right) • Horizontal curvature • Vertical curvature • Presence of interchange	• Median roadway lighting proportion • Right roadway lighting proportion • Both-side roadway lighting proportion • Point roadway lighting proportion • No roadway lighting proportion

* The lighting variables are measured as proportion by length values for interchange and non-interchange segments.

The segmentation included interchange segments to allow WSDOT to consider different scenarios during LED conversion: a) installing LED lighting at interchanges only, b) LED lighting at point lighting locations, c) LED lighting at interchange and non-interchange locations, d) lighting removal at interchanges with small footprints with point lighting retention.

Random Parameter Modeling

Overview

The focus of the first safety predictive modeling was on continuous mainline lighting on freeways (limited access highways) in Washington State. Prior to the 1980s WSDOT eliminated lighting as part of a lighting reduction program and in the late 1990s continuous lighting were removed from parts of the interstate to reduce energy costs. WSDOT did not observe any adverse impacts on the safety performance of these facilities. From a modeling perspective the presence of these unlit segments are appealing in that it creates variation in lighting conditions across similar location characteristics across the system. The updated segment dataset was used to estimate random parameter (RP) models with lighting variables such as median continuous, right side continuous, both side continuous, point lighting and no lighting values.

Findings

Based on the random parameter modeling of nighttime safety performance on continuous mainline lighting on freeways, it was concluded that continuous illumination makes no measurable contribution to nighttime safety performance. It is important to note that the research did not cover point lighting locations but instead only evaluated the performance of continuous mainline illumination on limited access highways.

CHAPTER 5. CONCLUSIONS, RECOMMENDATIONS AND NEXT STEPS

Conclusions

Based on the findings from the random parameter safety prediction modeling of continuous lighting on mainline freeway segments in Washington State the research team concludes that the installation of continuous mainline lighting on freeways for safety performance is not warranted. Further, findings from the pilot LED project on US101 (Black Lake Blvd) indicate that LED roadway lighting can significantly increase energy efficiency, that the general public experienced the LED project as positive and that illumination reform is a reasonable and practical way to improve the sustainability of the system while maintaining environmental stewardship.

Recommendations

The research team recommends that WSDOT modify its design criteria to discontinue and no longer install continuous mainline lighting on freeways and where appropriate consider illumination removal.

Next steps

If funding is available and this illumination reform continues to be identified as a statewide priority, the department would benefit from continued evaluation of safety performance provided by illumination on the remainder of the highway system. These findings will, together with the findings from the continuous mainline freeway findings inform performance based design and operational decision making for the Washington transportation system.

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APPENDIX B. CMFS IN THE CMF CLEARINGHOUSE (January, 2013)

Comments	CMF	CRF (%)	Quality	Crash Type	Crash Severity	Area Type	Analysis approach	Year of research publication	Reference
Countermeasure: Illumination	0.69	32	★★★★☆	All	Serious injury, Minor injury	Urban	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.84	16	★★★★☆	All	Property damage only (PDO)	Urban	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.73	27	★★★★☆	All	Serious injury, Minor injury	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.69	31	★★★☆☆	All	Property damage only (PDO)	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.31	69	★★★☆☆	All	Fatal	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.8	20	★★★☆☆	All	Serious injury, Minor injury	Rural	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.68	32	★★★☆☆	All	Property damage only (PDO)	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.7	30	★★☆☆☆	All	Property damage only (PDO)	Rural	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004

Comments	CMF	CRF (%)	Quality	Crash Type	Crash Severity	Area Type	Analysis approach	Year of research publication	Reference
Countermeasure: Illumination	0.27	74	★☆☆☆☆	All	Fatal	Rural	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.37	64	★☆☆☆☆	All	Fatal	Urban	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Illumination	0.27	73	★☆☆☆☆	All	Fatal	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Install intersection lighting	0.881	11.9	★★★☆☆	Nighttime	All	All	Multivariate using night-to-day crash ratio	2010	Donnell, Porter, Shankar, 2010
Countermeasure: Provide highway lighting	0.72 [B]	28	★★★★☆	Nighttime	Serious Injury, Minor Injury	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide highway lighting	0.83 [B]	18	★★★★☆	Nighttime	Property Damage Only (PDO)	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide highway lighting	0.31	69	★★★☆☆	All	Fatal	All	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004

Comments	CMF	CRF (%)	Quality	Crash Type	Crash Severity	Area Type	Analysis approach	Year of research publication	Reference
Countermeasure: Provide intersection illumination	0.62 [B]	38		Nighttime	Serious Injury, Minor Injury	Not Specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.58 [I]	42		Nighttime, Vehicle/ pedestrian	Serious Injury, Minor Injury	Not Specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.41	59		Vehicle/pedestrian	Serious injury, Minor injury	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.69	31		All	Property damage only (PDO)	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.23	77		All	Fatal	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.5	50		All	Serious injury, Minor injury	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.52	49		All	Property damage only (PDO)	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004

Comments	CMF	CRF (%)	Quality	Crash Type	Crash Severity	Area Type	Analysis approach	Year of research publication	Reference
Countermeasure: Provide intersection illumination	0.19	82		Vehicle/pedestrian	Fatal	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004
Countermeasure: Provide intersection illumination	0.67	32.6		Angle	All	Rural	Multi-variate (simultaneous equations crash frequency model)	2008	Ye et al., 2008
Countermeasure: Provide intersection illumination	0.56	43.8		Vehicle/pedestrian	All	Rural	Multi-variate (simultaneous equations crash frequency model)	2008	Ye et al., 2008
Countermeasure: Provide intersection illumination	1.05	-5		Day time	All	All	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	0.92	8		Nighttime	All	All	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	1.03	-3		Day time	All	Urban and suburban	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012

Comments	CMF	CRF (%)	Quality	Crash Type	Crash Severity	Area Type	Analysis approach	Year of research publication	Reference
Countermeasure: Provide intersection illumination	0.97	3	★★★☆☆	Nighttime	All	Urban and suburban	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	1.05	-5	★★★☆☆	Day time	All	Urban and suburban	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	0.91	9	★★★☆☆	Nighttime	All	Urban and suburban	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	1.09	-9	★★★☆☆	Day time	All	Rural	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	1.07	-7	★★★☆☆	Nighttime	All	Rural	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	0.98	2	★★☆☆☆	Day time	All	Rural	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012
Countermeasure: Provide intersection illumination	0.98	2	★★☆☆☆	Nighttime	All	Rural	Multivariate using night-to-day crash ratio	2012	Bullough et al., 2012

Comments	CMF	CRF (%)	Quality	Crash Type	Crash Severity	Area Type	Analysis approach	Year of research publication	Reference
Countermeasure: Provide intersection illumination	0.22	78		Vehicle/pedestrian	Fatal	Not specified	Meta-analysis	Research between 1948 and 1989	Elvik, R. and Vaa, T., 2004

APPENDIX C: WSDOT ILLUMINATION REFORM PRESENTATIONS

Date	Topic	Meeting/ Conference	Speakers
05/08/2013	US 101 at Black Lake Boulevard Adaptive LED Lighting Project and Illumination Reform	WSDOT Annual Traffic Engineers Meeting, Wenatchee WA	Ted Bailey and Keith Calais
10/21/2013	LED Adaptive Roadway Lighting & WSDOT Illumination Reform	IMSA-Northwest Section 81st Conference, Tacoma WA	Ted Bailey
02/06/2014	Roadway Lighting Reduction / LED Roadway Lighting Conversion Project Update	WSDOT Quarterly Maintenance Engineers Meeting, Olympia WA	John Nisbet and Ted Bailey
02/28/2014	Illumination Research	Municipal Solid State Lighting Consortium Peer Exchange	Ted Bailey, Keith Calais and Ida van Schalkwyk
06/03/2014	Illumination Reform WSDOTs journey on rethinking why we light	Washington Transportation Professionals Forum; Olympia WA	Ted Bailey and Ida van Schalkwyk
06/03/2014	Illumination Reform Case study 3: WSDOT's LED Adaptive Lighting Pilot, US 101 in Olympia, WA	Washington Transportation Professionals Forum; Olympia WA	Keith Calais
06/18/2014	WSDOT LED Adaptive Roadway Lighting & Illumination Reform	Western States Rural Transportation Technology Implementers Forum, Yreka CA	Keith Calais
07/29/2014	WSDOT LED Adaptive Roadway Lighting & Illumination Reform / TIB Relight WA Projects	WSDOT Peer Exchange with TIB	Ted Bailey and Ida van Schalkwyk
09/03/2015	Practical Solutions at WSDOT: Performance-based Practical Design and Risk-based vs Standards-based Approach	AASHTO Standing Committee on Highway Traffic Safety - Subcommittee on Safety (SCOHTS-SM) Management (SCOHTS-SM) Meeting	John Milton
09/15/2014	WSDOT LED Adaptive Roadway Lighting & Illumination Reform	NWR Design Construction Conference; Seattle, WA	Keith Calais

Date	**Topic**	**Meeting/ Conference**	**Speakers**
09/17/2014	WSDOT Illumination Reform and LED Adaptive Roadway Lighting	IES Street and Area Lighting Conference; Nashville TN	Ted Bailey
09/20/2014	Illumination Reform, Reduction and Removal	Annual WSDOT Traffic Engineers Meeting; Richland WA	Ted Bailey
11/06/2014	Roadway Lighting Reduction / LED Roadway Lighting Conversion Project Update	WSDOT Quarterly Maintenance Engineers Meeting, Olympia WA	John Nisbet and Ted Bailey
11/20/2014	FHWA Roadway Lighting Design - Review of the 2012 FHWA Roadway Lighting Design Handbook; WSDOT LED Adaptive Lighting Project	FHWA Roadway Lighting Design Workshop, Olympia WA	Keith Calais and Ida van Schalkwyk
12/16/2014	Roadway Lighting Reforms Rethinking why we light	2014 WSDOT Tort Risk Summit; September 16, 2014	John Nisbet, Mike Dornfeld
03/03/2015	Data Governance: The Data Scientist Perspective	Peer Exchange: Improving Safety Programs through Data Governance and Data Business Planning, Washington, D.C.	Ida van Schalkwyk
03/09/2015	Using road lighting to minimise vehicle crashes in Washington State – a cost-benefit approach	Road Lighting 2015 Conference, Auckland, NZ	John Milton
03/30/2015	Use of LED adaptive lighting to reduce power consumption costs at WSDOT / Webinar	North/West Passage Transportation Pooled Fund TPF-5(190) Peer Exchange on Efficiencies / Webinar	Ted Bailey
07/25/2015	Illumination Reform and LED Adaptive Roadway Lighting WSDOTs journey on rethinking why we light	15th COTA International Conference of Transportation Professionals Efficient, Safe, and Green Multimodal Transportation, Beijing, China	Ted Bailey
07/28/2015	Illumination Reform and LED Adaptive Roadway Lighting WSDOTs journey on rethinking why we light	Peer Exchange with Urban Transport of China; Beijing China	Ted Bailey
09/10/2015	Illumination Reform and LED Adaptive Roadway Lighting WSDOTs journey on	Arizona DOT Briefing, Webinar	Ted Bailey, Ida van Schalkwyk and John Milton

Date	Topic	Meeting/ Conference	Speakers
	rethinking why we light		
10/19/2015	Illumination Reform and LED Adaptive Roadway Lighting WSDOTs journey on rethinking why we light	Minnesota DOT Briefing, Webinar	Ted Bailey
10/26/2015	Statewide Roadway Lighting Conversion and Removal	WSDOT Executive Leadership Team briefing	John Nisbet, John Milton and Ted Bailey
09/03/2015	Practical Solutions at WSDOT – Performance-based Practical Design and Risk-based vs. Standards-based Approach	Standing Committee on Highway Traffic Safety - Subcommittee on Safety (SCOHTS-SM) Management	John Milton
10/15/2015	Data Integration	Washington Traffic Safety Conference, SeaTac, WA	Ida van Schalkwyk
01/12/2016	Data Value Mapping	Session 603: Making the Case for Investing in Information: Demonstrating Value, Transportation Research Board Annual Meeting, Washington, D.C.	Ida van Schalkwyk
01/14/2016	WSDOT and Illumination – the journey to discovery	TRB ANB25 Highway Safety Performance Committee Meeting, Transportation Research Board Annual Meeting, Washington, D.C.	Ida van Schalkwyk

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APPENDIX D: CALCULATING DUSK AND DAWN TIME

The calculations are based on the algorithms included in the NOAA excel spreadsheet (http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html with notes: http://aa.usno.navy.mil/data/docs/RS_OneYear.php#notes); and supplemented by code provided by http://alaska.usgs.gov/science/biology/spatial/archive/filter_distributions/calc_dar3.sas.

```
timezone=-8;
pi=4*atan(1);
degs=180/pi;
rads=pi/180;
JulianDate=FullDate_+2436934.5;
JulianCentury=(JulianDate-2451545)/36525;
GeoMeanLongSunDeg=MOD(280.46646+JulianCentury*(36000.76983 +
JulianCentury*0.0003032),360);
GeoMeanAnomSunDeg=357.52911+JulianCentury*(35999.05029 -
0.0001537*JulianCentury);
EccentEarthOrbit=0.016708634-
JulianCentury*(0.000042037+0.0000001267*JulianCentury);
SunEqofCtr=SIN(rads*GeoMeanAnomSunDeg)*(1.914602-
JulianCentury*(0.004817+0.000014*JulianCentury))+SIN(rads*2*GeoMeanAnomSunDeg
)*(0.019993-0.000101*JulianCentury)+SIN(rads*3*GeoMeanAnomSunDeg)*0.000289;
SunTrueLongDeg=GeoMeanLongSunDeg+SunEqofCtr;
SunTrueAnomDeg=GeoMeanAnomSunDeg+SunEqofCtr;
SunRadVectorAUs=(1.000001018*(1-
EccentEarthOrbit*EccentEarthOrbit))/(1+EccentEarthOrbit*COS((SunTrueAnomDeg)/
degs));
SunAppLongDeg=SunTrueLongDeg-0.00569-0.00478*SIN(rads*(125.04-
1934.136*JulianCentury)/degs);
MeanObliqEclipticDeg=23 +(26+((21.448-
JulianCentury   *(46.815+JulianCentury*(0.00059-
JulianCentury*0.001813))))/60)/60;
ObliqCorrDeg=MeanObliqEclipticDeg+0.00256*COS((125.04-
1934.136*JulianCentury)/degs);
```

```
SunRtAscenRads=(atan ((COS(RADS*ObliqCorrDeg)*SIN(RADS*SunAppLongDeg))/
COS(RADS*SunAppLongDeg)));
SunRtAscenDeg=DEGS*SunRtAscenRads;
SunDeclinDeg=DEGS*(ArSIN(SIN(RADS*(ObliqCorrDeg))*SIN(RADS*(SunAppLongDeg))));
VarY=TAN((ObliqCorrDeg/2)/degs)*TAN((ObliqCorrDeg/2)/degs);
EqofTimeMin=4*DEGS*( VarY *SIN(2*RADS* GeoMeanLongSunDeg)-2* EccentEarthOrbit
*SIN(RADS* GeoMeanAnomSunDeg)+4* EccentEarthOrbit * VarY *SIN(RADS*
GeoMeanAnomSunDeg)*COS(2*RADS* GeoMeanLongSunDeg)-0.5* VarY * VarY
*SIN(4*RADS* GeoMeanLongSunDeg)-1.25* EccentEarthOrbit * EccentEarthOrbit
*SIN(2*RADS* GeoMeanAnomSunDeg));
SolarDepression=6;
HADawnDeg=degs*(ARCOS(COS(rads*(90 +
solardepression))/(COS(rads*Latitude)*COS(rads*SunDeclinDeg))-
TAN(rads*Latitude)*TAN(rads*SunDeclinDeg)));
DuskTimeLST=86400*(((720-4*Longitude-EqofTimeMin+timezone*60)/1440)*1440-
HADawnDeg*4)/1440;
DawnTimeLST=86400*(((720-4*Longitude-
EqofTimeMin+timezone*60)/1440)*1440+HADawnDeg*4)/1440;
DaylightSavingsInd=dst;
DawnTimeDST=DuskTimeLST+DaylightSavingsInd*('01:00't);
DuskTimeDST=DawnTimeLST+DaylightSavingsInd*('01:00't);
```