Impact of Roadway Lighting on Nighttime Crash Performance and Driver Behavior – Final Summary Report

SHRP2 Implementation Assistance Program Round 4 Safety: Concept to Countermeasure – Research to Deployment Using the SHRP2 Safety Data

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PHASE I RESEARCH RESULTS

INTRODUCTION

More than half of the traffic fatalities occur during night even though nighttime traffic represents only 25 percent of the total travel on the nation's roadway system (*1*, *2*). Roadway lighting has been widely used as a countermeasure for nighttime crashes. However, safety engineers and researchers frequently lack effective tools when determining exactly how lighting should be optimized to maximize safety while conserve energy. Lighting characteristics may affect crash risks, such as the vertical and horizontal illuminance, roadway luminance, and lighting uniformity. The problem becomes more complex when variables such as human perception and behavior, roadway configuration, and traffic control measures are considered.

Assessing the impacts of roadway lighting on driver behavior and traffic safety is challenging due to a combination of factors. Traditionally, many safety studies rely on crash data. However, most crash databases at state Departments of Transportation (DOTs) only contain a binary variable indicating whether lighting is present on the crash site. Most state DOTs do not maintain a comprehensive database about roadway lighting characteristics, making it virtually impossible to clearly understand how different lighting characteristics play a role in preventing crashes. In addition, solely using crash data will not provide critical information about how exactly lighting affects risky driver behavior and the sequences of events of crashes. Different roadway configurations at crash sites further add complexity to the problem.

Recently, the second Strategic Highway Research Program (SHRP 2) completed the Naturalistic Driving Study (NDS) which collected a significant amount of detailed naturalistic driving and roadway data. During approximately the same time frame, a Federal Highway Administration (FHWA) project (Strategic Initiative for Evaluation of Reduced Lighting on Roadways) collected detailed lighting performance data on a large number of freeways and principal roads in seven states. The availability of these datasets provides an opportunity for understanding detailed safety impacts of lighting at a much higher degree of confidence.

Recognizing the potential of the aforementioned datasets and the research need, the SHRP 2 Implementation Assistance Program (IAP) in partnership with the Washington State DOT (WSDOT) selected this project to investigate in-depth the safety impact of roadway lighting. To ensure depth and remain consistent with WSDOT safety priorities, WSDOT requested this project to focus on interchange areas where traffic conditions are more complicated. This summary report describes the results of the Phase I study. The preliminary results showed great potential for helping the transportation community understand how different lighting characteristics contribute to driver behavior and nighttime safety. The results also showed great potential for helping state DOTs develop more optimized lighting designs (not necessarily higher level of lighting) at different roadway settings to reduce nighttime crashes while minimizing energy consumption.

LITERATURE REVIEW

Previous research on the safety impact of roadway lighting mostly focused on how the presence of lighting affected crash rates by comparing highways with and without lighting and the relationship between day and night crashes (*3*, *4*, *5*, *6*, *7*, *8*, *9*, *10*). Results of those studies varied but many pointed to improvements in safety performance with the presence of lighting. Some recent studies, however, suggested that continuous lighting on freeways could be counterproductive in reducing crashes (*11*). Notice that most previous studies lacked the support of detailed lighting measurement data and therefore could not identify exactly what level of lighting would improve the safety performance of the roadway. An early effort was made to determine the relationship between crash rates and illumination levels (*12*). That study used data on 203 miles of sample roadways but failed to conclude a statistically significant correlation between different illumination levels and crash rates.

Nationally, FHWA, American Association of State Highway and Transportation Officials (AASHTO), and Illuminance Engineering Society of North America (IES) are the major sources for lighting design guidelines and standards (*13*, *14*). In 2014, IES published its latest national lighting design standard: ANSI/IES RP-8-14 *Roadway Lighting* (*15*). RP-8-14 defines roadways into several classifications based on lighting needs and roadway configurations, such as freeway, expressway, major roadway, isolated interchange, isolated intersection, and isolated traffic conflict area. RP-8-14 uses luminance for lighting design of straight roadways and streets, horizontal and vertical illuminance for pedestrian areas, and horizontal illuminance for intersections, interchanges, and curved roadway sections.

Many state DOTs have developed their own versions of lighting design guides based on national guidelines including particularly the IES RP-8 standard. WSDOT, for example, includes detailed guidance on roadway lighting design in the *Design Manual* (*16*) and general warrants and requirements in the *Traffic Manual* (*17*). The WSDOT *Design Manual* currently does not require continuous lighting to be provided on state-maintained roadways. For freeways, however, the *Design Manual* requires necessary illumination for critical locations such as ramps and lane reduction areas. The guide in general uses 200-ft. basic design areas and specifies in detail where and how much lighting should be provided at interchange areas.

METHOD OF ANALYSIS

Phase I Objectives

The objective of the Phase I research was to explore the feasibility of using SHRP 2 NDS and RID data and VTTI in-situ lighting measurement data for a comprehensive understanding of lighting impacts on nighttime crash performance and driver behavior at freeway interchanges. In particular, this proof-of-concept research looked at the feasibility to investigate the following:

- The effects of roadway lighting characteristics on crashes and driver behavior relevant to safety; and
- The recommended lighting levels needed to maintain safety for different roadway geometries and traffic-control settings.

Phase I Methods of Analysis

Methodology Overview. During Phase I, the research team conducted SHRP 2 time series data analysis, SHRP 2 events data analysis, and crash data analysis. Figure 1 is an overview of the

Phase I data analysis methodology, followed by more detailed descriptions of the methods used to complete the various data analyses.

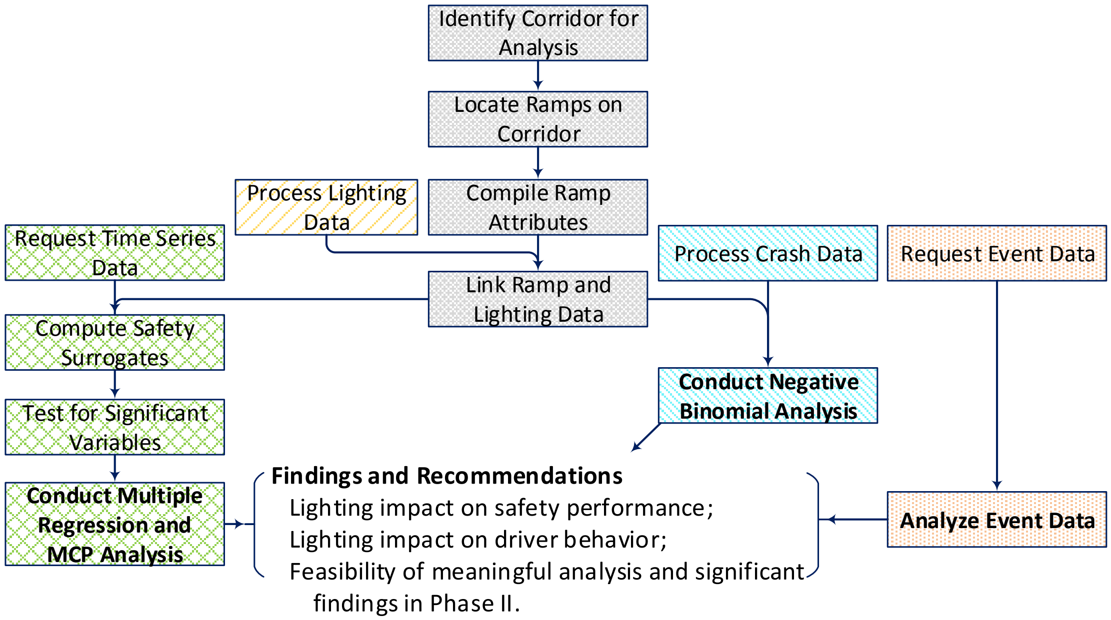

Figure 1. Data Analysis Methodology Overview.

Lighting Variables for Analysis. During this project, the research team used four roadway lighting variables:

- Right-lane horizontal illuminance, which is the average horizontal illuminance calculated based on measurements took for right lanes. Horizontal illuminance is the measurement of the amount of light falling on the roadway surface and is used frequently as the basic lighting parameter during roadway lighting designs.
- Overall horizontal illuminance, which is the average horizontal illuminance for all lanes calculated based on measurements across all lanes collected for on a specific roadway segment.
- Right-lane uniformity, which is the average lighting uniformity for right lane. Uniformity measures the difference in lighting intensity across a lighted area.
- Overall uniformity, which is the average lighting uniformity for all lanes.

During both time series analysis and crash analysis, the research team treated the four variables as continuous (i.e., using the original measured values). In addition, the researchers also analyzed the lighting variables as discrete variables (i.e., by combining the values into broader ranges) during the multiple comparison procedure (MCP) analysis of the time series data analysis to enable mean comparisons for different roadway settings. The discrete lighting levels were defined based on a careful consideration of ANSI/IES RP-8-14 recommendations.

Analysis Segments and Roadway Variables. After consideration of freeway ramp design guidance outlined in the AASHTO green book (*18*) and in accordance with the lighting design criteria in the WSDOT *Design Manual* (*16*), the research team used 200-foot segments as basic analysis areas during the time series data analysis (Figure 2). At a speed limit of 60 mph, a 200-foot analysis length translates to approximately 2.3 sec. of travel time. Combining the five analysis areas, the researchers were be able to analyze data reflecting a total of 11.4 sec. travel time. Note that, during the crash data analysis, the five analysis segments were combined into two analysis areas (before-ramp segment and after-ramp segment) due to the low spatial resolution associated with the crash data.

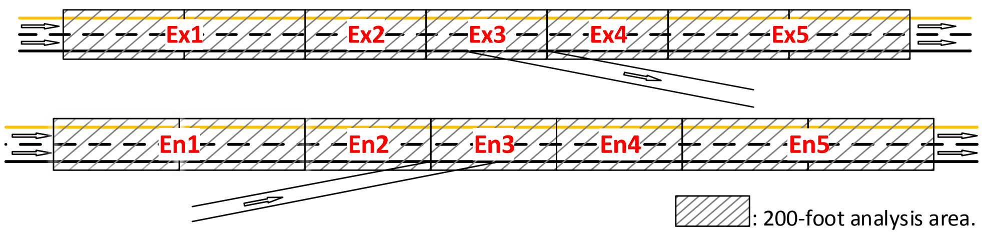

Figure 2. Analysis Areas at Entrance and Exit Ramps.

The research team used a number of roadway-related variables during the time series and crash data analyses: ramp type (i.e., entrance or exit); area type (i.e., urban or rural); facility functional classification; ramp geometric alignment type (e.g., direct or semi-direct connection, free flow outer connection, or free flow loop); main lane geometric alignment type (i.e., tangent or curve); number of main lanes; number of ramp lanes; and auxiliary lane length.

Time Series Data Safety Surrogates and Analysis Methodology. The time series data contains detailed vehicle kinematic and driver behavioral information collected continuously at high frequencies (e.g., 10 Hz for vehicle speed). The researchers used the following safety surrogates during the time series data analysis, most of which were correlated with safety performance in previous research *(19, 20, 21, 22, 23, 24, 25, 26*):

- Speed-related measures including travel speed, percent of speed exceeding the speed limit, and percent of speeding trips;
- Longitudinal acceleration rate, which is a measure of speed;
- Lane keeping measures including lane position offset (i.e., distance of the vehicle to the center of the lane) and lateral acceleration rate;
- Time to collision, which measures the speed difference between two successive vehicles (or a vehicle and a fixed object) with the assumption that a collision occurs if none of the involved parties change the current speed or deviate from the travel path; and
- Head position including head location and head rotation in an effort to understand driver distraction and driver workload/stress.

The research team analyzed the correlations between each lighting variable with both the mean values (μ) and the variances (σ^2) of the safety surrogate measures listed above for each different analysis area. The research team used two statistical analyses to explore the time series data:

- Multiple regression. Multiple regression analyses are popularly used to explore the correlations between dependent variables and multiple independent variables. The method measures both the strength and the direction of linear correlations between variables. It is proven to be robust when analyzing correlations between a continuous

dependent variable and multiple continuous and/or discrete independent variables. During Phase II 2, the research team will explore other types of correlations (e.g., log-linear) based on the larger datasets used.
- MCP analysis. The researchers used two MCPs to identify significantly different mean values and variances: Fisher's Least Significant Difference (LSD) and Tukey-Kramer test. Significantly different means were identified when so indicated by either test. The MCP analysis helped identify significant correlations and trends among smaller, more homogeneous data groups divided based on roadway variables to better understand the lighting impacts relevant to different roadway settings and driver characteristics.

During the tests, a significant correlation was identified at a 0.05 significance level and using a critical R-Square value of 0.1.

SHRP 2 Events Data Analysis. This activity included a thorough examination of the events detail data for nighttime crashes and near crashes that were related to interchange areas or ramps. In addition, the research team examined the video files of all suitable events including front-, rear-, face-, and steering wheel- view videos in the SHRP 2 secure enclave. Within the secure enclave, the research team also analyzed the continuous speed, acceleration, and eye glance data associated with all the events. Due to the limited number of suitable events, the research team could not apply statistical modeling methods. As such, the analysis was conducted as case studies in an effort to understand at a microscopic level how exactly lighting could have played a role in the sequences of events during crashes or near crashes. This analysis attempted to answer the following questions:

- Was lighting a contributing factor to the event (very likely, probably, or not sure)? If yes, how did lighting contribute to the event? Were there other direct contributing factors?
- Was the driver distracted during the event? Did lighting play a role in the distraction?
- How lighting could be improved to prevent this event?

Crash Data Analysis. This activity involved analysis of actual crashes contained in the RID database and the correlation between right-lane and overall horizontal illuminance, and night-to-day crash ratio and proportion of injury and fatal crashes. During this analysis, the research team used both random parameter negative binomial and regular negative binomial regressions. The negative binomial regression method is frequently used for modeling count variables that follow a Poisson distribution but where over dispersion exists. Random parameter negative binomial regression attempts to add randomness to the regular negative binomial models to better account for time variation or road segment-specific effects (*27*). Due to the increased analysis segment length, the research team did not use lighting uniformity in this analysis. In addition, the research team added vertical illuminance (i.e., intensity of light falling on a vertical surface) in the analysis.

DATA USED

The research team used the following data for the aforementioned Phase I analyses:

- Ramp data: 89 ramps mostly from two 10-mile corridors (IH5 and IH405) in the Seattle area.
- Lighting data: field lighting measurements collected during multiple runs at a frequency of 20Hz in January 2013.
- Time series data: 1,270 trips made by 313 different drivers representing approximately 1.8 million data points.
- Event data: 31 nighttime events in Washington were identified as interchange or ramp related (six crashes and 25 near crashes).
- Crash data: Over the three year period, 2011 to 2013, 69 nighttime crashes occurred on the 46 ramp analysis segments on the three selected corridors.
- VTTI lighting measurements that were collected in January 2013. The research team used 2011 as a cut-off year for the historical crash data to ensure the concurrence with the lighting level condition.

During this study, data processing was a major task as it involves linking lighting, time series, and roadway data into an integrated dataset to enable data analysis. The large number of time series data points demanded significant computing resources for processing. The research team performed the data linking primarily based on spatial relationships among them on the Esri® ArcGIS platform. Figure 3 shows the VTTI lighting data and the ramp locations.

Figure 3. Corrected Ramp Locations on I-5.

PHASE I RESULTS

Lighting Impacts on Driver Behavior Relevant to Safety

Impacts for Entrance Ramps. Table 1 illustrates the statistically significant correlations between safety surrogates and right-lane horizontal illuminance and overall horizontal illuminance. Table 2 summarizes the significant correlations between safety surrogate variables and right-lane and overall lighting uniformity.

- Effects of right-lane and overall horizontal illuminance. The proof of concept analysis results seemed to suggest that higher right-lane illuminance generally correlated with slower speed and more gradual or fewer lane changes. In terms of illuminance impact distance, the research results seemed to suggest that the effects of right-lane illuminance lasted into EN5, which is 400 – 800ft. away from the painted gore nose. The results also suggested that traffic entering freeways with higher right-lane illuminance tend to have higher acceleration rates in the auxiliary lanes. The right-lane illuminance level generally had less impact on the through traffic. In the case of overall illuminance, the results suggested that traffic entering freeways with higher overall illuminance seemed to drive and merge faster. In terms of acceleration, the results seemed to suggest that ramp traffic tended to accelerate early after entering freeways when the overall illuminance levels were higher. The results also suggested that ramp traffic tended to deviate more from the center of travel lanes on EN5 (i.e., 400 ft. – 800 ft. from ramp) with higher overall illuminance.

Table 1. Driver Behavior Correlation with Increase in Horizontal Illuminance.

Analysis Segment	**Traffic Type**	**Right-Lane Illuminance**					**Overall Illuminance**				
		EN1	**EN2**	**EN3**	**EN4**	**EN5**	**EN1**	**EN2**	**EN3**	**EN4**	**EN5**
Speed	Ramp	-	-	↘	↘	NS	-	-	NS	↗	NS
	Through	NS	NS	NS	NS	NS	NS	NS	↗	NS	NS
Longitudinal Acceleration Rate	Ramp	-	-	↗	↗	↗	-	-	↗	↘	↘
	Through	NS	NS	NS	↗	↗	NS	NS	NS	↘	↘
Longitudinal Acceleration Variance	Ramp	-	-	NS	NS	NS	-	-	NS	NS	NS
	Through	NS	NS	NS	↘	NS	NS	NS	NS	NS	NS
Lateral Acceleration Rate	Ramp	-	-	↘	↘	↘	-	-	↗	↗	NS
	Through	↘	NS	↘	NS	↘	↗	NS	↗	↗	↗
Lateral Acceleration Variance	Ramp	-	-	NS	NS	NS	-	-	NS	NS	NS
	Through	NS	NS	↘	NS	NS	NS	NS	↗	NS	NS
Lane Offset	Ramp	-	-	NS	NS	↘	-	-	NS	NS	↗
	Through	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS = not significant. This table did not list safety surrogate variables without significant correlations.

Table 2. Driver Behavior Correlation with Increase in Lighting Uniformity.

Analysis Segment	**Traffic Type**	**Right-Lane Illuminance**					**Overall Illuminance**				
		EN1	**EN2**	**EN3**	**EN4**	**EN5**	**EN1**	**EN2**	**EN3**	**EN4**	**EN5**
Speed	Ramp	-	-	NS	NS	↗	-	-	NS	NS	↗
	Through	↗	NS	NS	NS	NS	NS	NS	NS	NS	NS
Longitudinal Acceleration Rate	Ramp	-	-	NS	↗	↘	-	-	NS	NS	↘
	Through	NS	NS	NS	↗	NS	NS	NS	NS	NS	↘
Longitudinal Acceleration Variance	Ramp	-	-	NS	NS	NS	-	-	NS	NS	NS
	Through	NS	NS	NS	NS	NS	↗	NS	NS	NS	NS
Lateral Acceleration	Ramp	-	-	NS	NS	↗	-	-	NS	NS	NS
	Through	↘	NS	↘	↘	NS	↘	NS	NS	↗	↗
Lateral Acceleration Variance	Ramp	-	-	NS	NS	NS	-	-	↗	NS	NS
	Through	NS	NS	↘	NS	NS	NS	NS	NS	NS	NS
Lane Offset	Ramp	-	-	NS	NS	↗	-	-	NS	NS	↗
	Through	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS = not significant. This table did not list safety surrogate variables without significant correlations.

Notice that the most significant correlations for through traffic with illuminance were found on EN3, EN4, and EN5. These locations had more traffic due to the addition of the traffic entering the freeway. This seemed to suggest that higher traffic volume and vehicle interactions increased lighting effects on driver behavior.

- Effects of right-lane and overall lighting uniformity. In general, right-lane lighting uniformity had less of an impact on driver behavior compared to right-lane illuminance.

For traffic entering freeways, the proof of concept results suggests that higher right-lane uniformity is associated with higher longitudinal acceleration rates on EN4 and lower lateral acerbation variance on EN3. On EN5, however, the results suggested that higher right-lane uniformity correlated with higher speed, lower longitudinal acceleration, higher lateral acceleration rate, and higher lane offset ratio for ramp traffic. The preliminary results also implies that higher right-lane uniformity correlated with lower lateral acceleration rates for through traffic. Overall lighting uniformity only appeared to effect a limited number of driver behavior variables. In addition, most effects were found on the EN5 segments.

- Higher overall lighting uniformity were associated with more abrupt lane changing behavior by ramp traffic on EN3. Under higher overall uniformity on EN5, ramp traffic had higher speeds, lower longitudinal acceleration, and higher lane offset rates. Under higher overall uniformity, through traffic had lower longitudinal acceleration rates but higher lateral acceleration rates.

Impacts on Exit Ramps. Table 3 and Table 4 illustrate the significant correlations between lighting metrics and driver behavioral variables for exit ramps.

Table 3. Driver Behavior Correlation with Increase in Horizontal Illuminance.

Analysis Segment	Traffic Type	Right-Lane Illuminance					Overall Illuminance				
		EX1	EX2	EX3	EX4	EX5	EX1	EX2	EX3	EX4	EX5
Longitudinal Acceleration Rate	Ramp	↗	↗	NS	-	-	↗	↗	↗	-	-
	Through	↘	NS	NS	NS	NS	↘	NS	NS	NS	NS
Lateral Acceleration Rate	Ramp	NS	↘	NS	-	-	↗	NS	NS	-	-
	Through	↘	NS	NS	NS	NS	NS	↘	↘	NS	NS
Lateral Acceleration Variance	Ramp	↘	NS	↗	-	-	↘	NS	↗	-	-
	Through	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Lane Offset	Ramp	NS	↗	NS	-	-	NS	NS	NS	-	-
	Through	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS = not significant. This table did not list safety surrogate variables without significant correlations.

Table 4. Driver Behavior Correlation with Increase in Lighting Uniformity.

Analysis Segment	Traffic Type	Right-Lane Uniformity					Overall Uniformity				
		EX1	EX2	EX3	EX4	EX5	EX1	EX2	EX3	EX4	EX5
Speed	Ramp	NS	NS	NS	-	-	NS	↘	NS	-	-
	Through	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Longitudinal Acceleration Rate	Ramp	NS	NS	↘	-	-	↗	↗	↗	-	-
	Through	NS	NS	NS	NS	NS	↗	NS	NS	NS	NS
Lateral Acceleration Rate	Ramp	↘	↘	↘	-	-	↗	NS	NS	-	-
	Through	NS	↘	NS	NS	NS	NS	↗	↗	NS	NS
Lateral Acceleration Variance	Ramp	NS	NS	↘	-	-	↗	NS	NS	-	-
	Through	NS	NS	↘	NS	NS	↗	NS	NS	NS	NS
Lane Offset	Ramp	NS	↘	NS	-	-	↗	↗	NS	-	-
	Through	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS = not significant. This table did not list safety surrogate variables without significant correlations.

- Effects of right-lane and overall horizontal illuminance.

- The effects of right-lane illuminance levels on exit ramps were most pronounced on analysis segments EX1 and EX2 and for longitudinal and lateral acceleration rates of ramp traffic. Exiting traffic tended to accelerate more before they exit on roadways with higher right-lane illuminance, possibly suggesting that drivers on roadways with higher right-lane illuminance were more confident about the roadway condition ahead. Exiting traffic had lower lateral acceleration rate on EX2 and lower lateral acceleration variance on EX1. The higher lane offset for exiting traffic on EX2 was probably due to drivers' tendency to drive closer to the edge line of the right lane before they exit the freeway. The higher lateral acceleration variance on EX3 with higher right-lane illuminance is interesting and needs to be further studied. In terms of through traffic, right-lane illuminance had fewer correlations on driver behavior variables.
- Higher overall illuminance were correlated with higher longitudinal acceleration rates for exiting traffic on analysis segments EX1 – EX3, which suggested that exiting drivers were more confident about the ramp location. On EX1, the results also suggested that higher overall illuminance correlated with higher lateral acceleration rate, which suggested that exiting drivers merged early when overall illuminance level was higher.
- For through traffic, higher overall illuminance levels were associated with lower longitudinal acceleration rates on EX1 and lower lateral acceleration rates on EX2 and EX3, suggesting fewer and/or more gradual lane changing maneuvers for through traffic when higher overall illuminance levels are present.

- Effects of right-lane and overall lighting uniformity.
  - Right-lane lighting uniformity mainly had effects on ramp traffic. Generally, higher right-lane uniformity correlated with lower longitudinal acceleration rate for exiting traffic right before they exited (i.e., EX3). It also correlated with lower lateral acceleration rate on all segments prior to exit and lower lane offset on EX2. These results seem to suggest that right-lane uniformity had positive safety effects on exiting traffic, but limited effects on through traffic.
  - Overall lighting uniformity mostly had significant impacts on EX1, which is the farthest analysis segment from ramp locations. In addition, higher overall uniformity correlated with higher longitudinal acceleration rates, lateral acceleration rates and variance, and lane offset on EX1 and to a certain extent, EX2 for both ramp and through traffic.

Lighting Impacts based on MCP Results. MCP analysis compared the mean values of the safety surrogate measures and identify statistically significant differences (at 0.05 level of significance) between different light levels. In general, the MCP analysis results showed clear trends of lighting impacts on driver behavior for roadways with more complex configurations (e.g., curved roadways with more traffic lanes) and for older drivers. Figure 4, for example, shows that the mean speed was lower when the lighting levels were higher for drivers older than 50 years of age and on roadways with three or more lanes. Notice that the MCP analysis showed interesting results for drivers between 31 and 40 years of age and roadways with three or fewer main lanes, which need to be further studied during Phase II.

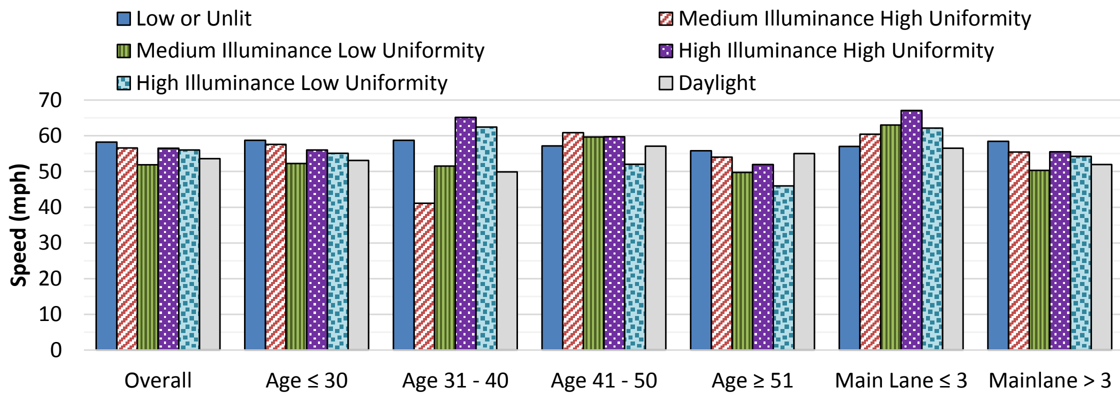

Figure 4. Mean Speed by Lighting Levels, Number of Main Lanes, and Driver Age (EN 3, Ramp Traffic).

Lighting Impacts on SHRP 2 Crashes and Near Crashes

During this phase, only 6 nighttime crashes and 25 nighttime near crashes were identified in the SHRP 2 database to be interchange or ramp related in the State of Washington. This limited number of events did not support meaningful statistical analysis at this time. However, the event data provides the potential for interpretation of driver behavior and the relationship to lighting. As an example, among the analyzed crashes and near crashes, the research team identified two fixed-object crashes and one near crash that were highly likely contributed by lighting. During both of the two fixed-object crashes, the drivers failed to see channelization islands at ramps and ran over them, although face video clearly suggested that both drivers were carefully observing the roadways ahead. The near crash occurred when a vehicle crossing underneath a freeway bridge where lighting levels changed significantly. The face video showed that the driver had difficulty adapting to the changing lighting levels at transition areas and almost collided with a slow vehicle driving ahead.

Lighting Impacts based on Crash Analysis

The random parameter crash prediction models failed to converge due to the small sample size. Out of the four regular negative binomial models, only right-lane vertical illuminance was found to be significant. The models seemed to suggest that an increase in the vertical illuminance by 1 lux was associated with a 10.1% decrease in the night-to-day crash ratio. The vertical illuminance measurements used in this study ranged between 0 – 14 lux and did not fall in the range of glare.

Preliminary Conclusions and Recommendations

Based on the limited data (i.e., ramps mostly from two roadway corridors in the same region and not controlling for geometric or cross sectional differences) used in the Phase I research, the results suggested the following:

- The effects of differences in illumination and uniformity varied in terms of speed, longitudinal and lateral acceleration, and lane offset. Lighting effects on head movements and time to collision were not significant enough based on current data.

- Overall, horizontal illuminance were more likely to impact the safety surrogate measures than lighting uniformity.
- The effects of lighting on driver behavior were more evident for entrance ramps than for exit ramps. Lighting effects were more evident on analysis areas prior to ramps for exit ramps or after ramps for entrance ramps. These analysis areas were associated with higher traffic volumes and more lane changing maneuvers.
- Higher right-lane illuminance and uniformity generally correlated with lower speeds and fewer or more gradual lane changes. Higher overall illuminance and uniformity seemed to have encouraged relatively faster or more lane changing behaviors.
- Lighting effects on driver behavior were more pronounced for drivers age 50 and over, and on segments with complex geometries. Lighting effects seemed to extend beyond 400 ft. from painted gore noses at ramps.

Combining results from the time series, events, and crash data analysis, the preliminary results based on a small data sample indicate that the research has a great potential for improving the current lighting design guidelines and practices, for example:

- Higher lighting levels for right lanes (i.e., ramp side) at ramp locations may result in slower speeds and less frequent or more gradual lane changes (sufficient levels to be determined in Phase II).
- There may be a need for State DOTs to consider designing lighting for at least 400 ft. (preferably 600 ft.) upstream for exit ramps or downstream for entrance ramps at interchange areas rather than using 200 ft. as a default.
- State DOTs should consider controlling design minimums at locations where complex or unexpected roadway features exist (detailed guidelines to be determined in Phase II).
- Determine if and to which extent higher ADT or more complex roadway geometric characteristics impact driver behavior (critical ADT to be determined in Phase II).

Data availability and Suitability for Phase II Analysis

The following assesses the data availability and suitability for Phase II for each type of data:

- SHRP 2 time series data is sufficient and suitable for the Phase II study. The Phase I research has clearly demonstrated that the SHRP 2 time series data contained rich information depicting vehicle kinematics and driver behavior. In particular, the database contains accurate and high-frequency data on speeds, longitudinal and lateral accelerations, and to a lesser extent, lane offsets. This research did suggest that the head movement information in the time series data generally had low confidence levels and were not fully populated. However, this data can be replaced by the SHRP 2 eye glance data to obtain more confident results.
- SHRP 2 events data can provide valuable information on how drivers acted in relation to lighting during crashes or near crashes. The events data, including in particular the detailed videos, clearly demonstrated how exactly drivers' actions are related to changes in vehicle kinematic variables, and therefore provided clear directions for understanding lighting effects. In addition, the event videos allowed researchers to clearly understand how lighting played a role in the events and provided unique lighting problems that

would not have been identified with only time series data. The entire SHRP 2 database contains 17 crashes and 87 near crashes that occurred during nighttime and were interchange or ramp related, which will provide more information and evidence on safety effects of lighting.

- The VTTI field lighting measurement data is sufficient and suitable for the Phase II study. The lighting measurement data contain accurate measurements of vertical and horizontal illuminance that enable the calculation of comprehensive and high-resolution lighting metrics for a total of 2,114 miles of Interstates and principal arterials. A total of 711 miles of roadway lighting measurements were collected in Washington and North Carolina on roadways overlapping with SHRP 2 data.
- The RID roadway information is limited and should be complemented by data directly from states. RID contains limited information for ramps and crashes. However, most state transportation agencies (e.g., WSDOT) maintain more comprehensive roadway and crash information and therefore can be used in conjunction with RID in Phase II.

Potential of Phase II Research for Developing Significant Findings

Roadway lighting has long been considered a countermeasure affecting safety-related driver behavior and crash performance. Few studies have established correlations between detailed lighting metrics and roadway safety. Currently, many states follow the IES recommendations for roadway lighting design. Such recommendations were mostly based on isolated, small-scale experiments and laboratory studies. This research is an unprecedented step towards a comprehensive and in-depth understanding of how specific lighting metrics, all used as key parameters in roadway lighting designs at states, exactly influence driver behavior relevant to safety. The results are expected to be instrumental in refining and improving existing lighting design guidelines for state DOTs to support improved safety performance and more energy-efficient roadways in a fiscally constrained environment.

The limited Phase I data and results have shed light on design areas at ramps (e.g., the preliminary results indicate that lighting may provide benefit on right lanes at ramps and light may need to be considered for more than 400 ft. from the ramp painted gore noses), design warrant factors (e.g., lighting effects vary across traffic volume and roadway geometry) and design control points (e.g., special consideration for complex geometric conditions based on events analysis results).

Based on a larger dataset that offers greater variance in roadway, driver, and ramp configuration, the Phase II research will verify if the preliminary results and further identify critical lighting values, warrant factor thresholds, and design area specifications. Such results are valuable for state transportation agencies to develop performance-based and optimized lighting designs. This will greatly improve current state and national lighting design guidelines, including improving the understanding of effects of lighting on older drivers.

Overall Assessment of Phase I Results for Meeting Research Goal

The Phase I research meets the research goal in several aspects:

- Phase I preliminary results were meaningful and encouraging. The preliminary results showed significant correlations for several safety surrogate measures based on the limited number of roadway locations. When verified, such results can clearly provide critical information leading to a comprehensive understanding of lighting impacts at interchanges. The results illustrated great potential for improving current design guidelines towards more safety effective and possibly energy-efficient roadway lighting.
- SHRP 2 data availability and validity for the proposed research were verified. As concluded previously, the time series data contain rich information that sufficiently meets the needs of the proposed research. The events data further complements the time series data by providing correlations between driver actions and vehicle kinematic performance. With RID, additional roadway and crash data from states, and roadway data from satellite images, the researchers were able to obtain sufficient roadway and crash information as well. The VTTI lighting performance data are uniquely suitable for this research as well.
- Phase II research will highly likely result in a comprehensive understanding of the impact of roadway lighting on driver behavior, and support improvements to current state and national lighting design standards. Such improvements will include the establishment of more safety-effective illuminance/uniformity minimums most likely to support safety performance, improve current practice of design areas around ramps, warrant thresholds, and design control points that can be directly adopted by national and state lighting design guidelines.
- The data analysis methodology is technically sound and suitable for the proposed study. This research used statistical modeling technics that are respectively suitable for analyzing continuous (i.e., lighting measures), discrete (i.e., combined lighting levels), and count variables (i.e., crashes). The methods successfully and effectively identified correlations between lighting and safety surrogate variables both in general and for smaller, more homogeneous data groups. The Phase I research also illustrated the GIS techniques used to integrate different, in some cases significantly large (e.g., 1.8 million time series data points), datasets spatially to enable integrated data analysis. The research team also went through the procedures and processes pertaining to the SHRP 2 IRB, data sharing agreement, Personally Identifiable Information (PII), and secure enclave, enabling hands-on experience for avoiding unexpected challenges in SHRP 2 data request during Phase II.

FUTURE DIRECTION

The Phase I results indicate that the originally proposed objectives are practical and significant. As such the Phase II research will maintain the same objectives, but with an expanded scope and using a larger and improved dataset:

- Understand the effects in detail of roadway lighting on safety-related driver behavior,
- Understand the role of roadway lighting on crashes and near crashes, and
- Recommend improvements to current national and state roadway lighting design guidelines.

Built on Phase I, the research team will conduct the following analyses during Phase II to fully achieve the objectives:

- Expanded time series data analysis with a larger SHRP 2 dataset, more roadways, and more ramps. The research team will also include unlit interchanges (e.g., rural interchanges) for comparison. The expected results of this analysis include conclusive effects of lighting characteristics on driver behavior such as speed, acceleration, and lane keeping, and critical roadway and traffic characteristics for lighting effects.
- Identification of recommended lighting levels by identifying threshold values for illuminance and uniformity. This analysis in reality is a part of the expanded time series data analysis. With a larger dataset and based on significant correlations, the research team will identify the critical lighting levels beyond which lighting only affects a trivial proportion of drivers (e.g., 5% or 1%). These critical values have the potential to be directly used as lighting design criteria.
- Eye glance data analysis for both regular trips and for events. The expected results of this analysis include the identification of critical locations where lighting should be designed for and how lighting affect driver behavior as is indicated by driver glancing behavior.
- Expanded events analysis with all suitable events of the entire SHRP 2 database. This analysis will help the research team to better understanding how lighting plays a role in the sequences of events of crashes and near crashes. The results will also provide direction on how the time series data analysis results should be correctly interpreted and applied.
- Expanded crash analysis. The expected results of this analysis will be correlations between lighting levels and crash rates and severity, which are direct indicators of the lighting effects on safety.

PHASE II PROPOSAL

Research Objectives and Scope

The primary objectives of the Phase II research are:

- Develop a comprehensive understanding of the effects of roadway lighting metrics (e.g., horizontal illumination and lighting uniformity) on safety-related driver behavior at interchanges and intersections on major roadways.
- Recommend improvements to current national and state roadway lighting design guidelines.

Data Needs

The research team plans to use the following expected datasets during Phase II:

- Roadways and ramps: a minimum of 300 ramps from 30 roadway corridors and 50 intersections in different geographic regions and with varying roadway configurations. The ramps and intersections will be identified in both Washington and North Carolina where significant amounts of roadway lighting measurement data overlap with the SHRP

2 data. The ramps and intersections will include locations without lighting to inform the understanding of lighting effects.

- SHRP 2 time series data: time series data from 30 trip segments for each of the 300 ramps and 50 intersections, including 25 nighttime trips (including 12 ramp trips and 13 through trips) and 5 daytime non-peak hour trips (including 3 ramp trips and 2 through trips). The total number of trips may be limited by the SHRP 2 data availability and extraction efforts.
- SHRP 2 events: all nighttime crashes (17), near crashes (87), and 200 baseline events that are interchange or ramp related, or occurred in an interchange area in the entire SHRP 2 database; 70 daytime crashes and near crashes that are interchange or ramp related for comparison; and all nighttime crashes (125) and nighttime near crashes (160) at intersections with 200 baseline events for comparison. For all events, the research team will study events detail data, time series data, eye glance data, and all video files.
- SHRP 2 eye glance data: eye glance data on the analysis segments for 1,000 time series trips randomly selected for the studied ramps and 500 trips for the 50 intersections. For the glance data, the researchers will not only look at the glance directions but also identify the type of glance (i.e., casual checking versus careful observing).
- Crash data: 2010-2014 crashes on the selected ramps and intersections. The research team will verify that the analyzed roadways did not undergo major lighting changes.

Research Approach

Task 1: Conduct kick-off meeting. Within two weeks of project award, the research team will schedule a kick-off meeting with the SHRP 2 task force and WSDOT project management team to discuss in detail project approach and timeline. During the meeting, the research team will work with the panel members to refine the project approach and develop a finalized project plan that are fully agreed by all parties.

Task 2: Undertake SHRP 2 IRP and Data Sharing Agreement Procedures. As soon as the project is awarded, the research team will initiate the SHRP 2 IRB and data sharing agreement process. The research team is familiar with this process based on multiple projects using SHRP 2 data that the research team has collectively worked on in the past. This research uses PII (i.e., SHRP 2 crash locations and event face-view videos), which will require slightly more time for the IRB review. Note that the result of this process is the initial data sharing agreement for the research team to begin data request. During the following tasks, the research team may request addendums to the original data sharing agreement if additional data is needed. This process is requires minimal effort and is typically completed within a few days.

Task 3: Extract SHRP 2 Data and Lighting Data. After the data sharing agreement is in place, the research team will begin to submit data requests to the SHPR 2 data team. Based on Phase I experience, the following are some considerations to optimally extract the data required:

- Communicate frequently with the SHRP 2 data team to ensure the data needs are completely understood,
- Prepare data requests carefully to avoid any potential ambiguities,

- Submit a test data request to ensure data extracted meet the project data needs, and
- Submit the formal data requests for all roadways together to ensure consistency in naming and organization of variables in the extracted data file.

This task involves the extraction of a large number of time series trips and the processing of eye glance data. Both of these tasks are relatively time consuming.

Task 4: Prepare SHRP 2 Data for Analysis. This task involves three major activities:

- Compile ramp and roadway data, which involves both manual and automatic data extraction and population to obtain all roadway variables required for the data analysis, such as ramp type, ramp alignment type, main lane alignment, number of ramp and main lanes, speed limit, traffic volume, auxiliary lane length, speed limit, and functional classification.
- Integrate SHRP 2, lighting, and roadway data. During Phase I, the research team used a highly efficient and relatively accurate spatial data conflation procedure to link all datasets. That procedure was proven to be sufficient for similar analysis and will be followed in general for the Phase II data integration task as well. If needed, the research team can adjust the procedure to better fit the Phase II data.
- Calculate aggregated variables. After all data elements are integrated, the research team will calculate the aggregated variables at the analysis segment level. This includes, for example, the lighting uniformity and illuminance, safety surrogate variables based on time series data, and night-to-day crash ratios.

Task 5: Conduct Data Analysis. During this task, the research team will conduct the analyses specified in the Future Direction section. Most analyses will maintain the same methodology but with larger datasets, including the multiple comparison and MCPs for time series data analysis (including eye glance data analysis), and random parameter negative binomial regression for crash data analysis. The following briefly describes the methodology differences in Phase II:

- Expanded events analysis with all suitable events of the entire SHRP 2 database. The research team will mostly use the same Phase I methodology for this analysis but will extend the analysis with the much larger event data with statistical measures such as odds ratios for different lighting levels. During this analysis, the research team will also look at how the presence and characteristics of lane markings affect driver behavior in conjunction of lighting.
- Analysis of lighting transition areas during time series data analysis. During the Phase II time series analysis, in addition to the five analysis areas at each ramp, the research team will also identify lighting transition areas (i.e., areas where lighting changes between lit to unlit areas) for each ramp. Safety surrogate methods and crash performance will be analyzed for these areas and compared with other areas to identify the safety performance of segments with abrupt lighting transitions.
- Lighting effects at intersections. The research team will use three analysis areas for intersections: 500 ft. upstream of the intersection, the intersection, and a 500 ft. downstream area (mainline only). The analysis of safety surrogate measures and crashes will be conducted by traffic type (i.e., through traffic, left-turn traffic, and right-turn

traffic) and intersection type (e.g., T intersection versus regular intersection). The research team will also take into accounts variables such as traffic volume and lane configuration at the analyzed intersections.

Task 6: Report Preliminary Results to SHRP 2 Task Force. As soon as preliminary results become available, the research team will conduct a meeting with the SHRP 2 task force and the WSDOT project manager to report preliminary findings and their implications. During this meeting, the research team will seek suggestions and directions for developing conclusions and recommendations meaningful to state transportation agencies.

Task 7: Prepare Phase II Deliverables. The research team will develop a comprehensive final research report detailing the research activities and findings. The research team will also develop a detailed plan for Phase III, including an assessment of the scale of impact and potential actions and costs in order to implement the recommendations.

Project Team

The Phase II will mostly maintain the same project team members led by Dr. Ronald B. Gibbons (FIES, Center Director, PI and project manager) as the Phase I experience suggested that the staffing plan was sufficient and successful. Collectively, the research team represents extensive expertise in the areas of roadway lighting, statistical data modeling, GIS data modeling and analysis, highway geometric design, and traffic flow theory. The WSDOT data management team including Dr. John C. Milton (Director: Quality Assurance and Transportation System Safety) and Dr. Ida van Schalkwyk (Traffic Safety Research Engineer) were extremely effective and knowledgeable. In addition to extensive knowledge in data analysis and lighting design, the WSDOT team brings to the project a perspective of state DOTs in terms of safety-related policy making, needs, and priorities.

Project Schedule

Due to the complexity of the Phase II research and the time required for requesting the extended datasets, the research team recommends 24 months to complete the entire project (Figure 5).

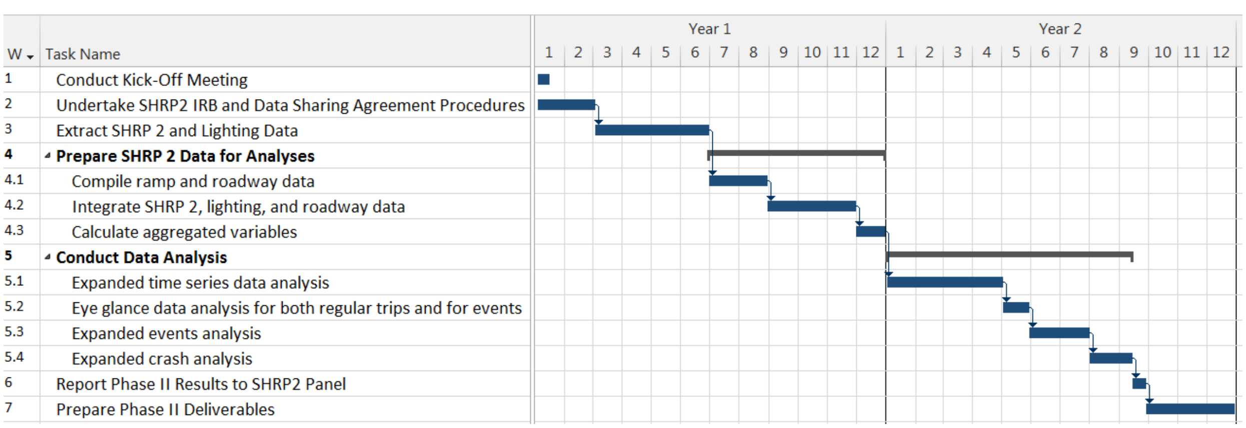

Figure 5: Project Schedule.

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