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

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

Ronnald B. Gibbons, Ph.D., FIES, Center Director, (540)231-1581, rgibbons@vtti.vt.edu

Yingfeng (Eric) Li, Ph.D., P.E., Senior Research Associate, (540) 231-8412, eli@vtti.vt.edu

Alejandra Medina, Senior Research Associate, (540) 231-1508, amedina@vtti.vt.edu

Rajaram Bhagavathula, Ph.D., Senior Research Associate, (540) 241-5209, rbhagavathula@vtti.vt.edu

Center for Infrastructure-Based Safety Systems (CIBSS)

Virginia Tech Transportation Institute, Virginia Polytechnic and State University

3500 Transportation Research Plaza, Blacksburg, VA 24061

Ida van Schalkwyk, Ph.D., Traffic Safety Engineer, (360) 705-7119, vanschi@wsdot.wa.gov

John C. Milton, Ph.D., P.E., Director of Quality Assurance and Transportation System Safety, (360) 704-6363, miltonj@wsdot.wa.gov

Washington State Department of Transportation, Olympia, WA 98504-7325

PHASE II RESEARCH RESULTS

SUMMARY OF PROJECT GOAL AND OBJECTIVE ATTAINMENT TO DATE

Assessing the impacts of roadway lighting on driver behavior and traffic safety is challenging due to the limited information associated with traditional crash data and a lack of detailed lighting information. Utilizing the Virginia Tech Transportation Institute (VTTI) field roadway lighting data and the SHRP2 safety data, this second phase of the SHRP2 IAP safety project is a full scale investigation of the roadway lighting impacts on safety performance and driver behavior. The primary objectives of this research phase 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 freeway mainline on- and off-ramp locations and intersections on surface streets.
- Recommend considerations for changes to current national and state roadway lighting design guidelines.

For both freeway merging/diverging locations at interchanges and intersections on surface streets (principal arterials, minor arterials, and major collectors), the Phase II research includes the following analyses:

- Expanded time series analysis: detailed vehicle kinematic data analysis to understand how exactly roadway lighting characteristics can be correlated with driver behavior variables relevant to safety.
- Eye glance data analysis: analysis of driver visual behavior to understand how visual scanning activities and workload during driving are correlated with lighting characteristics.
- Expanded SHRP2 events analysis: analysis of all available intersection- and mainline on- or off-ramp related SHRP2 crashes, near crashes, and a sample of baseline events, including both detailed event data and the associated video files to determine how lighting may have contributed to these crashes.
- Expanded crash data analysis: traditional crash data analysis for the studied freeway mainline on- and off-ramp locations and intersections to evaluate how the findings from time series, eye glance and event analysis correlate with computed safety performance.

Figure 1 outlines the original project schedule and the project progress by task. As shown in the figure, the Phase II research is a two-year effort with the contract ending in January 2018. At the time when this report is written, the research team has finished a significant portion of the time series data analysis, and made significant progress on the eye glance and event data analyses. Overall, the project is ahead of schedule.

Based on the analysis completed to date, it is likely that the results of this project will lead to preliminary recommendations for:

- Lighting design criteria at freeway merging/diverging locations, including right-lane illuminance and uniformity, overall illuminance and uniformity, and potentially right-lane-overall illuminance ratio;
- Lighting design criteria at intersections, including both intersection approach and box illuminance and uniformity, and box-approach illuminance ratio;
- Lighting design control locations at freeway mainline on- and off-ramp locations and intersections; and
- Warranting conditions for determining if, when, where, and/or how lighting should be used for merging/diverging locations at freeway mainline on- and off-ramp locations and intersections on surface streets.

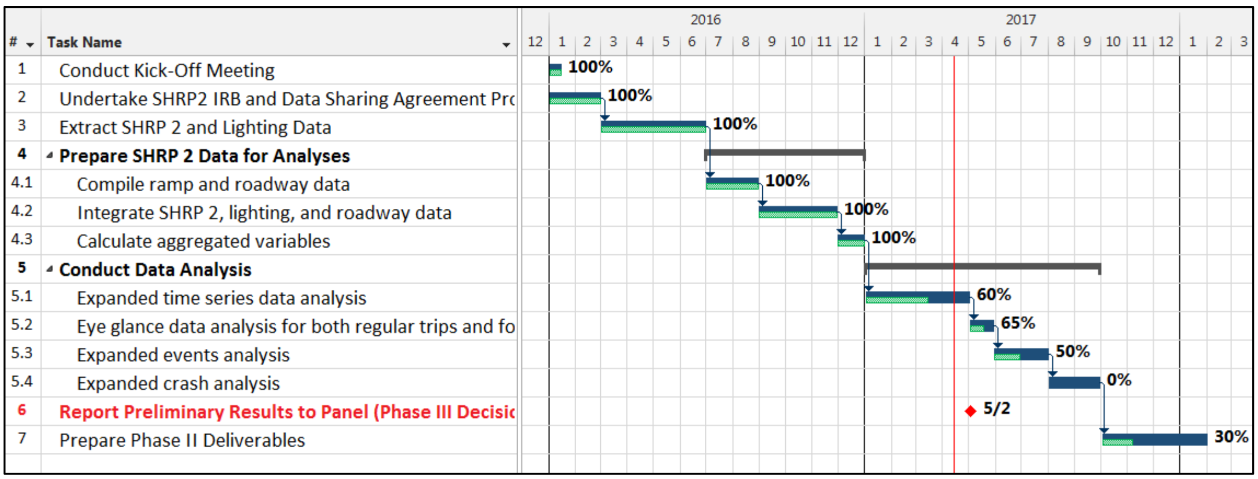

Figure 1. Phase II Project Schedule and Progress (as of 04/05/2017).

The following sections of this summary report includes more detailed information on the preliminary findings and the potential recommendations that may follow upon completion of the analysis for the Phase II project.

DATA AND METHODS USED FOR DATA ANALYSIS

Analysis Methodology

This project involves the following analyses: SHRP2 time series data analysis, SHRP2 events analysis, SHRP2 eye glance analysis, and crash analysis.

- **SHRP2 time series data analysis**: the analysis is being conducted for freeway merging/ diverging locations and surface street intersections. The freeway analysis is organized by traffic type (i.e., merging/diverging vs. through), location type (i.e., merging or entrance ramp vs. diverging or exit ramp), and driver type (i.e., all drivers vs. drivers 65 and older). The intersection analysis is organized by maneuver (i.e., straight through, left turn, and right turn), trip type (i.e., stop vs. non-stop), and driver type (i.e., all drivers vs. drivers 65 and older). The time series data analysis is designed to identify significant correlations between lighting metrics and driver behavior variables relevant to safety. This analysis serves as the basis for identifying critical lighting design criteria.

The lighting variables involved in this analysis are:

- Right lane illuminance (E_{right}) and uniformity (U_{right}),
- Overall illuminance (E_{all}) and uniformity (U_{all}), and
- Right lane-overall illuminance ratio (E_{right}/E_{all}).

The driver safety performance measures include:

- Speed in mph relative to speed limit (ΔV), mean (ΔV-μ) and standard deviation (ΔV-σ).
- Lateral (a_{lat}) acceleration rate, mean (a_{lat}-μ) and standard deviation (a_{lat}-σ).
- Longitudinal (a_{long}) acceleration, mean (a_{long}-μ) and standard deviation (a_{long}-σ).
- Lane offset from center (L_{off}), mean (L_{off}-μ) and standard deviation (L_{off}-σ).
- Mean time to collision (TTC).

Figure 2 and Figure 3 show the analysis segments for freeways and intersections, respectively.

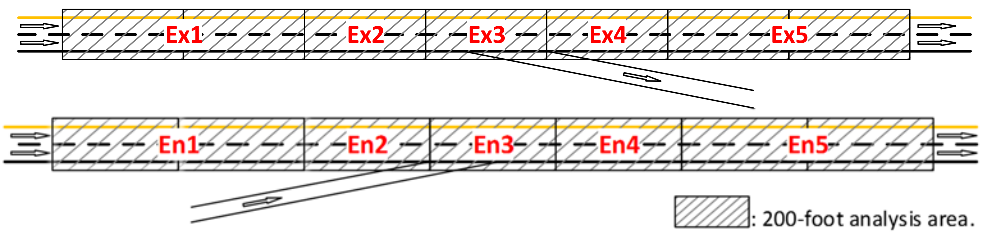

Figure 2. Analysis Areas at Entrance and Exit Ramps.

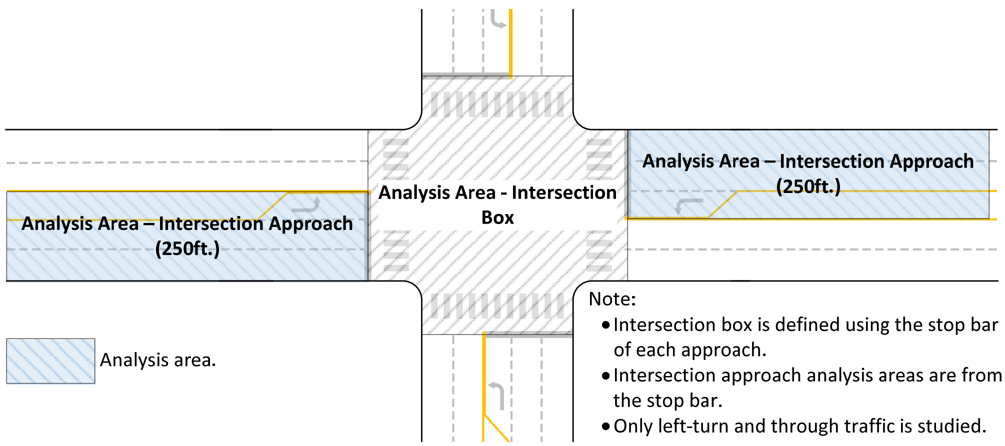

Figure 3. Analysis Areas at Entrance and Exit Ramps.

- **SHRP2 events analysis**: the events analysis includes all the SHRP2 nighttime interchange- or intersection-related crashes and near-crashes. During this analysis, the research team is examining the forward-facing and face videos to understand in-depth how each event occurred and if lighting may reduce the potential for crashes. This analysis also includes development of logistic regression models of the event detail data to identify correlation with driver behavior that may affect the factors leading to a crash or near miss.

- **SHRP2 Eye glance data analysis**: this analysis evaluates the visual driver for a sample of the trips included in the time series analysis. The eye glance data variables included:

    - Percent forward dwell time,
    - Percent right window/mirror dwell time,
    - Percent left window/mirror dwell time,
    - Percent right windshield dwell time,
    - Percent left windshield dwell time,
    - Percent distracted dwell time, and
    - Visual entropy, which is a commonly used indicator of the degree of how randomly a driver's eye glances were located among the different targets and throughout each study period. High randomness of visual scan behavior arguably implies that the driver's visual task is relatively casual while low randomness implies concentration or higher visual workload (*1*, *2*). Visual entropy in this study was calculated as:

    $$E = -\frac{1}{2.08}\sum_{i=1}^{n} p(x_i)lnp(x_i)$$

    Where E is the entropy of the analyzed eye glance data, x_i is an individual eye glance location, and $p(x_i)$ is the probability (proportion in this case) of x_i in the analyzed time period. 2.08 is a constant determined based on the eye glance data to normalize E onto a 0-1 scale, with 1 indicating highest randomness. The driver age information in the SHRP2 data allows this variable to be analyzed for different age groups.

- **Crash data analysis**: the research team will analyze the police-reported nighttime crashes between 2010-2014 for the studied freeway locations and intersections. The purpose of this study is to provide insights on the nighttime safety performance of these locations and evaluate how findings from the naturalistic driving data analysis correlate with actual nighttime safety performance.

Figure 4 illustrates in detail the types of analyses conducted during this project and their steps and expected outcomes. All statistical analyses were conducted using the SAS® software.

Data Description

Table 1 through Table 4 present detailed descriptions and statistics of the data used during this research phase. All intersections and freeway interchanges analyzed in this study are located in North Carolina and Washington State. The SHRP2 time series data processing involved a large amount of data, and required the integration of roadway, lighting, and driver behavior data.

---

1. Angell, L., S. Aich, J. Antin, and B. Wotring. *An Exploration of Driver Behavior during Turns at Intersections (for Drivers in Different Age Groups)*. Report #17-UM-047, National Surface Transportation Safety Center for Excellence. June 2015.
2. Tole, J. R., A. T. Stephens, M. Vivaudou, A. R. Ephrath, and L. R. Young. Visual Scanning Behavior and Pilot Workload. Report NASA-CR-3717, National Aeronautics and Space Administration, 1983.

During the data processing, the research team used a variety of relational database and spatial conflation techniques.

In addition to the existing SHRP2 NDS data variables, the research team manually collected a large number of variables based on video files and satellite images, including particularly detailed roadway, event, and trip variables.

Note that the research team has obtained the crash data, but has not processed the data yet.

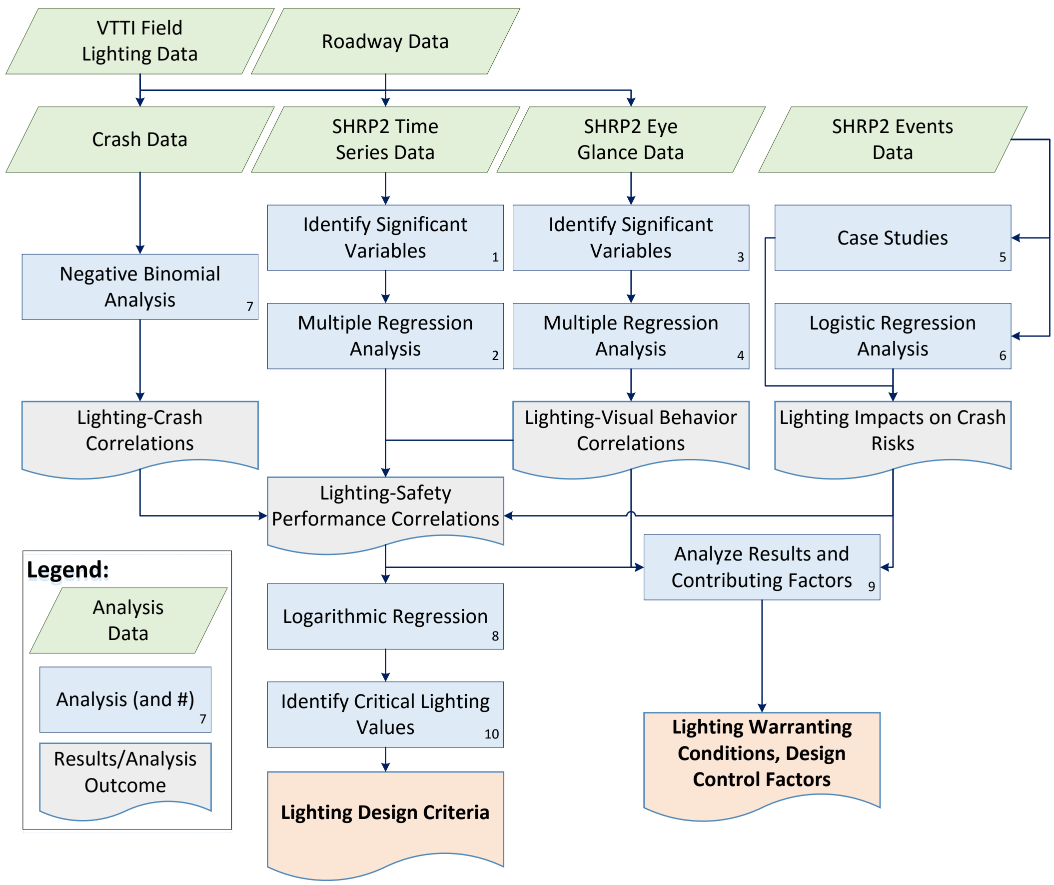

Figure 4. Phase II Data Analysis Methodology.

Table 1. Total Roadway Locations Analyzed.

Roadway	Original	Final
Total Freeway Merging/Diverging Locations	305	246
Entrance Ramps (Merging)	141	118
Exit Ramps (Diverging)	164	128
Intersection	62	62

Table 2. Overview of SHRP2 Events Analyzed.

Relation To Junction	Crash	Near-Crash	Balanced-Sample Baseline	Total
Entrance/Exit ramp	9	19	94	**122**
Interchange area	11	53	106	**170**
Intersection	70	92	200	**362**
Intersection-related	49	70	-	**119**
Total	**139**	**234**	**400**	**773**

Table 3. Time Series and Eye Glance Data Statistics.

SHRP2 Time Series and Eye Glance Data	Requested	Extracted	Analyzed	Total Drivers	Drivers ≥ 65
Freeway time series trips	**10,340**	**11,671**	**11,558**	**1,724**	**360**
Merging/diverging trips	4,440	4,959	4,959	881	186
Through trips	5,900	6,712	6,599	843	174
NDS data rows	-	4,449,641	1,363,719	-	-
Data aggregated by analysis segment-merging/diverging	-	-	15,051	-	-
Data aggregated by analysis segment-through	-	-	30,993	-	-
Intersection time series trips	**4,175**	**2,128**	**1,954**	**1,113**	**240**
Through trips	1,575	1,610	1,459	853	187
Left-turn trips	1,560	249	236	142	27
Right-turn trips	1,040	269	259	118	26
NDS data points	-	1,023,194	425,142	-	-
Aggregated Data Points for Analysis - approach	-	-	1,968	-	-
Aggregated Data Points for Analysis - box	-	-	1,968	-	-
Freeway eye glance data trips	**1,000**	**852**	**852**	**485**	**52**
Merging/diverging trips	500	388	388	234	27
Through trips	500	464	464	251	25
Eye glance data points	-	148,425	148,425	-	-
Aggregated Data Points for Analysis	-	-	3,374	-	-
Intersection eye glance data trips	**602**	**538**	**538**	**307**	**46**
Through trips	357	328	328	156	24
Left-turn trips	143	113	113	73	8
Right-turn trips	102	97	97	78	14
Eye glance data points	-	165,915	165,915	-	-
Aggregated Data Points for Analysis	-	-	538	-	-

Table 4. Data Variables Involved in Phase II.

No.	Intersection	Freeway	Events	Trip	Driver
1	AADT	AADT	Lighting Area	Time	Age
2	Approach control type	Area	Lighting Condition	Duration	Frequency
3	Approach crosswalk	Auxiliary Lane	Object Height	Maneuver	-
4	Approach Func_Class	Facility Type	Object Retroreflectivity	Trip Type - Stop	-
5	Approach left-turn lane length	Left Shoulder Barriers	Object Visibility	Trip Type - Traffic	-
6	Approach Median	Left Shoulder Width	Roadside Object Location	Traffic Light	-
7	Approach Median Width	Main-Lane Geometric Alignment	Visual Direction	Traffic Level	-
8	Approach No. of lanes	Main-Lane Speed Limit	Visual Type	Work Zone	-
9	Approach No. of left-turn lanes	Median type	Conflicting Object	Weather	-
10	Approach No. of right-turn lanes	Median width	Alignment	-	-
11	Approach No. of through lanes	Number of Main Lanes	Construction Zone	-	-
12	Approach right-turn lane length	Number of ramp lanes	Driver Impairments	-	-
13	Approach speed limit	Pavement type	Driver Behavior	-	-
14	Approach width of lane	Ramp Geometric Type	Event Severity1	-	-
15	Area	Ramp Speed Limit	Fault	-	-
16	Bike Lane on approach	Ramp Type	Final Narrative	-	-
17	Bike lane on exit	Right Shoulder Guardrail	Grade	-	-
18	Distance from last intersection	Right Shoulder Width	Incident Type	-	-
19	Distance to first driveway	-	Intersection Influence	-	-
20	Distance to signalized intersection	-	Lighting	-	-
21	Exit crosswalk	-	Maneuver Judgment	-	-
22	Exit Func_Class	-	Precipitating Event	-	-
23	Exit Median	-	Pre Incident Maneuver	-	-
24	Exit Median Width	-	Relation To Junction	-	-
25	Intersection alignment	-	Secondary Task	-	-
26	Intersection geometry	-	Surface Condition	-	-
27	Intersection type	-	Traffic Flow	-	-
28	On street parking on approach	-	Traffic Density	-	-
29	On street parking on exit	-	Weather	-	-
30	Pavement type	-	-	-	-

No.	Intersection	Freeway	Events	Trip	Driver
31	Sidewalk on approach	-	-	-	-
32	Sidewalk on exit	-	-	-	-
33	Type of last intersection	-	-	-	-

FINDINGS TO DATE

Time Series Data Analysis Results

The research team has completed a significant proportion of the time series data analysis, except for two additional lighting variables: the ratio of right lane illuminance to overall illuminance for freeways and the ratio of box illuminance to approach illuminance for intersections. These two new variables will be added soon to complete all time series analysis tasks.

Table 5 to Table 7 show examples of the time series analysis results, including the significant correlations between lighting variables and driver behavior variables for: (1) mainline on-and off ramp locations – all drivers and through traffic; (2) mainline on-and off ramp locations – all drivers and diverging traffic; (3) mainline on-and off ramp locations – all drivers and merging traffic; and (4) intersections – all drivers. Not discussed in this report are findings for time series analysis for senior drivers (i.e., drivers 65 and older) due to limited space this information will be shared in a future report. A correlation is identified as significant in this analysis when the model R^2 is great than 0.0625 (i.e., with the R value greater than 0.25) and p-Value is less than 0.05. A sample list of complete models (including non-lighting variables and major goodness-of-fit statistics) using the analysis for freeway merging/diverging traffic and all drivers as an example is included in the Appendix section.

To simplify the correlation results, the research team only included an arrow for each significant correlation to indicate if it is a positive or negative correlation. For example, to obtain the significant correlations between $\Delta V\text{-}\mu$ and the four lighting variables for EX1 (first analysis segment at exit ramp locations) for diverging traffic, all drivers (see highlighted cells in Table 5), the research team fitted the following multiple regression model ($R^2 = 0.10$, $p\text{-}Value < 0.01$):

$$\Delta V\text{-}\mu = 8.9 + 0.22\,E_{all} - 0.30\,E_{right} + 1.9\,No\_Ramp\_Lns - 7.5Area - 4.8Facility\_Type - 1.4\,MainLn\_Geom\_Alligmt + 3.0No\_Mainlan\_Grp + 0.96Ramp\_Spd - 0.70Median\_Wdth - 0.94Trp\_Frqnc$$

This model shows that, there is a positive correlation (➚) between $\Delta V\text{-}\mu$ and E_{all}, a negative correlation (➘) between $\Delta V\text{-}\mu$ and E_{right}, at EX1 for diverging traffic and all drivers (as shown in Table 5). The model is highlighted in gray in Table 12 (see Appendix).

Table 5. Significant Correlations at Freeway Mainline On- or Off-Ramp Locations – All Drivers, Merging/Diverging Traffic.

Variable	E_{all} (Overall illuminance)			E_{right} (Right lane illuminance)			U_{all} (Overall uniformity)			U_{right} (Right lane uniformity)		
Diverging Traffic												
Segment	EX1	EX2	EX3	EX1	EX2	EX3	EX1	EX2	EX3	EX1	EX2	EX3
ΔV-μ	↗	-	↘	↘	-	-	-	-	-	-	-	↗
ΔV-σ	-	-	↗	-	-	-	-	-	-	-	-	↘
a_{long}-μ	-	-	-	-	-	-	-	-	↗	-	↗	↗
a_{long}-σ	↗	↗	-	-	-	-	↗	↘	-	-	-	↘
a_{lat}-μ	↗	-	↘	↗	-	-	↗	↘	-	-	↗	↘
a_{lat}-σ	↗	-	-	↘	-	-	↗	↗	-	↘	-	↘
L_{off}-μ	-	↘	-	-	-	-	-	-	-	-	-	-
L_{off}-σ	-	-	-	-	-	-	-	-	-	-	-	-
TTC	-	-	-	-	-	-	-	-	-	-	-	-
Merging Traffic												
Segment	EN3	EN4	EN5	EN3	EN4	EN5	EN3	EN4	EN5	EN3	EN4	EN5
ΔV-μ	↘	-	-	-	-	-	-	-	-	-	-	-
ΔV-σ	-	↗	-	-	-	-	-	-	-	-	-	-
a_{long}-μ	-	↘	-	-	-	↘	-	-	↘	-	-	↗
a_{long}-σ	-	-	-	-	-	-	-	-	-	-	-	-
a_{lat}-μ	-	-	-	-	-	-	-	↘	↘	-	↗	-
a_{lat}-σ	-	-	-	-	-	-	-	-	↗	-	-	↘
L_{off}-μ	-	-	-	-	-	-	-	-	-	-	-	-
L_{off}-σ	-	-	-	↗	-	-	↗	-	-	-	-	-
TTC	-	-	-	-	-	-	-	-	-	-	-	-

Table 6. Significant Correlations at Freeway mainline On- or Off-Ramp Locations – All Drivers, Through Traffic.

Variable	E_{all} (Overall illuminance)					E_{right} (Right lane illuminance)					U_{all} (Overall uniformity)					U_{right} (Right lane uniformity)				
Through Traffic at Entrance Ramp Locations																				
Segment	EN1	EN2	EN3	EN4	EN5	EN1	EN2	EN3	EN4	EN5	EN1	EN2	EN3	EN4	EN5	EN1	EN2	EN3	EN4	EN5
ΔV-μ	-	-	-	-	-	-	-	-	-	-	-	-	↘	-	-	↘	↗	-	-	↘
ΔV-σ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	↘	-	-	-	-	-
a_{long}-μ	↗	-	-	-	-	↘	-	-	↘	-	↗	-	-	-	↘	-	-	-	-	↗
a_{long}-σ	↗	↗	↗	↗	↗	-	-	-	↗	↘	↗	-	↘	-	↘	-	-	-	-	-
a_{lat}-μ	↗	-	↗	-	-	↘	-	↘	↘	-	↗	↘	-	↘	-	-	↗	-	↗	↘
a_{lat}-σ	↘	-	↗	-	-	↗	-	-	-	-	-	↗	-	↘	↘	↗	-	-	-	-
L_{off}-μ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L_{off}-σ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TTC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Through Traffic at Exit Ramp Locations																				
Segment	EX1	EX2	EX3	EX4	EX5	EX1	EX2	EX3	EX4	EX5	EX1	EX2	EX3	EX4	EX5	EX1	EX2	EX3	EX4	EX5
ΔV-μ	-	-	-	-	-	-	-	-	↘	-	-	-	-	-	↗	-	-	-	-	-
ΔV-σ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
a_{long}-μ	-	↗	-	-	-	-	↘	-	-	↘	-	-	↗	-	↗	-	↗	↘	-	-
a_{long}-σ	-	-	↗	-	-	-	-	↘	↗	↗	↗	-	-	-	-	-	-	-	↗	-
a_{lat}-μ	↗	-	↗	-	↗	-	-	↘	↗	↘	↗	-	-	↗	-	↘	-	-	-	-
a_{lat}-σ	↘	-	↗	-	↘	↗	-	↘		↗	-	-	-		↗	-	-	-	-	↗
L_{off}-μ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L_{off}-σ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TTC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 7. Significant Correlations at Intersections – All Drivers.

Variable	Trips Stopped at Intersection						Trips Did not Stop at Intersection					
	E_{all} (Overall illuminance)			E_{right} (Right lane illuminance)			U_{all} (Overall uniformity)			U_{right} (Right lane uniformity)		
	T	L	R	T	L	R	T	L	R	T	L	R
Intersection Approach												
ΔV-μ	↗	↗	↗	-	-	-	-	↗	↗	-	↗	-□
ΔV-σ	-	-	-	-	-	-	↗	-	↗	-	-	-
a_{long}-μ	-	-	-	↘	-	-	↗	-	□	-	-	-
a_{long}-σ	-	-	-	-	-	-	-	-	↗	-	-	-
a_{lat}-μ	↘	-	↗	-	-	-	-	-	↗	-	-	↗
a_{lat}-σ	↘	-	-	-	-	-	↗	-	-	-	-	-□
Intersection Box												
ΔV-μ	-	-	-	-	-	-	-	-	↘	-	-	-
ΔV-σ	-	-	-	-	-	-	-	↗	-	-	↘	-
a_{long}-μ	-	-	-	-	-	-	-	-	-	-	-	-
a_{long}-σ	-	-	-	-	-	-	-	-	-	-	-	-
a_{lat}-μ	↘	-	-	↘	-	-	-	-	-	-	-	-
a_{lat}-σ	-	-	-	-	-	-	↘	-	-	-	-	-

Note: T = through traffic; L = left-turning traffic; R = right-turning traffic.

Based on the preliminary results, significant correlations were found primarily for longitudinal and lateral acceleration-related variables, indicating the likely effects of roadway lighting characteristics on speed change and lane change behavior for mainline freeway segments at on and off ramp locations may be limited. In addition, more correlations were found for diverging traffic (i.e., traffic exiting main lanes) than for merging traffic (i.e., traffic entering main lanes) at freeway mainline on- or off-ramp locations. In terms of intersections, the analysis indicated more significant correlations with the driver behavior variables on intersection approaches than within the intersection boxes.

Eye Glance Data Analysis Results

The research team has completed eye glance data analysis for freeway merging and diverging locations. The eye glance data analysis for intersections are currently underway. Table 8 and Table 9 show the major correlations identified during this analysis thus far. In general, the research team did not find many significant correlations for freeway mainline on- or off-ramp locations between lighting variables and visual behavior. This observation is somewhat expected due to the limited eye glance tasks required to complete the driving tasks on freeway mainline segments at on or off ramps during nighttime conditions. Due to the limited sample size for senior drivers, the results were not statistically significant for most models for the freeway mainline segment analysis.

Table 8. Correlations for Visual Behavior at Freeway Mainline Ramp Locations –Through Traffic.

Variable	Segment		Intercept	E_{all}	E_{right}	U_{all}	U_{right}	E_r/E_{all}	Ramp Speed Limit	Model R^2	Model p-Value
Forward Dwell Percent	EN4	Parameter	0.68	-	-	**0.01**	-	-	-	0.07	0.09
		Pr > |t|	<0.01	-	-	**0.04**	-	-	-		
Left Window/ Mirror Dwell Percent	EN2	Parameter	-0.03	**8.9E-03**	**-7.9E-03**	-	-	-	0.04	0.10	0.02
		Pr > |t|	0.21	**0.01**	**0.02**	-	-	-	0.04		
Right Windshield Dwell Percent	EN3	Parameter	-0.03	**9.9E-03**	-	-	-	-	-	0.07	0.07
		Pr > |t|	0.33	**0.03**	-	-	-	-	-		

Entropy	EN4	Parameter	0.19	-	**0.02**	**-5.9E-03**	-	-	-	0.10	0.01
		Pr > |t|	0.01	-	**0.04**	**0.03**	-	-	-		

Table 9. Correlations for Visual Behavior at Mainline Ramp Locations – All Drivers, Merging/Diverging Traffic.

	Segment		Intercept	E_{all}	E_{right}	U_{all}	U_{right}	E_r/E_{all}	Ramp Geometric Type	Model R^2	Global p-Value
Forward Dwell Percent	EN4	Parameter	0.92	-	-	-	-	**-0.29**	-	0.07	0.05
		Pr > |t|	<.0001	-	-	-	-	**0.04**	-		
Right Window/Mirror Dwell Percent	EN5	Parameter	-0.03	-	-	-	-	**0.05**	-	0.07	0.04
		Pr > |t|	0.20	-	-	-	-	**0.02**	-		
Left Windshield Dwell Percent	EX3	Parameter	3.6E-03	-	-	-	-	**1.0E-03**	-	0.14	<0.01
		Pr > |t|	0.75	-	-	-	-	**0.05**	-		
Entropy	EN4	Parameter	0.05	-	-	-	-	**0.25**	-0.08	0.11	0.01
		Pr > |t|	0.63	-	-	-	-	**0.01**	0.02		

Events Data Analysis Results

The research team is currently conducting a descriptive analysis and a logistic regression analysis to identify likely impacts of lighting conditions on event likelihood. The descriptive analysis results will be used to further evaluate findings from the time series analysis results and the development of recommendations for lighting design related guidelines. During the logistic regression, the research team will particularly look at presence of lighting and how lighting characteristics may have impacted event likelihood (e.g., crash versus near crash). Notice that lighting traditionally has been put at intersections and interchanges after considering their crash history or based on a potential for crashes through the warranting process. These warrants also traditionally include consideration of traffic volume. As a result, the crash frequency at intersections and interchanges with lighting may be higher than those of intersections without lighting.

IMPLICATIONS OF PRELIMINARY PHASE II FINDINGS

Previous research on the impacts of roadway lighting on safety performance 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*). Results of those studies varied significantly with some pointed to a positive safety impact associated with lighting. Many of these studies also relied on crash rates or daytime-nighttime crash rate ratios. These analysis methods are highly unreliable and some agencies, such as WSDOT no longer use crash rates for any decisions during project development or system management. A recent research effort by Van Schalkwyk et al (*4*) indicated with random parameter modeling that continuous lighting on limited access freeways in WA State had no measurable safety performance impacts. Many of the previous studies lacked the inclusion of detailed lighting measurement data, relying on

3. Box, P. C. "Major road accident reduction by illumination." *Transportation Research Record: Journal of the Transportation Research Board, No.1247*, 32–38, 1989.
4. Van Schalkwyk, I., N. Venkataraman, V. Shankar, J. Milton, T. Bailey, and K. Calais. Evaluation of the Safety Performance of Continuous Mainline Roadway Lighting on Freeway Segments in Washington State. Report WA-RD 855.1, Washington State Department of Transportation, March 2016.

general indicators of lighting presence but not identifying lighting characteristics. An analysis in 1971 attempted to determine the relationship between crash rates and illumination levels (*5*). However, the study did not find statistically significant correlations between different illumination levels and crash rates. The most comprehensive study of the lighting level and crash rate to date was an analysis of crash rate ratio and lighting level on over 1000 miles of roadway (the lighting data from that study is used as part of this investigation). In this case, the team identified correlation between crashes and lighting presence and characteristics in some cases (*6*).

The current *FHWA Lighting Handbook*, a lighting need can be justified based on a warrant analysis (showing that lighting is a warranted safety feature), a project criteria document showing that AASHTO or IES design criteria are used for the design, and a safety analysis showing that a lighting system is a cost-effective safety alternative (*7*). The warranting conditions included in the FHWA guide are limited to AADT, interchange and intersection density, and night-to-day crash ratios, without sufficiently addressing of different roadway characteristics or contexts. The latest national lighting design standard ANSI/IES RP-8-14 *Roadway Lighting* (*8*) includes updated criteria for roadway lighting at interchanges and intersections. The design criteria are mostly based on experience and consensus rather than scientific results, leading to what some may argue high lighting levels and uniformity requirements. For example, the earlier FHWA effort for adaptive lighting has shown that lighting levels slightly lower than the current standards might be just as beneficial based on crash and field lighting data (*6*).

This study is the first of its kind because of the availability and use of the SHRP2 NDS data and the VTTI field lighting measurement data. It is the first comprehensive lighting study for freeway mainline ramp locations, and to a limited extent, intersections, by analyzing both crash and driver behavior data. The findings of this study will likely result in targeted and more sustainable (potentially more energy conservative) lighting design criteria. In addition, this study will also provide insights on warranting factors and design controls for lighting design at mainline ramp locations and intersections.

Currently, none of the national and state lighting design guides consider the concepts of right lane-overall illuminance ratio and intersection box-approach ratio as part of the justification or design process. In the case of intersection design, current standards typically simply add the lighting levels of both intersecting streets as to the amount of lighting that should be provided for intersection box, although many recognize that this method likely results in excessive lighting being required to support safety performance. This research will provide insights and recommendations directly leading to new criteria for these two topics.

Note that this research has not reached the conclusion and recommendation stage yet and therefore no preliminary recommendations have been developed. Recommendations will be provided for the following lighting characteristics minimum illuminance values, illuminance

5 . Box, P. C. *Relationship between illumination and freeway accidents*. Illuminating Engineering Research Institute, 1971.
6. Gibbons, R., F. Guo, A. Medina, T. Terry, J. Du, P. Lutkevich, and Q. Li. *Design Criteria for Adaptive Roadway Lighting*. Report No. FHWA-HRT-14-051, Virginia Tech Transportation Institute, July 2014.
7. Lutkevich, P., D. McLean, and J. Cheung. *FHWA Lighting Handbook*. Parsons Brinckerhoff, Boston, MA, August 2012.
8. *Roadway Lighting*. ANSI/IES RP-8-14, Illuminating Engineering Society.

ratios, warranting conditions, and design areas/controls after completing all analyses. The following sections include more details on the potential findings.

PHASE III IMPLEMENTATION PLAN

IMPLICATIONS OF FINDINGS AND IMPLEMENTATION PLAN

Implications of Findings for Countermeasure Implementation

The preliminary findings of this project showed significant correlations between driver safety performance variables and roadway lighting characteristics. Combining these results with findings from the events and crash data analysis, the project findings will likely have significant impacts on several aspects of current lighting design standards and guidance.

Lighting design criteria. The research team will use the following procedure to develop preliminary lighting design criteria:

- Identify statistically significant correlations for determining lighting criteria. Among the various correlations identified during time series and eye glance data analyses, the research team will select a subset of correlations critical to the development of lighting criteria. This selection will be based on a combination of factors, including the safety performance implications of variables, the correlation coefficients of models, the coefficients of lighting variables in individual models, and p-Values of each individual variable.

- Identify potential lighting design criteria related to each lighting characteristic. For each lighting characteristic, there can be several slightly different potential critical values identified based on the statistical analysis. For example, a method for identifying lighting criteria for each pair of lighting and driver behavior related variable is to identify the critical lighting level that would minimize the variance of the driver behavior related variable (e.g., mean lateral acceleration) among different drivers by plotting the observations of the mean standard deviation of the safety variable by lighting level.

  After this process, multiple criteria can be selected for each lighting variable based on multiple significant correlations with driver behavior variables. The research team will evaluate the magnitude of correlations with each of the lighting characteristics and determine a single potential critical value for each lighting variable (e.g., illuminance or uniformity) and location (e.g., intersection box or EX3). For each lighting variable, the research team may use the arithmetic mean value determined by different safety variable correlations, a weighted mean for different safety performance variables based on their correlation coefficient and perceived importance, or the value dictated by the correlation that has the highest correlation coefficient.

  The identified critical values will be used as the basis for phase III to identify the final recommended design criteria. The final design criteria will be developed based on the preliminary criteria, existing lighting design standards, and input from stakeholders and designers. The research team will use findings from the older driver (65 and older) analysis to the extent possible, possibly in the form of a older driver weighting factor.

The following presents an example of the identification of critical illuminance levels based on the findings from this study. The correlations with the mean lateral acceleration (a_{lat}-μ) for segment EX3, diverging traffic, and all drivers (highlighted in light green in Table 12 of Appendix) had a R^2 of 0.28 (R value of 0.5) and p-Value less than 0.01. Figure 5 shows the plot of mean standard deviation of a_{lat}-μ by illuminance. From the figure, a critical illuminance of approximately 8.5 lux can be identified to minimize mean standard deviation of a_{lat}-μ, which can be considered as a potential minimum design value for E_{all} at EX3. This value is within the illuminance range recommended by AASHTO and IES for freeways (i.e., 8-12 lux). Note that illuminance values will need to be converted to corresponding illuminance or luminance values at the ground level during later stages of Phase II.

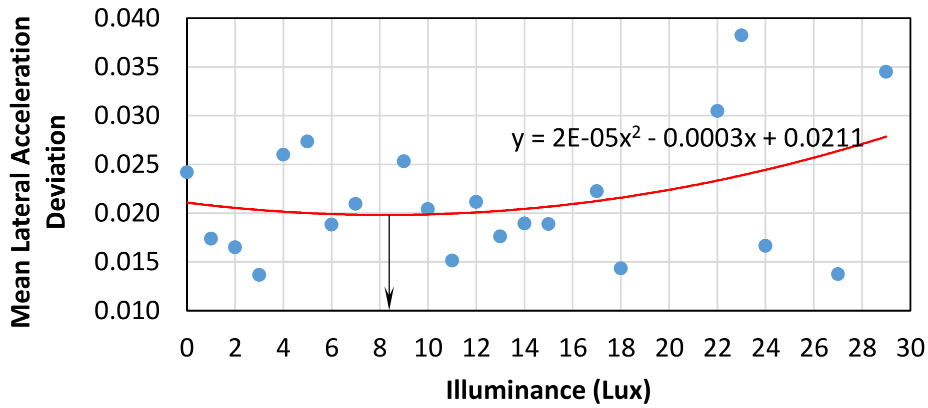

Figure 5. Mean Lateral Acceleration Deviation by Overall Illuminance – Merging/Diverging Traffic, EX3, All Drivers.

Lighting design warranting conditions. In the multivariate correlation modeling process, the research team identified a number of roadway, traffic, and/or trip variables that are significantly correlated with the driver behavior related variables in the study. The research team will compare and analyze these variables based on different correlation models (i.e., for different safety performance variables). Such findings will provide important justification and research evidence for updating several lighting warranting conditions. The results are likely to significantly extend the warranting factors that need to be considered when analyzing lighting needs and specific lighting characteristics.

For example, in the correlation model for the previous example (i.e., overall illuminance, EX3, diverging traffic, and all drivers), main lane geometric alignment, number of main lanes, ramp speed limit, auxiliary lane, right shoulder width, median width, pavement type, continuous lighting, trip duration, and trip frequency are significantly correlated with a_{lat}-μ (see Appendix). These variables will be further analyzed to determine the magnitude and nature of their likely impact, and feed into potential warrant identification.

Lighting design controls. The results of the freeway time series data analysis will provide important insight into lighting needs and criteria at 200-ft segment and lane levels for mainline freeway segments at on and off-ramps, and for intersection approach and boxes. The research team is currently conducting events analysis and expects that some results of this analysis will provide additional valuable insights particularly relevant to where and how roadway lighting at a microscopic level may impact driver behavior relevant to safety. Results like these will likely lead to lighting guidelines for designers on lighting control locations (or focuses) within a lighted area when designing and modeling lighting for freeway mainline on- and off-ramp locations and intersections.

New lighting design concepts. During this project, the research team introduced the concepts of right lane illuminance (traditionally lighting for freeways is designed for the entire segment regardless of lanes) and right lane-overall illuminance ratio for freeway mainline on- and off-ramp locations, and box-approach illuminance ratio for intersections. Findings and recommendations relevant to these concepts will further improve lighting design guidelines and practice. Existing lighting standards significantly lack guidance at such design areas/topics.

Lighting as a behavioral crash reduction countermeasure at intersections and freeway mainline on- and off-ramp locations. This research is providing findings that will help the engineering community to improve their understanding of how lighting characteristics can affect driver behavior in different contexts. These insights can potentially offer tools to engineers where lighting characteristics can be modified in order to bring about driver behavioral change. For example, if an intersection is identified to have a larger proportion of speed related crashes at nighttime, lighting characteristics at the intersection might be adjusted accordingly in conjunction with other countermeasures to reduce speeding at the intersection. This approach holds particular promise because of the increased use of adaptive lighting and conversions to Light Emitting Diodes (LED) luminaires with advanced controllers. The research team will develop guidelines on this topic during the Phase III of this project.

Other lighting design concepts and design-relevant issues. In addition to this project, members of this research team have conducted a large number of other national and state lighting studies at intersections and freeways, including evaluating and understanding the LED technology and the adaptive lighting design concept. This experience along with demonstrated performance in development of lighting criteria and warrants will allow the research team to develop comprehensive and practical roadway lighting design guidelines that will significantly benefit transportation agencies and the traveling public.

Implementation Plan

Task 1: Recommend modifications to existing lighting design guides and standards. The Phase II research will result in a number of findings to assist practitioners for selecting appropriate lighting designs. With the performance goals for lighting, minimizing energy use and any negative impacts of lighting, the Phase II findings support the update of current lighting design criteria (e.g., minimum illuminance, warrants, and design control locations) and introduce new lighting design concepts (e.g., right lane-overall illuminance ratio and intersection box-approach illuminance ratio). The preliminary recommendations in Phase II will need to be verified and finalized with inputs from the design, policy, and engineering communities. This task includes the following activities:

- Identify specific national and state design standards that need to be revised. During this activity, the research team will conduct a comprehensive and in-depth assessment of specific design guidelines/requirements that likely need to be revised based on the Phase II findings. These will include: minimum illuminance veiling luminance ratio and uniformity criteria, warranting conditions for lighting at freeway mainline on- and off-ramp locations and intersections, design procedures, and roadway locations/features for design control.

  In addition, the research team will introduce new and emerging design concepts such as right lane-overall illuminance, and intersection box-approach illuminance ratios, adaptive lighting, and lighting as a countermeasure to affect driver behavior and in turn target behavioral factors that are associated with increased crash potential at locations.

  The lighting design guides to be analyzed will include, at a minimum, the IES *Roadway Lighting* (ANSI/IES RP-8-14), the AASHTO *Roadway Lighting Design Guide*, the FHWA *Roadway Lighting Handbook*, and WSDOT and other states' (if selected) roadway lighting design guidelines.

- Solicit input from stakeholders. During this subtask, the research team will conduct a number of interviews with practitioners to discuss the potential lighting design changes. Examples of interviewees include staff responsible for safety programs and major electrical systems at State DOTs, State DOT leads that are responsible for the development of design manuals, and lighting designers at state transportation agencies and private companies. Interviews will in person, or through conference calls or webinars. The research team will also reach out to IES Roadway Lighting Committee, AASHTO Lighting Committee, FHWA, SHRP IAP panel and TRB task forces and committees through emails, and/or conference calls.

- Recommend changes to existing lighting design and operations guidelines. Based on research findings and feedback gathered during the interviews, the research team will recommend modifications to text and exhibits of existing lighting design guides.

Task 2: Develop tools to support and facilitate state roadway lighting design. Currently, lighting design guides and practices at different states vary significantly. Some states are use a significant amount of lighting while others only provide minimal lighting. There are also states who do not own and maintain any lighting on state roadways. To guide lighting design at the state, some DOT have developed robust lighting design guidelines in their state manuals. During this task, the research team will develop user-friendly tools to assist designers for safety performance oriented lighting designs. Example tools include guidelines to review their lighting design criteria to incorporate safety performance into their decision-making process, checklists of steps and/or factors to address during lighting designs, and decision making matrices to facilitate lighting design, treatment, and/or maintenance for designers, project managers, and safety engineers. To ensure the tools can be easily used and implemented, the research team will most likely develop the tools in Microsoft Excel™. These tools can also be web-based. This task will also involve an in-depth state lighting practice review.

Task 3: Develop guidelines for potential roadway lighting Crash Modification Factors. The current edition (2010) of the *Highway Safety Manual* (HSM) includes crash modification factors (CMFs) for roadway lighting. However, existing lighting CMFs were developed by studies that used crash rates as a basis for evaluation, daytime crashes for comparison, and relied on limited lighting data (i.e., with versus without). As the latest update to the HSM is underway, many researchers and safety officials identify CMFs relevant to lighting as a major need moving forward. Some results of this SHRP2 project provides insights on factors that can impact the reliability of lighting CMFs. This task will address this need and develop guidelines for the development and use of lighting CMFs and include, for example, critical factors to address: lighting levels, analysis locations, identification of nighttime crashes (target crashes), and roadway/environmental factors. The task will also incorporate critical components highlighted in FHWA guides related to CMF development and quality.

Task 4: Dissemination of results and develop training and other materials for safety-oriented lighting design. The successful implementation of this research depends on the widespread dissemination of the results. To facilitate implementation at state transportation agencies, the research team envisions several ways to reach the intended audiences. As part of this task we will develop a package of training materials, including presentations summarizing research findings; newly proposed lighting design changes; and implementation products; tutorials for use of the implementation products including hands-on examples and exercises; and fliers and other handout materials. To the extent possible, the training materials will be developed to follow any applicable National Highway Institute (NHI) course standards. Additional efforts include presentation of results to national conferences and multiple AASHTO, IES and TRB task forces and committees and short presentations that can be used by state professionals to convey the message of the importance of lighting.

Task 5: Conduct pilot training. The research team will deliver pilot training to test and demonstrate the training materials. The training will likely be conducted to WSDOT officials and contractors at a suitable venue selected by WSDOT. However, if requested, the training can also be conducted in a different state or during a national conference (e.g., IES, AASHTO, or TRB). Outreach will occur to other nearby states to facilitate additional input and participation.

Task 6: Implementation of standards and guidelines in pilot lighting design projects. The research team will work with WSDOT, the SHRP2 IAP panel, and other participating states (if applicable) to select up to two pilot lighting design projects to implement the newly proposed lighting design standards and guidelines. During each pilot project, the research team will provide necessary training, technical support, and design audits/reviews to insure successful implementation of the research outcomes. To the extent possible, the research team will collect field lighting measurements after projects completion to verify if the design process has resulted in the desired lighting outcome and if current lighting design software can meet the new lighting requirements.

Task 7: Assess cost-benefits of new lighting design standards. During this task, the research team will conduct a detailed cost-benefit analysis of the new lighting design standards, considering a wide range of factors, such as potential reduction in fatal and serious injury crashes, power savings, infrastructure and materials, and maintenance. In addition to demonstrating the research benefits of this SHRP2 IAP project, the results of this cost-benefit analysis can be used to support state transportation officials in the development of policies relevant to lighting.

Task 8: Prepare Phase III deliverables. During this task, the research team will document the tasks and findings of Phase III in a detailed final report. The research team will also finalize and deliver the following additional implementation products:

- Training package including all training materials,
- Guidelines for lighting design guides at state transportation agencies, and
- Design tools to facilitate roadway lighting design at state transportation agencies.

OPTIONAL TASK: Investigate lighting impacts on safety performance during rainy weather or wet pavement conditions. This optional task is intended to be approved separately. If approved, the task will involve a further investigation that also incorporates pavement marking conditions. This task includes the following activities:

- Request nighttime NDS time series data during wet weather conditions. For each of the analyzed freeway locations, the research team will request 10-20 trips during wet weather conditions, including short video clips for the selected trips. The wet weather conditions will be identified based on local weather data and verified from the associated NDS video data.
- Qualify pavement marking conditions. Due to the lack of pavement marking retroreflectivity and condition data, the research team will develop qualitative pavement condition measurements based on the video files for the NDS trips requested and the confidence scores associated with the lane detection data in the SHRP2 database. Examples of such qualitative measures include good, fair, poor, and/or invisible.
- Conduct time series data analysis. The research team will follow the same methods used for Phase II to conduct a detailed time series data analysis with weather and pavement marking conditions as control factors.
- Analyze NDS events for wet pavement conditions. In reality, Phase II has included the analysis of events during both favorable and wet weather conditions. During this subtask, the research team will further focus on the nighttime events occurred during wet weather conditions to identify additional findings on lighting impacts.
- Document findings and develop recommendations. Based on the findings, the research team will develop conclusions of the safety impacts of lighting during wet weather conditions and recommend potential countermeasures.

Figure 6 shows the proposed Phase III project schedule. The research team proposes a 2-year timeframe to complete the aforementioned tasks.

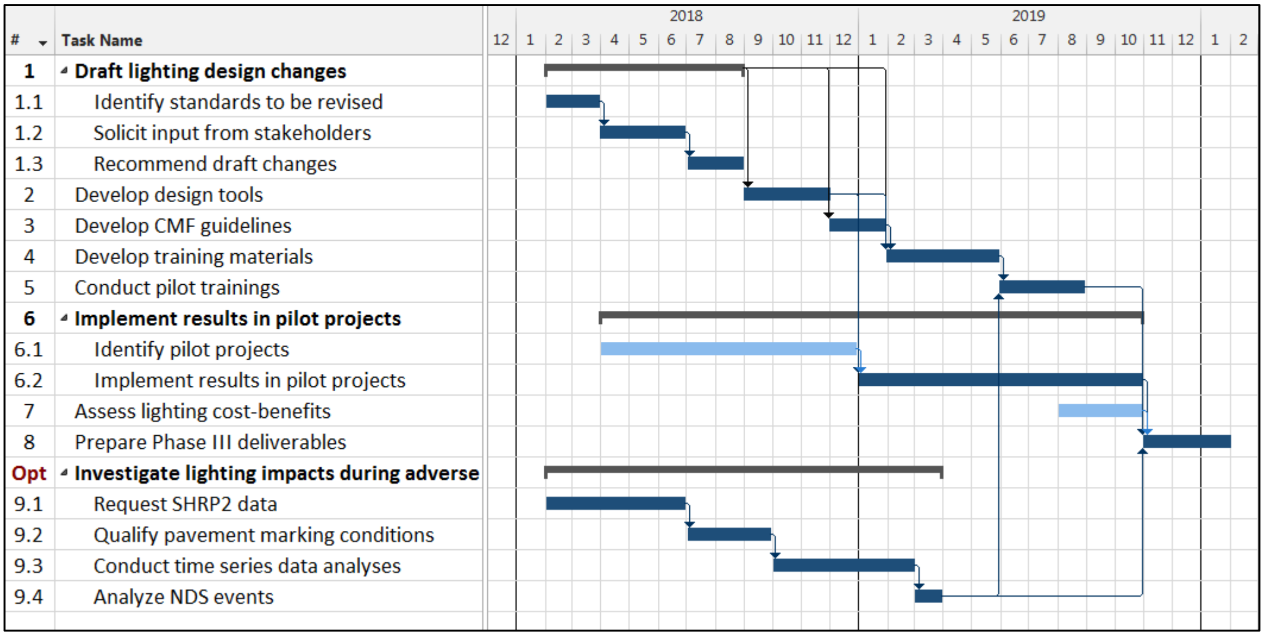

Figure 6. Phase III Schedule.

MANAGEMENT APPROACH AND RISK MITIGATION

A potential challenge that may impact the successful implementation of the Phase II findings and recommendations is the potential lack of support for new design criteria from certain stakeholders. Depending on the minimum illuminance values recommended by this research, certain states and/or designers may not fully support them. From the preliminary analysis findings, the project will most likely result in lower minimum illuminance values at certain locations. How much lighting is needed has been a subject of debate among many states and designers. Such results might be well accepted by some users, while less recognized by others. The opposite may hold as well if the research recommends higher illuminance values for certain locations.

Solution: During the third phase, the research will solicit input from multiple stakeholders. The opinions from individual stakeholders will be assessed and addressed collectively potentially as a range of possible actions to advance the science of lighting safety. In addition, the research team will carefully develop the recommendations to optimally accommodate different opinions and concerns in regards to implementation. Without creating bias in the results, these opinions and concerns will be addressed to the extent practicable. In cases when doing so is not practicable, the research team will document the different opinions for users to consider.

The Phase III will maintain the same project team members led by Dr. Ronald B. Gibbons (FIES, Center Director, PI and project manager) as the Phase I and II experience suggested that the staffing plan was sufficient and successful. Collectively, the research team represents extensive expertise in the areas of roadway lighting, project implementation, and knowledge transfer. The WSDOT management team: Dr. Ida van Schalkwyk (Traffic Safety Engineer), and Dr. John C. Milton (Director: Quality Assurance and Transportation System Safety) were extremely professional and knowledgeable in statistical methods and practical implementation regarding this safety topic. This SHRP2 research has enjoyed strong support and implementation commitment from the WSDOT officials, which will significantly help the research team implement the Phase II findings successfully. The WSDOT team also brings to the project a perspective of state DOTs in terms of safety-related policy making, needs, and priorities.

APPENDIX

Table 12. Multiple Regression Results for Freeway Merging/Diverging Traffic, All Drivers.

Segment			Intersept	E_{all}	E_{right}	U_{all}	U_{right}	No_Ramp_Lns	Area	Facility type	Rmp_Geom_Type	MainLn_Geom_Alligmt	No_Mainlan_Grp	Ramp_Spd	Aux_Ln	RShoulder_Wdth	Rshoulder_Barrier	LShoulder_Wdth	LShoulder_Barrier	AADT	Median_Wdth	Pavement_Type	Conti_light_Num	Trp_Durtn	Trp_Frqnc	Global R^2	Global p-Value
ΔV-μ	EN3	Parameter	-9.2	-0.15	-	-	-	1.6	2.7	-	-	-	8.6	-	-	-	1.4	-3.0	-	-2.9E-05	2.5	-	-	-	-0.94	0.08	<0.01
		Pr > |t|	<0.01	<0.01	-	-	-	<0.01	0.04	-	-	-	<0.01	-	-	-	<0.01	<0.01	-	<0.01	<0.01	-	-	-	0.03		
	EX1	Parameter	8.9	0.22	-0.30	-	-	1.9	-7.5	-4.8	-	-1.4	3.0	0.96	-	-	-	-	-	-	-0.70	-	-	-1.2	-	0.10	<0.01
		Pr > |t|	<0.01	<0.01	<0.01	-	-	<0.01	<0.01	<0.01	-	<0.01	<0.01	<0.01	-	-	-	-	-	-	0.03	-	-	<0.01	-		
	EX3	Parameter	-2.5	-0.09	-	-	-2.3E-15	1.4	-	-5.5	-1.1	-1.1	7.9	0.79	1.6	-	-0.81	-	-	-	-	-	-	-1.3	-1.7	0.14	<0.01
		Pr > |t|	0.04	<0.01	-	-	<0.01	<0.01	-	<0.01	<0.01	<0.01	<0.01	0.04	<0.01	-	0.05	-	-	-	-	-	-	<0.01	<0.01		
ΔV-σ	EN4	Parameter	0.49	0.01	-	-	-	-0.15	-	-	-	-	-0.34	-	-	0.14	-	0.17	-	1.9E-06	-0.12	-	-	-	-	0.07	<0.01
		Pr > |t|	<0.01	<0.01	-	-	-	<0.01	-	-	-	-	<0.01	-	-	<0.01	-	<0.01	-	<0.01	<0.01	-	-	-	-		
	EX3	Parameter	0.62	-	-	-	4.4E-16	-0.09	-	-0.29	0.15	-	-	-	-0.14	-	-	-	-	1.3E-06	-	-	-	0.08	-	0.30	<0.01
		Pr > |t|	<0.01	-	-	-	<0.01	0.07	-	<0.01	<0.01	-	-	-	<0.01	-	-	-	-	<0.01	-	-	-	0.01	-		
a_{long}-μ	EN4	Parameter	0.05	-7.3E-04	-	-	-	-0.01	-	-	-0.01	-0.01	-	0.01	-	-	-	-0.03	-	-	-	4.6E-03	-	-	4.9E-03	0.10	<0.01
		Pr > |t|	<0.01	<0.01	-	-	-	<0.01	-	-	<0.01	<0.01	-	<0.01	-	-	-	<0.01	-	-	-	0.02	-	-	0.02		
	EN5	Parameter	0.04	-	-4.1E-04	2.3E-04	-1.2E-04	-0.01	-	-	-0.01	-5.0E-03	-	0.01	-	-	0.01	-	-0.02	-	-	-	-	-	0.01	0.11	<0.01
		Pr > |t|	<0.01	-	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	0.02	-	<0.01	-	-	<0.01	-	<0.01	-	-	-	-	-	<0.01		
	EX2	Parameter	0.06	-	-	-	-9.4E-04	-0.01	-	0.02	-0.01	-0.01	-0.03	-0.01	-	-0.01	-	-0.04	-0.04	-	-4.8E-03	-1.9E-03	-	-4.5E-03	-	0.10	<0.01
		Pr > |t|	<0.01	-	-	-	<0.01	0.03	-	<0.01	<0.01	0.01	<0.01	<0.01	-	<0.01	-	<0.01	<0.01	-	0.02	0.42	-	0.02	-		
	EX3	Parameter	-0.02	-	-	-3.3E-04	-1.3E-17	-	-	0.02	-0.01	-0.01	-0.02	-0.01	-	-	-	-	-	-	-	-	-	-	-	0.13	<0.01
		Pr > |t|	<0.01	-	-	<0.01	<0.01	-	-	<0.01	<0.01	0.02	0.04	<0.01	-	-	-	-	-	-	-	-	-	-	-		
a_{long}-σ	EX1	Parameter	0.02	2.4E-04	-	-6.8E-05	-	-	-	0.01	1.8E-03	1.6E-03	-0.01	-	-	-	2.8E-03	-	1.9E-03	1.6E-08	-1.4E-03	-	-4.8E-03	-	-	0.08	<0.01
		Pr > |t|	<0.01	<0.01	-	<0.01	-	-	-	<0.01	<0.01	0.01	<0.01	-	-	-	<0.01	-	<0.01	0.16	0.02	-	<0.01	-	-		
	EX2	Parameter	0.02	2.2E-04	-	2.0E-04	-	-2.1E-03	-	-	2.2E-03	-	-0.01	-	-	-	1.7E-03	-	-	3.5E-08	-	-3.5E-03	-	-	2.6E-03	0.09	<0.01
		Pr > |t|	<0.01	<0.01	-	<0.01	-	<0.01	-	-	<0.01	-	<0.01	-	-	-	0.01	-	-	<0.01	-	<0.01	-	-	<0.01		
	EX3	Parameter	0.04	-	-	-	3.6E-18	-	-	-	2.6E-03	-1.8E-03	-0.01	-	-3.7E-03	-2.0E-03	2.9E-03	-	-	-	-	-	-	-	-	0.10	<0.01
		Pr > |t|	<0.01	-	-	-	<0.01	-	-	-	<0.01	0.01	<0.01	-	<0.01	0.03	<0.01	-	-	-	-	-	-	-	-		
a_{lat}-μ	EN4	Parameter	0.02	-	-	5.2E-04	-1.5E-16	0.01	-	-	-0.01	-0.01	-	0.01	-0.01	-	4.8E-03	-0.03	-0.01	-	4.8E-03	0.01	4.0E-03	3.9E-03	-	0.12	<0.01
		Pr > |t|	0.02	-	-	<0.01	0.03	<0.01	-	-	<0.01	<0.01	-	<0.01	<0.01	-	<0.01	<0.01	<0.01	-	<0.01	<0.01	0.04	0.01	-		
	EN5	Parameter	5.3E-04	-	-	2.1E-04	-	0.01	-0.02	-	-	-0.01	-0.01	0.01	-0.02	-	0.01	-	0.01	2.1E-07	-	0.01	-	-	-	0.23	<0.01
		Pr > |t|	0.94	-	-	<0.01	-	<0.01	<0.01	-	-	<0.01	0.04	<0.01	<0.01	-	<0.01	-	<0.01	<0.01	-	<0.01	-	-	-		
	EX1	Parameter	-0.01	9.1E-04	4.1E-04	-3.0E-04	-	-0.01	-	-	0.01	-	0.01	-	0.01	-	-	-	0.02	-	-0.01	-	-0.02	-	-0.01	0.16	<0.01
		Pr > |t|	0.04	0.03	0.29	<0.01	-	<0.01	-	-	<0.01	-	<0.01	-	<0.01	-	-	-	<0.01	-	<0.01	-	<0.01	-	<0.01		
	EX2	Parameter	0.03	-	-	6.9E-04	-8.9E-04	0.01	-	-	-	-	-0.02	4.6E-03	0.01	0.01	-	-	-	-	-0.02	0.01	-	-	-	0.10	<0.01
		Pr > |t|	<0.01	-	-	<0.01	<0.01	0.02	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	-	-	<0.01	<0.01	-	-	-		
	EX3	Parameter	0.09	-4.9E-04	-	-	5.1E-18	0.01	-	0.02	5.0E-03	0.02	-0.04	0.01	-	-0.01	-	-0.02	-0.02	-9.6E-08	-0.01	0.01	0.01	4.3E-03	-	0.28	<0.01
		Pr > |t|	<0.01	<0.01	-	-	<0.01	0.02	-	<0.01	<0.01	<0.01	<0.01	<0.01	-	<0.01	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-		
a_{lat}-σ	EN5	Parameter	0.02	-	-	-1.5E-04	1.2E-04	-	-	-	-	-	-	4.4E-03	-	-	0.01	-	-	4.7E-08	-	3.3E-03	-2.8E-03	-1.6E-03	-	0.09	<0.01
		Pr > |t|	<0.01	-	-	<0.01	<0.01	-	-	-	-	-	-	<0.01	-	-	<0.01	-	-	<0.01	-	<0.01	<0.01	0.04	-		
	EX1	Parameter	0.01	6.1E-04	-5.0E-04	-2.6E-04	2.0E-04	-2.9E-03	-	-4.3E-03	9.5E-04	2.7E-03	-	-	2.6E-03	-	-	-	-4.7E-03	5.8E-08	-2.5E-03	2.4E-03	-	-	2.0E-03	0.14	<0.01
		Pr > |t|	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-	<0.01	0.17	<0.01	-	-	<0.01	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	0.02		
	Ex2	Parameter	0.02	-2.6E-04	-	-1.0E-04	-	0.01	0.01	-4.4E-03	3.4E-03	-3.6E-04	-3.5E-03	-	-3.8E-03	-	4.0E-03	-0.01	-0.01	3.8E-08	3.0E-03	2.7E-03	-	-	-	0.13	<0.01
		Pr > |t|	<0.01	<0.01	-	0.04	-	<0.01	0.02	0.02	<0.01	0.58	0.19	-	<0.01	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-	-	-		
	EX3	Parameter	0.04	-	-	-	5.1E-18	-	-	-	3.3E-03	-1.6E-03	-0.01	-	-4.2E-03	-	2.1E-03	-	-	-	-1.3E-03	-	4.1E-03	-	-	0.17	<0.01
		Pr > |t|	<0.01	-	-	-	<0.01	-	-	-	<0.01	0.02	<0.01	-	<0.01	-	<0.01	-	-	-	0.03	-	<0.01	-	-		
L_{off}-μ	EN3	Parameter	-115.5	-	-	-	-0.27	37.9	-	23.3	9.6	-	40.9	-	-	-16.1	-	-	16.0	-	-	11.4	-	-	-	0.09	<0.01
		Pr > |t|	<0.01	-	-	-	<0.01	<0.01	-	<0.01	0.01	-	<0.01	-	-	<0.01	-	-	<0.01	-	-	<0.01	-	-	-		
	EX2	Parameter	31.5	-0.74	-	-	-	7.3	-	-14.0	-	-5.5	-	-7.6	-11.3	13.5	-	-	-	-	-	-	-	-	8.1	0.09	<0.01
		Pr > |t|	<0.01	<0.01	-	-	-	0.02	-	<0.01	-	0.02	-	<0.01	<0.01	<0.01	-	-	-	-	-	-	-	-	0.01		
L_{off}-σ	EN3	Parameter	51.9	-	0.42	-0.11	-	7.9	-	-	6.5	-6.3	-14.3	-	-17.5	-	-	-5.5	-	-	-	-7.6	-	-	-	0.07	<0.01
		Pr > |t|	<0.01	-	<0.01	0.03	-	<0.01	-	-	<0.01	<0.01	<0.01	-	<0.01	-	-	0.02	-	-	-	<0.01	-	-	-		

-: Variable is not significant, eliminated from model.

Models are included when the model R^2 is greater than 0.0625 (R > 0.25).