# FREEWAY TRAFFIC SAFETY AND EFFICIENCY ENHANCEMENT THROUGH ADAPTIVE ROADWAY LIGHTING AND CONTROL ENABLED BY CONNECTED INFRASTRUCTURE NETWORKS

## FINAL PROJECT REPORT

by

Yinhai Wang
University of Washington

Kristian Henrickson
University of Washington

John Ash
University of Washington

Zhibin Li
University of Washington

Haizhong Wang
Oregon State University

Shangjia Dong
Oregon State University

Hao Yang
University of Washington

Chen Chen
Oregon State University

Sponsorship
US Department of Transportation

for
Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700
In cooperation with US Department of Transportation-Research and Innovative Technology Administration (RITA)

## Disclaimer

# Technical Report Documentation Page

**1. Report No.**

**2. Government Accession No.**

**3. Recipient's Catalog No.**

**4. Title and Subtitle**

Freeway Traffic Safety and Efficiency Enhancement through Adaptive Roadway Lighting and Control Enabled by Connected Sensor and Infrastructure Networks

**5. Report Date**

12/15/2018

**6. Performing Organization Code**

**7. Author(s)**

Yinhai Wang, Haizhong Wang, Kristian Henrickson, Shangjia Dong, John Ash, Hao Yang, Zhibin Li, and Chen Chen

**8. Performing Organization Report No.**

2016-M-UW-2

**9. Performing Organization Name and Address**

Department of Civil and Environmental Engineering
University of Washington
Seattle, WA 98195-2700

**10. Work Unit No. (TRAIS)**

**11. Contract or Grant No.**

DTRT13-G-UTC40

**12. Sponsoring Organization Name and Address**

United States of America
Department of Transportation
Research and Innovative Technology Administration

**13. Type of Report and Period Covered**

Research

**14. Sponsoring Agency Code**

**15. Supplementary Notes**

Report uploaded at www.pactrans.org

**16. Abstract**

Visibility of the roadway and roadside objects often decreases as light (from natural and artificial sources) diminishes under a certain level. Roadway lighting, when used appropriately for the given context and conditions, can be an effective means for increasing visibility; however, inappropriate lighting can lead to issues such as glare. Recently, adaptive roadway lighting has been given increasing attention as a means to reduce lighting levels to save energy while maintaining safety performance. Adaptive lighting scenarios have the ability to adjust roadway lighting levels on the basis of real-time data such as traffic volume and weather conditions. In this project, an adaptive lighting methodology was developed on the basis of a comprehensive review of the literature, as well as data collected in Washington State at sites where systems capable of adaptive lighting (dimming and on/off operation of specific lights by time of day) were installed by the Washington State Department of Transportation (WSDOT). Data sources considered in the methodology included traffic data, weather data, crash data, etc. The methodology employed an active traffic management component that allowed for provision of advisory messages based on data used in the lighting methodology itself. An adaptive lighting simulation platform was also developed and used to compare the lighting index (a dimensionless quantity based on illuminance) of the developed methodology versus other conventional and common adaptive lighting methodologies. The platform made use of both traffic and communication simulation platforms to enable real-time vehicle detection and influence on lighting conditions. Results from comparing the indices showed that the proposed method was comparably more efficient than existing adaptive methods and hence allowed for energy savings over these conventional methods. Thus, the proposed adaptive methodology has the potential to cut down energy spending remarkably without degrading traffic safety and efficiency.

**17. Key Words**

Roadway lighting, adaptive lighting, active traffic management

**18. Distribution Statement**

No restrictions.

**19. Security Classification (of this report)**

Unclassified.

**20. Security Classification (of this page)**

Unclassified.

**21. No. of Pages**

101

**22. Price**

NA

**Form DOT F 1700.7 (8-72) Reproduction of completed page authorized**

## TABLE OF CONTENTS

## TABLE OF FIGURES

# TABLE OF TABLES

# Executive Summary

Visibility of the roadway and roadside objects often decreases as light (from natural and artificial sources) diminishes under a certain level. Roadway lighting, when used appropriately for the given context and conditions, can be an effective means for increasing visibility; however, inappropriate lighting can lead to issues such as glare. Recently, adaptive roadway lighting has been given increasing attention as a means to reduce lighting to save energy while maintaining safety and operational efficiency. Adaptive lighting scenarios have the ability to adjust roadway lighting levels on the basis of real-time data such as traffic volumes and weather conditions. Such lighting control systems allow the output of each luminaire to be controlled to avoid over- or under-lighting. In this project, an adaptive lighting methodology was developed and tested via simulation experiments.

Recently, the state departments of transportation in Washington and Oregon have upgraded portions of their roadway lighting facilities to include new light-emitting diode (LED) luminaires that are capable of adaptive control through a central system. In Washington, for example, the Washington State Department of Transportation (WSDOT) installed LED lights with a corresponding adaptive control system (that allows dimming and turning on/off of specific lights by time of day) along US Highway 101 (US 101) in 2013 and later along Interstate 5 (I-5). WSDOT is actively researching this issue before beginning to adjust lighting levels on their facilities in real time.

At the core of any adaptive lighting methodology are the data on which the decisions to change lighting levels are based on. In this project, researchers collected weather data, crash data, traffic flow data, and various other types of data in the study areas in Washington. Preliminary analyses of these data were done to investigate patterns for factors such as primary and secondary incidents. The results of these analyses, coupled with a thorough review of the literature from both the academic and transportation agency perspectives, led to development of a methodology for control of illumination levels along a given facility. The method considers real-time, multi-source data and has requirements in place to ensure properties such as the illumination level and number of LED lights act together to ensure safety and operational efficiency.

To test the methodology, a simulation platform was developed, and experiments were carried out. The platform was built by using a combination of a traffic microsimulation platform (Simulation Of Urban Mobility - SUMO), a communications simulator to provide a link between traffic and the lighting control system (OMNet++), and an interface to link the two simulators together (Vehicles in Network Simulation – Veins). The simulation tests compared the lighting index (a dimensionless quantity based on illuminance) of the adaptive lighting methodology developed for this project with those of several adaptive and conventional lighting approaches proposed by industry, government, and academia. Different lighting scenarios were compared on the basis of the lighting index and energy consumption. The tests found that the proposed adaptive lighting algorithm had better performance as indicated by a high lighting index value in comparison to other adaptive and conventional approaches. While the simulation platform provided a means to test certain components of the methodology in controlled settings, it would be ideal to test the proposed algorithm in a real-world field environment, and this is a topic we propose for future work.

# 1.0 Introduction

Visibility of the roadway and roadside objects often decreases as light (from natural and artificial sources) diminishes under a certain level. Roadway lighting, when used appropriately for the given context and conditions, can be an effective means for increasing visibility; however, inappropriate lighting can lead to issues such as glare (Cheung, 2019). Recently, adaptive roadway lighting has been given increasing attention as a means to reduce lighting to save energy while maintaining safety and operational efficiency. Specifically, adaptive lighting plans can adjust the lighting level based on real-time traffic, weather, road surface, and natural light conditions. They also enable the output of each luminaire to be controlled to avoid over- or under-lighting. If no traffic is present on a given facility, lights can be simply turned off or dimmed to conserve energy. In general, development of an adaptive lighting mechanism involves balancing tradeoffs among operational costs, carbon footprint, energy conservation, etc. Typically, adaptive lighting systems consist of a "home base" (i.e., master) controller and individual modules in each luminaire, allowing for separate and direct control of each luminaire via the master. Thus, adaptive lighting control algorithms can be developed by making conditional controls of luminaire in the lighting system.

Beginning in 2013, the Washington State Department of Transportation (WSDOT) installed roadway lighting systems capable of adaptive control along US Highway 101. In Oregon, a similar pilot project in the Salem area (at I-5 and Market St.), which includes light-emitting diode

(LED) lighting replacement and wireless dimming control (via the same adaptive system used by WSDOT), has been implemented by the Oregon Department of Transportation (ODOT). Because the Pacific Northwest Transportation Consortium (PacTrans) has been a research partner with both agencies in addressing mobility and safety challenges, the aforementioned agencies provided PacTrans with the opportunity to help develop an adaptive roadway lighting methodology on the basis of a review of the state of the practice and multi-source data (e.g., roadway geometrics, traffic flow data, crash data, weather data, etc.). The large volumes of data collected for the lighting methodology development also proved to be valuable for drivers using the road. Indeed, the research team also included an active traffic management component in the control algorithm to provide real-time information and messages to drivers, the benefit of which can be even further realized when connected vehicles infrastructure becomes available. The method was tested via simulation experiments with the hope of a field test in the future.

The contents of this report are structured as follows. Section 2 provides a comprehensive literature review. The literature review covers the state of the practice related to the energy and safety implications of roadway lighting, an overview of previous work on adaptive lighting, and simulation of adaptive lighting. Section 3 discusses the data sources used in the development of the adaptive lighting methodology and provides some analysis of each of them. Section 4 presents the development of the adaptive lighting methodology and the corresponding active traffic management component that provides advisory messages to travelers. The development of a simulation platform by which the lighting index and energy consumption of the proposed adaptive lighting methodology was tested and compared with existing lighting methodologies is presented in Section 5. Results and discussion of the simulation are provided in Section 6. Finally, Section 7 discusses general conclusions of the project as well as future work.

# 2.0 Literature Review

## 2.1 Literature Review Summary

Roadway illumination is an important aspect of transportation management and in reducing some nighttime visibility-related crashes. Typically, roadway illumination is delivered in a uniform manner and switched on and off based on time of day. Recent studies, however, have found that uniform roadway lighting does not necessarily reduce crash potential; Gibbons et al. (2014) take a stronger stance and note that “there is no information on how the uniformity measure would affect safety.” Instead, adaptive lighting based on roadway, traffic, environmental, and weather conditions is likely to result in greater efficiency, reliability, and energy conservation benefits than conventional lighting scenarios.

Relevant literature is reviewed in four categories: lighting for energy savings, lighting for safety enhancement, adaptive control systems for lighting, and adaptive lighting system simulation platforms. Although the benefits of combining adaptive lighting and active traffic management (a control strategy demonstrated effective in reducing crashes and enhancing vehicle throughput) are obvious, very little research has been done in this area. It is important to note that a substantial body of research on roadway lighting has been conducted over the past decades and in an effort to highlight trends over time, a range of studies, newer and older, are presented in the literature.

## 2.2 Lighting for Energy Savings

It is well agreed upon that LED lighting is energy efficient and has a lower cost over the long term than a variety of other lighting sources (Li et al., 2013; Bullough and Radetsky, 2013).

When compared to conventional high-pressure sodium (HPS) luminaires, LED lights often display more benefits to be considered for use in adaptive lighting systems; such benefits include, higher levels of luminous efficacy under a range of dimming conditions, as well as longer luminaire lifespan under reduced lighting (Li et al., 2009). Therefore, rather than focusing on energy savings by lighting type, we reviewed different strategies for using lighting systems to gain better energy efficiency.

In terms of lighting design for energy saving, Gómez-Lorente et al. (2013) developed a framework to guide design of roadway lighting based on an optimization approach. The objectives under the optimization algorithm were to maximize illuminance uniformity and "installation efficiency," with the latter component of the objective referring to energy efficiency (Gómez-Lorente et al., 2013). The algorithm works by finding the optimal configuration of a lighting installation for parameters such as mounting height of luminaires and intra-light distance when considering a given geometric configuration of the roadway. Li et al. (2013) surveyed 19 cities in Indiana on their main reasons for switching from conventional lighting systems (i.e., HPS) to new systems, such as those that use LED or plasma lighting. Of the nine respondent cities, five cities including Fort Wayne, Valparaiso, Lafayette, Indianapolis, and Scottsburg cited either "energy reduction," "energy savings," or "energy efficiency" as their primary reason for switching to a new system (Li et al., 2013). They also investigated energy savings of LED lighting systems compared to conventional HPS systems. For their analysis, they estimated energy usage of luminaires assuming 240 volts (V) and 4380 hours of usage per year. LED luminaires were found to incur energy savings of between 12 to 20 percent over 250 watt (W) HPS luminaires and 44 to 52 percent over 400 watt HPS luminaires. In each case, energy savings were expressed in terms of energy consumption in kilowatt hours (kWh) (Li et al., 2013). Bullough (2012) performed a scan of the state-of-the-practice and surveyed engineers in New York in order to inform development of a guide for lighting installation/upgrades that apply new lighting technologies, such as LED luminaires. He found that LED and induction fluorescent lighting systems can lead to 7 to 50 percent energy savings over conventional HPS systems. The magnitude of the savings varied with roadway type, and in the study, parkways, residential streets, and rural intersections were considered (Bullough, 2012).

Kovács et al. (2016) developed an adaptive lighting framework and algorithms to study how use of solar powered street lights could produce electricity to sell back to the grid. The system is adaptive in the sense that light levels can be dimmed in accordance with observed traffic. By predicting energy production and consumption, the algorithm can decide when electricity for the luminaires should be bought from or sold to the grid through an optimization-based approach. The objective of the optimization problem can either be to incur a minimum in electricity costs or to maximize the amount of money from selling back to the grid. A case study was conducted to study the algorithms performance on a system of 191 LED luminaires and it was observed that a 55.71 percent energy savings could be attained from the adaptive LED system, compared to an LED lighting system that did not have adaptive behavior (Kovács et al., 2016).

Janoff, Staplin, and Arens (1986) performed a field test on I-95 in Pennsylvania that sought to compare six lighting reduction scenarios for mainline freeway segments. While energy savings can be associated with lighting reduction, this study investigated driver performance under reduced lighting. Specifically, drivers' object detection performance was evaluated in the context of the six lighting scenarios. The metric considered was the distance from which drivers were able to recognize a six-inch tall object located in the roadway. Object detection was found to be best under the full-lighting scenario and worst under the scenario with no lighting. In between these two extremes, driver performance in response to lighting scenario declined in response to the following order of lighting scenarios: luminaires at 75 percent power level, luminaires at 50 percent power level, and every other luminaire turned off (Janoff et al., 1986). Bullough and Radetsky (2013) studied new and emerging lighting systems as part of a larger project done on behalf of the National Cooperative Highway Research Program (NCHRP). They performed a comprehensive literature review on new lighting technologies, investigated the photometric performance of a variety of new lighting technologies, and described ways to objectively compare performance measures between new lighting systems. A key conclusion of their study was that LED roadway lighting systems can lead to a decrease in energy consumption of at least 15 percent as well as lower costs over their life span, compared to conventional lighting technologies. It is important to note, however, that the magnitude of the benefit in terms of energy savings and lifecycle costs will depend on specific considerations for the given installation (Bullough and Radetsky, 2013).

## 2.3 Lighting for Safety Enhancement

Several researchers have sought to investigate the relationship between crash potential and lighting in a variety of different contexts. Richards (1981) studied a 7.2 mile stretch of southbound I-35 in Austin, Texas on which mainline lighting was turned off for the southbound direction of travel. When comparing the crash frequency between the two year before- and the two year after-periods, he noted a 47 increase in crash frequency for the southbound sections where lighting was extinguished (Richards, 1981). Jackett and Frith (2013) examined the impact of roadway lighting on safety for a selection of different lighting plans across urban areas in New Zealand. They collected measurements for parameters including average luminance, overall uniformity (defined as the ratio of minimum luminance to average luminance), longitudinal uniformity (defined as the ratio of minimum luminance to maximum luminance), and threshold increment (also known as “disability glare", it measures the “loss of contrast a driver suffers because of light shining directly from the luminaire into the driver’s eye”). Such measurements were collected in the field at the study sites with annual average daily traffic (AADT) values from less than 9,000 to 30,000 (Jackett and Frith, 2013). These parameters, along with information on whether or not the luminaire was a source of white light, were then used in a regression model to predict the ratio of the number of crashes (both injury and non-injury, as well as intersection- and midblock-related) occurring at nighttime to the number occurring in the daytime. It is important to note that the authors did not appear to mention what conditions specifically defined daytime and nighttime in terms of time of day or dawn/dusk conditions. Ultimately, they found that the average luminance and threshold increment variables were significant in their model at or beyond the 95% confidence level (Jackett and Frith, 2013).

Monsere and Fischer (2008) investigated impacts of lighting reduction scenarios on safety at a selection of interchanges and urban freeway segments in Oregon. They attempted to control for weather and volume impacts by including features to describe these variables in some of their negative binomial modeling efforts. Their model results for sites where lineal lighting was reduced (either by turning off all luminaires for one or both directions of travel) showed that both the total number of night crashes and injury night crashes increased. With regard to locations where interchange lighting was reduced from full lighting to partial lighting, night crashes increased by approximately two percent. It is important to note, however, that at the same locations, injury crashes were shown to have decreased by approximately 12 percent. For interchange sites where the lighting configuration was reduced from partial plus to the partial lighting scenario, total crashes decreased by approximately 35 percent and injury crashes were shown to have decreased by nearly 40 percent. Interchange lighting scenarios were described (in order of most to least lighting) as full, partial plus, and partial (Monsere and Fischer, 2008).

Isebrands et al. (2006) studied the impact of lighting on crash potential at rural intersections. They examined 3,622 sites, both lighted and unlighted, and developed a regression model for which features including traffic volume, number of approaches at the intersection, and whether or not streetlighting was used were found to impact the ratio of nighttime to total intersection crashes. Lamm, Kloeckner, and Choueiri et al. (1985) studied the impact of lighting scenarios on German suburban freeway segments. They acknowledged their work was an initial study into the area and noted that they found “positive effects of lighting on reducing accident rates and accident cost rates on freeways in suburban areas cannot be excluded, even if no real convincing results could be statistically proven” (Lamm et al., 1985).

Monsere and Fischer (2008) noted that the design and traffic characteristics of freeways (specifically speed, volume, and geometrics), compared to facilities of another functional class, make it such that these facilities are often chosen as candidates for application of roadway lighting scenarios. Griffith (1994) investigated crash potential for urban freeway segments in Minnesota; 54.6 miles had continuous lighting and the other 35.5 miles had lighting only at the interchanges. He analyzed data for all crash types in the study area (injury and non-injury) between 1985 and 1990 and used data from the U.S. Naval Observatory to classify the crashes into daytime or nighttime occurrence. He then computed the ratio of night to day crash rates for the two different types of study sites and found that the night to day crash rate ratio was 12 percent greater for locations with interchange only lighting compared to continuous lighting (Griffith, 1994). Prior to the aforementioned work by Griffith (1994), Box (1976) investigated lighting impacts on crash potential for 203 miles of urban freeway in North American cities including Toronto, Chicago, Atlanta, Dallas, Phoenix, and Denver. He observed that the average night to day crash rate ratio was 1.43 for segments with roadway lighting and 2.37 for segments without roadway lighting (Box, 1976).

While the aforementioned research has primarily concluded reductions in lighting can lead to increased crash potential and higher crash rates at night, this is not a universal conclusion. A recent study used a random parameters model to predict crash counts (considering crashes that occurred during “the end of civil dusk twilight to the start of civil dawn twilight”) for mainline freeway segments in Washington State (van Schalkwyk et al., 2016). The main idea of the study was to focus only on nighttime crashes occurring between 2009 and 2013 for segments with the following lighting configurations: continuous lighting in the median, continuous lighting on the right side of the roadway, continuous lighting on both sides of the roadway, lighting at specific points, and absence of lighting. Based on the modeling results, the team stated that “continuous illumination makes no contribution to nighttime safety performance” (van Schalkwyk et al., 2016). In the same report, van Schalkwyk et al. (2016) noted that light poles can pose a safety risk to drivers, as they are fixed objects that can be struck. A series of studies by Venkataraman et al. (2011, 2013, and 2014) used random parameter negative binomial models to model crash frequencies on freeways in Washington. Venkataraman et al. (2011) noted that “lighting variables (e.g., point lighting, no lighting, and continuous lighting) have a counterproductive effect with respect to both side lighting as the baseline.” Venkataraman et al. (2013) observed that median continuous lighting often led to an increase in crashes resulting in property damage, and lighting on the right side of the road was associated with an increase in “evident injury” crashes. They also concluded from their models that locations with no lighting saw a reduction in disabling injury crash frequency, but an increase in property damage crash frequency. Finally, Venkataraman et al.

(2014) modeled interchange crash frequency and noted that “median continuous lighting” was correlated with increased interchange crash frequency, except at full diamond interchanges.

Cheung (2019) noted that one of the key drawbacks of roadway lighting is the potential for it to lead to disability glare, which can restrict vision, especially for the elderly driving population. Jackett and Frith (2013) stated that disability glare leads to reduced contrast of objects and is caused by light sources shining straight into the eyes of a driver. In a paper describing the issue of light pollution, another consequence of roadway lighting, Lyytimäki et al. (2012) took a more philosophical approach when discussing lighting and note that the assumption of the benefits of traffic lighting “stems partly from the notion that darkness presents threats and inconveniences … to traffic.” While the relationships between roadway lighting, visibility, and crash potential are quite complex, they are essential for engineers to understand to properly design lighting scenarios that are best suited to the context of the installation (Bullough et al., 2013).

## 2.4 Adaptive Control Systems for Lighting

Recently, the Netherlands, Japan, and Canada have begun to put adaptive lighting systems into practice. These lighting systems allow for adjustment of lighting levels based on a variety of conditions (McLean, 2006). To examine the practicality of their streetlight monitoring and control system, Jing et al. (2007) created a platform for a wireless sensor network. Their system was comprised of several components including sensor nodes, remote terminal units, and a control center. Denardin et al. (2011) developed a control scenario for an LED roadway lighting system. Their system allowed remote control of each light at different time periods. It further led to reductions in energy consumption, lower maintenance expenses, and allowed for real-time connections to each light for status checks (Denardin et al., 2011).

An adaptive roadway lighting system was installed in the Netherlands in 1995. Luminaires were dimmed by 80 percent for volumes of less than 800 vehicles per hour per lane (vphpl). Nonetheless, the cost to install the new system was higher than that of traditional systems by about 10 percent, but this upfront cost came with lower costs for operations and maintenance over time (Adams and Hamel, 2006). In Finland, Wilken et al. (2001) began to test an adaptive lighting system on a 3.5-kilometer portion of a two-lane roadway in 2000. They considered traffic volume and weather information as inputs from which decisions to modify speed limits and illumination levels could be based; such application was novel in that it combined elements of adaptive lighting and active traffic management) (Wilken et al., 2001). Bacelar (2005) examined how dimming roadway lighting affects driver visibility and conducted the work on a 400-meter-long test track. Their results showed that dimming had little impact on driver visibility at levels below 50 percent (Bacelar, 2005). Chung et al. (2005) investigated an adaptive lighting installation in China. In the subject system, 1,350 (out of 8,000) luminaires had dimming capability via a remote system. At the study site, the lighting levels of the dimmable luminaires were decreased to 80 percent between 6:20 PM to midnight and decreased to 70 percent from midnight to 5:00 AM, compared to the pre-study lighting levels. Following a nine-month test period, energy consumption was reduced by 27 percent (Chung et al., 2005).

Transportation agencies in the United States have also been working to put adaptive lighting systems into practice. In 2013, WSDOT launched a pilot adaptive LED lighting system on US Highway 101 in Washington state (WSDOT, 2013). The new lighting system can save much more energy than traditional roadway lights because of the efficiency of the LED technology used in the luminaires. Additionally, the LED lights can be remotely adjusted to different light levels or turned on/off. A curfew system was applied during which select luminaires were turned off between 11 PM and 5 AM. The pilot project resulted in a reduction of lighting energy consumption by 74 percent and 68 percent at the two test locations, respectively (WSDOT, 2013). The City of Seattle has been working on transitioning from conventional HPS roadway lighting systems to LED systems with adaptive capabilities (Clanton &Associates, 2014). It is believed that the adaptive nature of these lights can reduce energy consumption by a further 25 percent beyond the savings afforded by simply switching from HPS to LED lights. In a field test on an urban street in Seattle, three conditions were evaluated by participants driven in a test vehicle at 35 miles per hour who were asked to indicate targets they detected in the roadway: HPS luminaires at “full light output,” LED luminaires at “50 percent of full light output” with HPS luminaires at full strength, and LED luminaires at “25 percent of full light output” with HPS luminaires at full strength (Clanton & Associates, 2014). Results of the test suggested that the decreased output of the LED lights under the adaptive scenarios did not significantly impact object detection distance for dry pavement scenarios. Written survey results, however, pointed out that participants found the 25 percent LED light level was “unacceptable,” primarily for sidewalk lighting (Clanton &Associates, 2014).

Recently, The City of Beverly Hills approved a plan to upgrade their street light system to LED luminaires (City of Beverly Hills, 2018). At the time of the study, the City had approximately 5,000 lights in its jurisdiction and had budgeted $2.5 million for the upgrade. They further estimate that the LED lights would lead to a 68 percent (3,253 MWh) energy savings compared to their original system, and this amount would translate to about $247,000 savings on a yearly basis. The City also estimated that they could reduce energy consumption by a further 10% if adaptive dimming capabilities were used for the lights (City of Beverly Hills, 2018). In Kansas, a new highway illumination system with LED luminaires and an adaptive control system (to provide for dimming outside of peak periods) was installed in 2015 (Cai, 2015). This adaptive lighting system shows a huge cost-benefit advantage since the energy cost savings was estimated to be approximately $18.89 to $71.22 per light; such costs are projected to be incurred over the system’s life cycle (Cai, 2015).

Besides implementations, U.S. cities such as San José have also begun including design provisions for adaptive lighting in their design manuals (City of San José, 2016). The City of San José recommends using adaptive lighting levels of 50 percent normal lighting levels between midnight and 5:00 AM on weekdays and 1:00 AM and 6:00 AM on weekends (City of San José, 2016).

### *2.4.1 Traffic Conditions*

Currently, several popular methodologies for adaptive lighting scenarios are based on past standards developed for conventional lighting systems. For example, Walton and Rowan (1974) presented a set of roadway lighting warrants that considered roadway geometrics, traffic conditions, environmental conditions (e.g., land use, distractions in the visual field, etc.), and historical crash data. Freeway and interchange Level of Service (LOS) was considered as a metric to classify operations and for the lighting warrants (Walton and Rowan, 1974). Walker and Roberts (1974) noted that application of roadway lighting at interchanges with daily traffic counts of less than 3,500 vehicles had minimal influence on crash potential. Results such as these may not apply to the study sites examined herein, but they do imply that benefits of enhanced lighting in low-volume scenarios are likely minimal. That said, the age of the study in this and other cases should be considered.

Current popular references and guidance for adaptive lighting scenario development include Gibbons et al. (2014) in the U.S. and the International Commission on Illumination (2010) in Europe. Both references take data on roadway and traffic parameters into account as inputs for use in weighting control framework that results in guidance on setting lighting levels. Additionally, both resources present discrete lighting classes on the basis of scenarios defined in terms of average luminance, uniformity ratio, and veiling luminance ratio. Gibbons et al. (2014), which considers LOS as the primary real-time criteria for adaptive lighting on controlled access facilities, offers the following guidance on adaptive lighting:

- The change in lighting class should be no more than 1 class/mile (classes defined as H1 – H4 in terms of average luminance, max/min uniformity ratio (UR), and the veiling luminance ratio in the report's Table 22).
- In general, drivers should not encounter a change in lighting class greater than two classes (over a corridor, for example).
- Dimming allows a reduction in lighting without impacting other design criteria (such as uniformity/glare control).
- Keep lighting at design levels under adverse weather (because of a lack of data/understanding)
- Real-time changes in lighting levels can be based on level of service, and are calculated as an adjustment from design lighting conditions. Higher level of service (greater density) corresponds to higher lighting requirements on uninterrupted facilities.

The International Commission on Illumination (2010) defines "normal lighting" as the minimum lighting level required to serve all hours of the night. Based on this standard, it would seem that a conservative interpretation of "normal lighting" would call for it to be applied under warranting traffic conditions, adverse weather or reduced visibility, or when an object or distraction is present in the roadway. However, it is not clear that these suggestions and claims are well supported by data analysis. For the current study, it is reasonable to define normal lighting as the design lighting levels for the current system or, alternatively, as the maximum light class during the peak hour, as defined by Gibbons et al. (2014). In terms of aligning lighting levels with traffic demand, the guidance offered by Gibbons et al. (2014) is the most applicable to the current study area, as it is based in part on data collected in Washington state.

Shahzad et al. (2016) described an adaptive lighting scenario through which engineers can access controls via a wireless mesh network and lighting levels change in response to observed traffic. That said, the study did not perform an in-depth examination of lighting level choice in response to changes in traffic or other conditions, but did comment on forecasting energy savings for adaptive systems. Rather, the luminaries were dimmed to a prescribed minimum level during times no vehicles were detected (e.g., late night and early morning periods in most cases) (Shahzad et al., 2016).

Nefedov et al. (2014) conducted a simulation experiment, using real-time data, to investigate an adaptive lighting system with vehicular traffic inputs. They measured reduction in energy consumption and provided information on several different system options, in terms of efficiency. Ultimately, they noted that their dimming adaptive system could lead to between 14 to 70 percent energy savings over different volume levels for rural roads (Nefedov et al., 2014). Knobloch and Braunschweig (2017) presented an adaptive lighting scenario whose main goal was energy savings; it applied dynamic information such as traffic speed as an algorithm input and led to energy savings of more than 20 percent, depending on speeds and compared to non-responsive systems.

### *2.4.2 Weather-Related Factors*

Very little research had been published describing the relationship between roadway lighting and crashes in inclement weather for controlled access highway facilities. Those studies that do exist have primarily focused on the impact of fixed lighting levels over many locations rather than variable lighting. In the following, a few studies that may be informative for developing an adaptive lighting scenario that considers weather factors are presented.

Niaki et al. (2014) modeled illumination for urban roadway lighting scenarios. They found that cloud cover can lead to higher roadway illumination levels, for a given lighting level. This result may arise since exogenous light can reflect off of the cloud cover, an issue that may solely be seen in locations with high levels of artificial lighting. However, other work has not found this to be a significant predictor of safety performance (Monsere and Fischer, 2008; Monsere, Yin, and Wolfe, 2007). Gupta et al. (2017) proposed an adaptive roadway lighting framework that adjusts lighting levels in response to traffic- and weather-related variables. The system was comprised of parts including a detection system through which different sensors can observe the environment and a communication system allowing exchange of information with a traffic management center. Golob and Recker (2003) presented a variable selection approach for traffic incidents considering various operational, lighting, and weather conditions. Their results suggested that wet road surface conditions may lead to increased crash potential (mostly during daylight hours), potentially due driver overconfidence. This sentiment was supported by Jägerbrand and Sjöbergh (2016), who investigated average speed during dark hours and under adverse weather conditions. They noted that for such conditions, average speed decreased less for roadway segments with lighting, compared to unlit segments. These studies suggest that one may want to investigate the impacts of reducing speeds instead of lighting level during nighttime periods with adverse weather as a topic of future work.

## 2.5 Adaptive Lighting Simulation Platforms

There are many existing traffic simulation platforms, such as VISSUM®, VISUM®, and more; however, the majority of them focus on network and intersection simulation rather than lighting-related simulation. There are also some other indoor lighting simulation tools, such as DIAL® (DIAL, 2017), which focus on lighting design and architectural layout. That said, there are also platforms that can be used in street lighting simulation (OSRAM, 2008). DAYSIM® was used to evaluate precise system energy consumption and lighting algorithms for installations in buildings (Roisin et al., 2008).

Park and Burke (2007) presented a framework and demonstration of a wireless sensor network-based intelligent lighting system. They described the design, system architecture, control algorithms, and test scenarios in their study. A core component of their system was a multi-modal and high-fidelity light sensor module that is ideal for interaction with a wireless sensor network. However, this study focused more on sensors than on transportation safety and energy evaluation.

Some systems have been designed to control, monitor, and record the operation of luminaires remotely, such as from a terminal or desktop computer. Such systems typically allow an owner to specify a database containing the control parameters and observe the performance either network-wide or at certain areas within the network. McLean used Microsoft MapPoint server and integrated mapping software to control an optimized adaptive lighting system. In their system, luminaires could be adjusted, issues/errors could be detected, and route choice information was also available (McLean, 2006). Jing et al. (2007) built a remote monitoring and control system for roadway lighting applications. It provided for control of each luminaire, which in turn could lead to reduced power consumption and more broadly available lighting. The system allowed display of the network topology and maps, as well as real-time information on the system, means to control lighting schedules, and it also provided and summary reports (Shu et al., 2007).

The University of Washington (UW) Smart Transportation Applications and Research Laboratory (STAR Lab) built the Digital Roadway Interactive Visualization and Evaluation Network (DRIVE Net) platform, whose aims are sharing data, integration, visualization, and analysis.  This system provides users with an open-source platform that can store, access, and manipulate a variety of transportation data. Its capability for integrating road lighting information into the platform is worthy of exploration (Wang et al., 2016). Further information on roadway lighting simulation platforms, specifically those used for the simulation component of this project, is discussed in Section 5.

To conclude, it is clear that the impact of roadway lighting on traffic safety has been a hot research topic over the past few decades. Roadway lighting, when used appropriately, has the potential to reduce some nighttime visibility-related crashes; however, the magnitude of the benefit varies with the condition and characteristics of the roadway facility. Through adaptive lighting management, energy consumption can be reduced and energy efficiency can be improved. In addition, the sparse amounts of research would indicate that specific conditions can be accounted for in a manner that can address some crashes related to lighting conditions. Generally speaking, the study of adaptive control methods and tools has been scarce; therefore, it is meaningful to perform this research and apply it in practice.

# 3.0 Data Collection

The key tasks before development of the adaptive lighting methodology include data collection, data processing, and building a project database. The overarching objective of this task was to compile the data necessary to assess the relationship between lighting levels, crash potential, roadway performance, and weather/road surface conditions that would ultimately help guide development of the adaptive lighting methodology. Specifically, the project team collected the following data:

- Incident data from the Washington State Patrol (WSP) Computer Aided Dispatch (CAD) system, including traffic incidents, objects in the roadway, and traffic stops;
- Roadway geometry, in the form of GIS files describing road line geometry, lane count, and roadway class;
- Weather data for National Weather Service stations around Olympia, Washington, from the UW Department of Atmospheric Sciences;
- Sun altitude and azimuth data from the US Naval Observatory;
- One month of vehicle trajectory data for the locations of interest from INRIX, Inc.; and
- Loop detector data (volume, occupancy, estimated speed) for the locations and time periods of interest from the Washington State Department of Transportation.

## 3.1 Study Sites in Washington State

For this project, data were collected from two field study sites where WSDOT installed LED roadway lighting systems with adaptive lighting capabilities. At the time of writing this report, the adaptive features of the system were not yet being used (i.e., real-time control was not taking place); however, a curfew system during which select luminaires were turned off was in place at one of the study sites. Both study sites were located in Olympia, Washington, the state capitol, a bit south of Seattle. The lighting systems were installed along (1) US Highway 101 (US 101) between Black Lake Blvd. and the Interstate 5 (I-5) interchange (the only site with the curfew in place at the time of writing this report) and (2) I-5 from exit 99 through exit 111 (running through the cities of Tumwater and Lacey, in addition to Olympia). A map of the study sites can be seen in Figure 3-1, where the yellow dots represent luminaires. Installation of the LED lighting system began at the US 101 site in 2013.

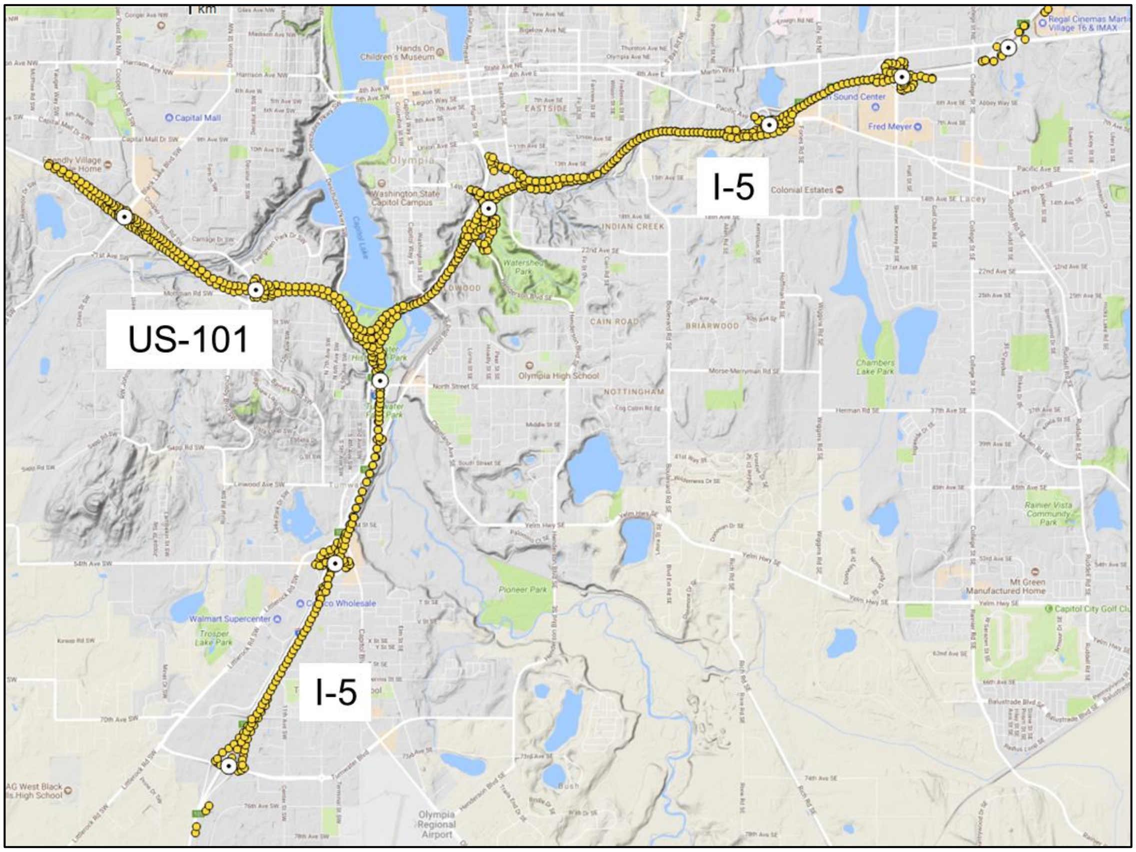


**Figure 3-1**: Study sites with LED adaptive lighting systems in Washington

## 3.2 Washington State Patrol Incident Data

A single Microsoft Excel file containing the CAD incident data and metadata was provided by Mr. Richard J. Warren who during the project served as WSP's CAD Systems Supervisor. In total, this file contained 52,901 records dating from December 31, 2009 to September 30, 2017 with global positioning system (GPS) locations placing them within the study sites shown in Figure 3-1. The data structure of the spreadsheet is shown in Table 3-1.

**Table 3-1**: CAD incident data format

| Field | Description | Field Type |
|---|---|---|
| District | District Identifier Code | integer code |
| Area | Area Identifier Code | character |
| DateTime | Time and Date of Incident | date time stamp |
| Source | Source of Record | Integer |
| Incident | Incident Identifier | character |
| Type | Incident Type Code | character |
| Unit | Reporting Unit Identifier | character |
| Disposition | Disposition Code | character |
| Location | Location Description | character |
| Latitude | Latitude of Incident Location | numeric |
| Longitude | Longitude of Incident Location | numeric |

The primary fields of interest for this project included location and time, type, and disposition. The type field is a text code referencing an incident type, which includes crash and injury types, crimes, traffic stops, and a variety of other incident types that are were associated with some WSP action. The disposition field is a text code indicating the conclusion and/or actions of the responding officer(s). For example, disposition codes include Driving Under the Influence (DUI) arrest, impounded vehicle, and various traffic citation types. This field was included primarily to provide some indication of whether an incident involved a commercial vehicle. Scripts were developed to load the CAD data into a PostGIS database, and several queries were developed to provide some initial insight into the overarching patterns and trends. Table 3-2 shows the incident count for the top eight incident types by occurrence. Together, these types constituted over 91 percent of all records. In total, 27 incident types were contained in the incident records database.

**Table 3-2**: Top eight incident types

| **Incident Type** | **Count** |
|---|---|
| DISABLED VEHICLE | 21998 |
| TRAFFIC HAZARD BLOCKING | 5191 |
| COLLISION PROPERTY DAMAGE | 4455 |
| ABANDONED | 4282 |
| TRAFFIC HAZARD | 3903 |
| DISABLED VEHICLE / TOW ENROUTE | 3646 |
| PEDESTRIAN | 3489 |
| DISABLED VEHICLE BLOCKING | 1587 |

Our initial investigation suggested that the incident locations were geocoded with a text description of the actual locations, and therefore, the spatial resolution of the locations was quite low. That is, in many cases dozens and even hundreds of incidents were (indicated to be) located at the exact same point in space, and there are substantial stretches of roadway with zero incidents. A heat map of the incident locations from January 2010 through August 2017 is shown in Figure 3-2.

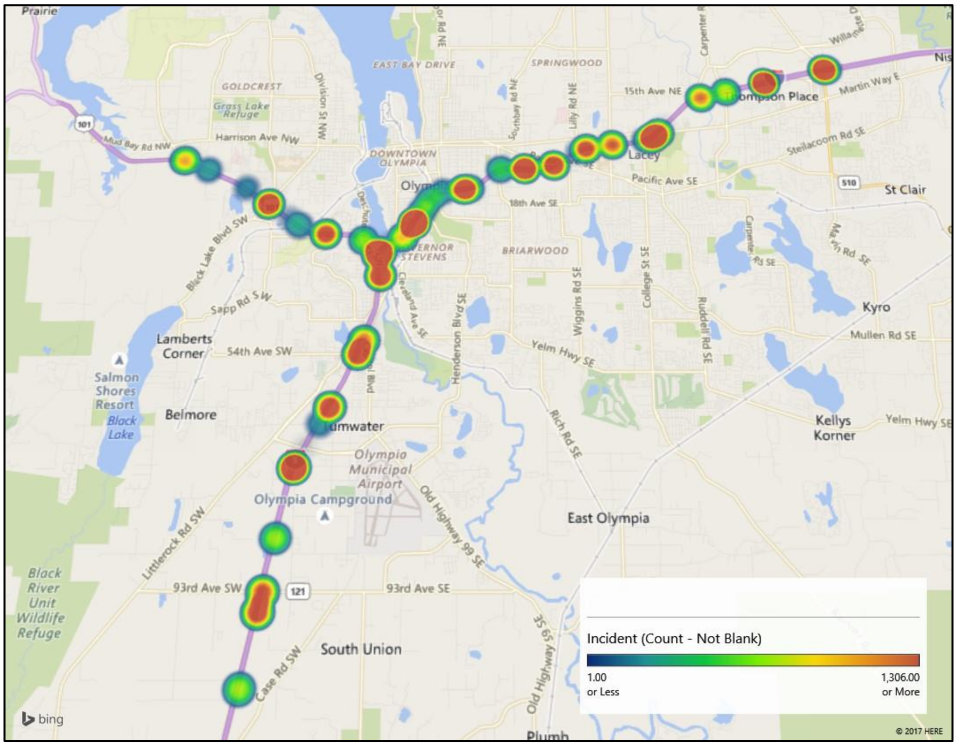


**Figure 3-2**: Heat map of all incident types from 2010 - 2017

## 3.3 Roadway Geometry

Because of the low spatial resolution of the incident data (i.e., that in many cases, dozens or even hundreds of incidents were noted to have taken place at the exact same point in space), the research team decided that roadway line geometry would provide sufficient detail for characterizing incident patterns. For this purpose, state route and interstate line geometries were obtained from the Washington State Department of Transportation at 1:24,000 scale. This data set is updated annually and is used primarily for linear referencing of features along the state highway network and for general purpose geospatial mapping (Blake, 2016). Scripts were developed to convert the ESRI shapefile into an appropriate format and load the file into a PostGIS database. The fields present in this data set are described in Table 3-3.

**Table 3-3**: WSDOT route data format

| **Field** | **Description** | **Field Type** |
|---|---|---|
| barm | Begin Accumulated Route Mile | numeric |
| direction | Travel Direction (increasing/decreasing/both milepost, ramp) | character |
| display | labels for shields | character |
| earm | End accumulated route mile | numeric |
| lrs_date | date for linear referencing operations | date string |
| objectid | feature id | integer |
| region | geographic/administrative area of WSDOT responsibility | character |
| RelRouteQual | Related Route Qualifier, description of feature location | character |
| RelRouteType | Related Route Type, coded route type | character |
| RouteID | Unique route identifier | character |
| RT_TypeA | Coded Route Type (text code) | character |
| Rt_TypeB | Coded Route Type (integer code) | integer |
| StateRouteNumber | Number assigned to state route | character |
| STLength | Length of feature | numeric |
| geom | Feature Geometry | geometry |

## 3.4 Weather Data

Weather data for the Olympia, Washington area were obtained through the UW Department of Atmospheric Sciences website. Data were obtained for the station located at the airport in Olympia, Washington, which was the nearest National Weather Service station providing data for the entire study period (2010 – 2017). No stations providing road surface condition observations for the locations of interest were found. A script was developed to perform the necessary conversions and load the weather data into a PostGIS database. A description of the weather data format is provided in Table 3-4. A number of additional summary fields were included in this data set, but these were not included in this report for brevity.

**Table 3-4**: Weather data format

| **Field** | **Description** | **Field Type** |
|---|---|---|
| Date | Date and time of Record (GMT) | character |
| date_julian | Date in Julian format | numeric |
| pressure | atmospheric pressure in millibars | numeric |
| air_temp | air temperature in degrees F | numeric |
| dew_temp | Dew Temperature in degrees F | numeric |
| wind_dir | Wind direction in degrees from north | integer |
| wind_spd | Wind Speed in Nautical Miles / Hour | numeric |
| cloud_cov | Cloud Cover in 1/8ths of sky | integer |
| cloud_hei | Cloud Height in 100's Feet | numeric |
| vis_miles | Visibility in Miles | numeric |
| solar_ird | Solar iradience in Watts/meter^2 | numeric |
| rel_humid | Relative Humididty in percent | numeric |
| rain | Rain in inches | numeric |
| sum_rain | Cumulative rain fall in inches | numeric |

A map of the weather station location is provided in Figure 3-3, along with the locations of road sections and interchanges of interest on I-5 and Highway 101.

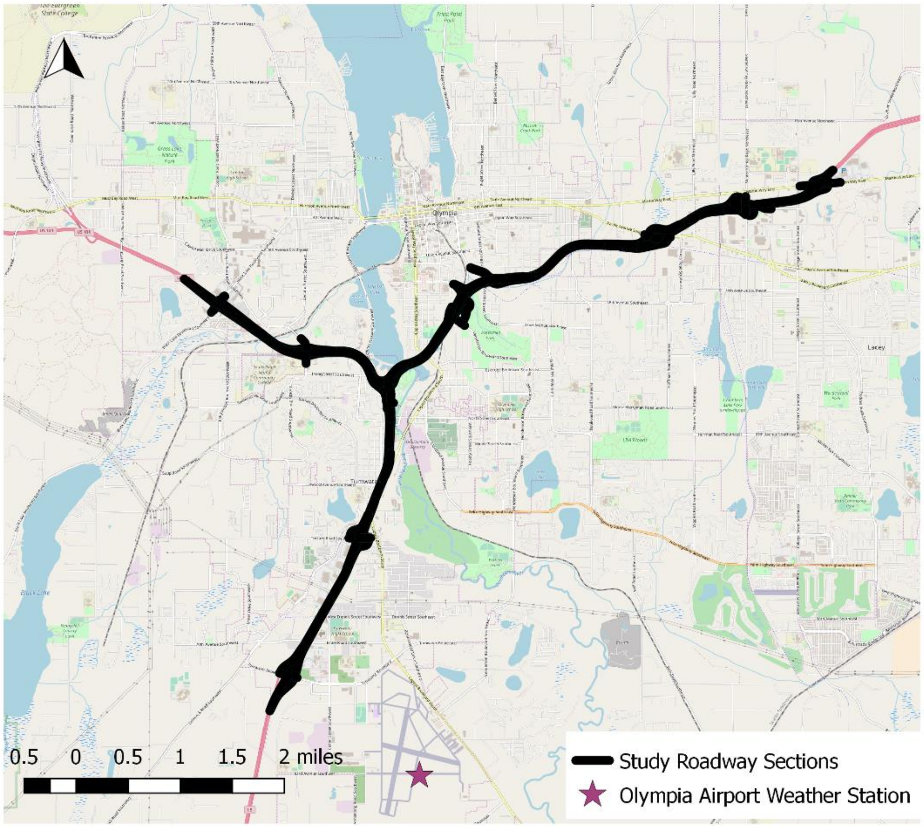


**Figure 3-3**: Weather station locations

## 3.5 Sun Altitude and Azimuth Data

Sun azimuth and altitude data were obtained for the City of Olympia, Washington, from the US Naval Observatory (USNO) website. A script was developed to obtain data from the USNO website at 10-minute intervals for the entire study period, perform the necessary format conversions, and load the data into a PostGIS database. These data were obtained to describe the natural lighting levels in consistent terms throughout the year. That is, the angle of the sun was assumed to be a sufficient indicator of the natural light that was supplied by the sun and to be a clearer and more precise indicator than others such as time of day or time until sunset. Details regarding the interpretation of sun azimuth and altitude can be found on the National Oceanic and Atmospheric Administration website (US Department of Commerce, NOAA, 2017). The format of this data set is shown in Table 3-5. Note that these data were extracted for each day in the study period, with the date specified in the request. When these data were loaded into a database, date information was determined locally for each request.

**Table 3-5**: Sun altitude and azimuth data format

| Field | Description | Field Type |
|---|---|---|
| Time | time of day | character |
| Altitude | Solar Altitude in decimal degrees | numeric |
| Azimuth | Solar Azimuth in decimal degrees | numeric |

## 3.6 Vehicle Trajectory Data

INRIX provided vehicle trajectory data for the month of May 2017 in the form of comma separated value (CSV) files. This data set described individual vehicle trajectories obtained from embedded GPS and mobile devices. Each trip consisted of a collection of waypoint locations and times, along with provider information, vehicle class, and trip summary information. The data set consisted of two primary data files: 1) a trip records report file summarizing each trip and 2) a trip waypoints file with individual trip waypoint records. Here, a trip is defined as a path traveled between a specified origin and destination by a single vehicle. The spatial resolution of the data is such that the roadway and direction of travel of each trip can be determined, whereas the exact lane cannot be determined due to GPS measurement error. The formats of these two data files are shown in Table 3-6 and Table 3-7. Some additional fields were included in these files that were not populated or otherwise not relevant to the present inquiry, and these were omitted for brevity.

Scripts were developed to perform the necessary formatting and load these two files into PostGIS database tables. Each record in the trip summary table can be uniquely identified by the TripID field, by the combination of TripID and WaypointSequence fields in the trip waypoint table. The two tables can be joined on the common TripID field.

By nature of the way in which the data were collected, this data set included the entirety of all trips that passed through the study area, most of which began and ended outside of the study area. As a result, trips reached locations all over the northwestern U.S., including Idaho, Oregon, California, and Montana. A sample of waypoints for the trips data is shown in Figure 3-4. The greatest density of waypoints can be found on I-5 along the study corridor.

**Table 3-6**: Trip summary data format

| **Field** | **Description** | **Field Type** |
|---|---|---|
| TripId | Unique trip Identifier | character |
| WaypointSequence | Within-trip waypoint sequence number | integer |
| CaptureDate | Date and time of observation | date time string |
| Latitude | Latitude of waypoint | numeric |
| Longitude | Longitude of waypoint | numeric |

**Table 3-7**: Trip waypoint data format

| **Field** | **Description** | **Field Type** |
|---|---|---|
| TripID | Unique Trip Identifier | character |
| DeviceID | Unique Device Identifier | character |
| ProviderID | Unique Provider Identifier | character |
| Mode | Code Representing the Travel Mode of Trip | integer |
| StartDate | Date and Time of Trips Start (UTC) | date time string |
| StartWDay | Weekday of Trip Start (UTC) | integer |
| EndDate | Date and Time of Trips End (UTC) | date time string |
| EndWDay | Weekday of Trip End (UTC) | integer |
| StartLocLat | Trip Start Latitude | numeric |
| StartLocLon | Trip Start Longitude | numeric |
| EndLocLat | Trip End Latitude | numeric |
| EndLocLon | Trip End Longitude | numeric |
| IsStartHome | If True, Trip Started at Home | bouline |
| IsEndHome | If True, Trip Ended at Home | bouline |
| ProviderType | Code representing the provider type | integer |
| ProviderDrivingProfile | Code Representing the Provider Driving Profile | integer |
| VehicleWeightClass | Code Representing the Vehicle Weight Class | integer |
| EndpointType | Code Representing Clean Trip start/end | integer |

The INRIX data set is summarized in Table 3-8 and Table 3-9. The average sampling intervals shown in Table 3-9 indicate the average time between subsequent observations; for example, local delivery vehicles report their location once every 90 seconds on average. Therefore, it can be inferred that, while consumer vehicles made up less than a fourth of all trips, they made up a much greater fraction of the total waypoints because of their short average sampling interval.

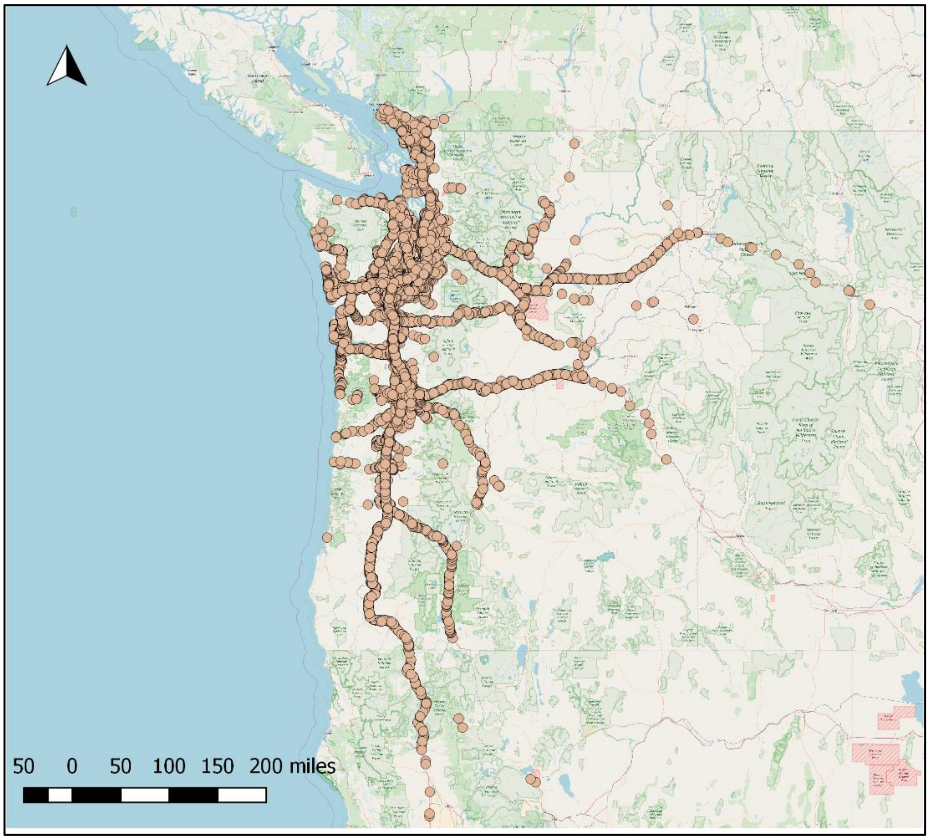


**Figure 3-4**: Sample of INRIX waypoints

**Table 3-8**: Summary of INRIX trips data

| | |
|---|---|
| Provider Count | 36 |
| Unique Device Count | 70,077 |
| Total Trip Count | 168,966 |
| Total Waypoint Count | 20,688,862 |
| Avg. waypoints / trip | 22 |

**Table 3-9**: INRIX trips data summarized by provider type

| **Provider Type** | **Avg. Sampling Interval** | **Trip Count** |
|---|---|---|
| Consumer | 11.44 s | 37,925 |
| Private Trucking | 59.30 s | 82,334 |
| Local Delivery | 89.86 s | 48,707 |

## 3.7 Loop Detector Data

Loop detector data were obtained from WSDOT. There were eight loop detector cabinets or stations within the study area (shown in Figure 3-5), one on Highway 101 and seven on I-5. These are listed in Table 3-10. Each of these stations supported multiple loop detectors in both travel directions (northbound and southbound for both Highway 101 and I-5), and all supported dual loops capable of measuring traffic volume, speed, and traffic counts categorized by vehicle length bins.

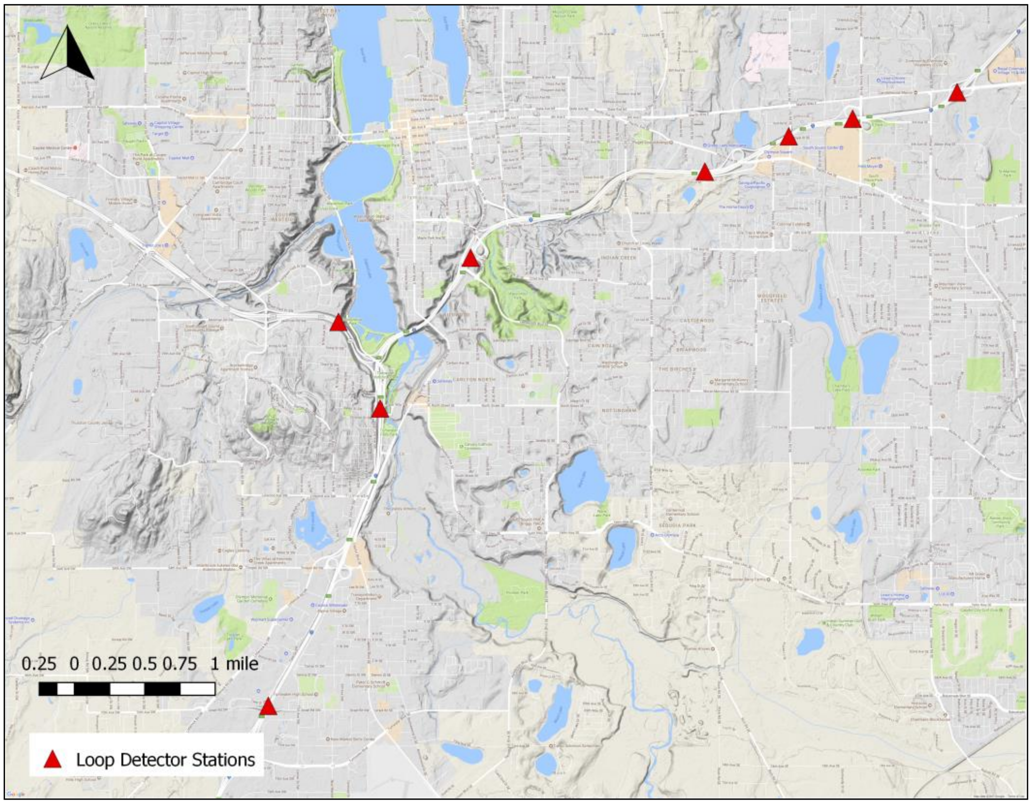


**Figure 3-5**: WSDOT loop detector stations in the study area

**Table 3-10**: Loop detector stations in the study area

| **Station Name** | **Route** | **Milepost** |
|---|---|---|
| 005es10177 | Interstate 5 | 101.77 |
| 005es10404 | Interstate 5 | 104.04 |
| 005es10538 | Interstate 5 | 105.38 |
| 005es10727 | Interstate 5 | 107.27 |
| 005es10792 | Interstate 5 | 107.92 |
| 005es10839 | Interstate 5 | 108.39 |
| 005es10918 | Interstate 5 | 109.18 |
| 101es36664 | Highway 101 | 366.64 |

Loop data were obtained at 20-second intervals and aggregated to 5-minute intervals. These data are managed in the STAR Lab DRIVE Net system (http://www.uwdrive.net/) and were subjected to rigorous quality control processes and data imputation. For details on these methods and the DRIVE Net platform, please refer to Wang et al. (2016).

# 4.0 Methodology Development

This section describes details of our development effort on the adaptive lighting control methodology.

## 4.1 Roadway Safety Analysis

We planned to analyze the incident patterns on the US 101 portions of the study site to determine whether the lighting installed in 2013 and the associated curfew scenario had resulted in any marked shifts in incident rates or patterns. However, the CAD data provided for this project did not contain the spatial accuracy needed to support such an analysis. As a result, the analysis could not address whether the curfew had a significant impact on late night crash risk.

As an illustration, Figure 4-1 shows the incident count for the curfew time period (11:00 PM – 5:00 AM) divided by the incident count for all other hours of the day for Highway 101. Each line in this plot indicates a milepost aggregation range, with the milepost 367 bin terminating at I-5. It is important to note that while incident data was initially collected regardless of type (e.g., collision vs. non-collision), only collision incidents were considered in this plot. A similar pattern was observed when individual incident types for all time periods were inspected, although for some incident types the number of occurrences was too small during the curfew period to make a comparison over the analysis period. Note an increase in the incident count ratio for milepost bins 364 and 365 following the new LED lighting and curfew on Highway 101. These results, however, should be interpreted with caution due to the aforementioned data resolution issue. Further, it is important to note that crashes are random in nature and the result of many interacting factors, many of which cannot be practically measured (e.g., driver behavior and attitudinal attributes). As such, it is hard to attribute and increase/decrease in crashes to one sole factor (e.g., the lighting in this case), due to the presence of numerous confounding factors. Additionally, one may also want to consider statewide crash trends in a similar time period for another frame of reference. Notably, the collision rate per 100 million vehicle miles traveled (as reported in the "Annual Collision Summary" for Washington, last published in 2015) increased from 174.3 in 2013, to 185.4 in 2014, to 196.2 in 2015; that is to say the collision rate increased statewide following the time period at which the study site began using the lighting curfew (Washington State Department of Licensing et al., 2013; Washington State Department of Licensing et al., 2014; Washington State Department of Licensing et al., 2015).

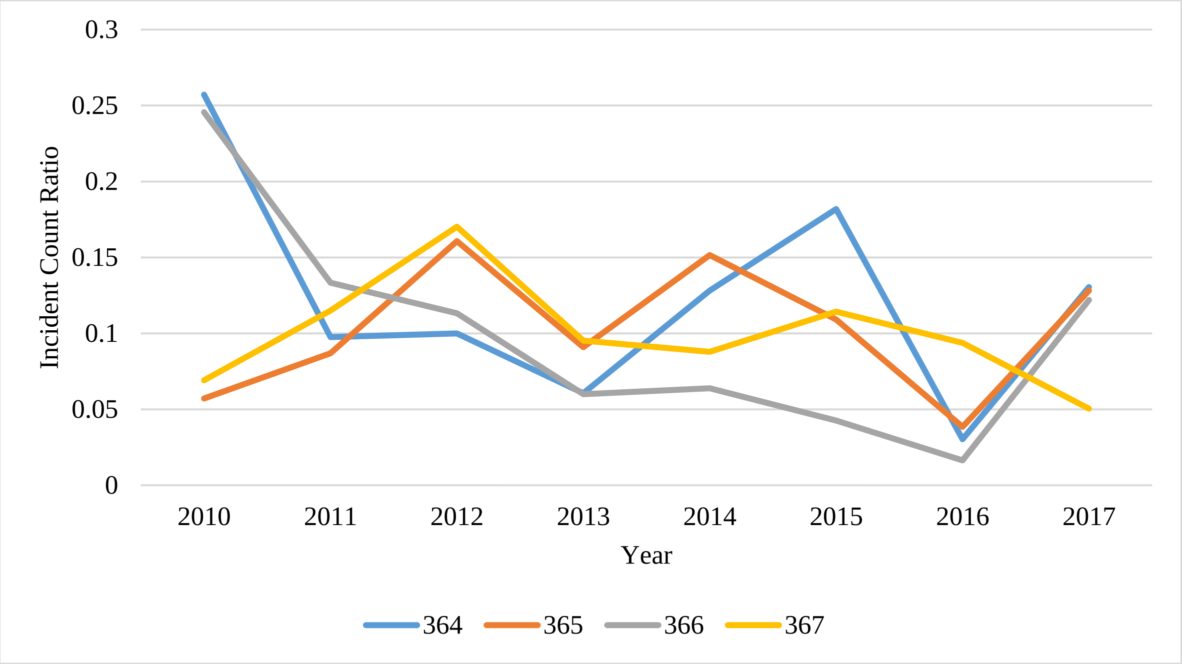


**Figure 4-1**: Incident ratio (crashes only) by milepost and year

Next, we looked at the occurrence of secondary incidents at the study site between 2010 and 2017, defined here as follows:

- A primary incident (any category considered to represent an opportunity for crash potential or distraction, including disabled vehicles, traffic enforcement operations, road debris, etc.) occurred within one hour prior within the same area (in terms of distance, including both directions of flow)
- Secondary incidents must be in a class broadly categorized as collisions, thus excluding disabled vehicles, traffic stops, and other non-collision classes.

It was clear that this definition would result in some errors, but the spatial granularity and lack of incident descriptive information excluded the applicability of a more robust definition. The objective was to determine whether the presence of a primary incident would contribute to greater secondary incident risk, and whether this relationship would change by time of day or day of week. To make this determination, we compared the overall rate of collision incidents (in terms of incidents/hour) for each spatial aggregation bin with the rate of collision incidents following a primary incident. We compared only the combinations of day of week, hour of day, and spatial aggregation bins for which a primary incident was observed.

The overall collision count was computed as the number of collisions occurring in each spatial aggregation bin during each unique combination of day of week and hour of day. The overall collision rate, then, was computed as the overall count divided by the total number of hours represented in the data set for each combination of hour of day and day of week. The secondary collision count was computed as the number of collisions occurring in each spatial/temporal aggregation bin that were preceded by a primary incident. The secondary collision rate was computed as the secondary collision count divided by the total number of hours for each spatial and temporal aggregation bin present in the data set that was preceded by a primary incident.

Some errors were likely introduced in this methodology because of duplicates and multiple, unrelated incidents occurring in a single aggregation interval. We attempted to exclude duplicates by including only secondary incidents that occurred at least 5 minutes after the primary incident. The issue of unrelated incidents was difficult to address because of the inherently low spatial resolution of the CAD. As a result, in many cases two incidents were coded as occurring at the same location even though they may have been separated by a half mile or more.

The results are plotted by hour of day in Figure 4-2. It is clear from this plot that collisions were much more likely to occur during the hour following a primary incident. However, the difference between secondary and all collision curves seems to be larger during the daytime periods, when traffic volumes were higher and roadway lighting provided no benefit (and was not applied for that matter). This is likely due to the shorter average time headway during higher volume hours and space constraints for collision avoidance. Considering that sight distance plays an important role for drivers to perceive and react to objects or distractions in the roadway, we consider it important to provide appropriate lighting following a primary incident, as it could increase sight distance and make resulting objects or distractions in the roadway stand out to drivers.

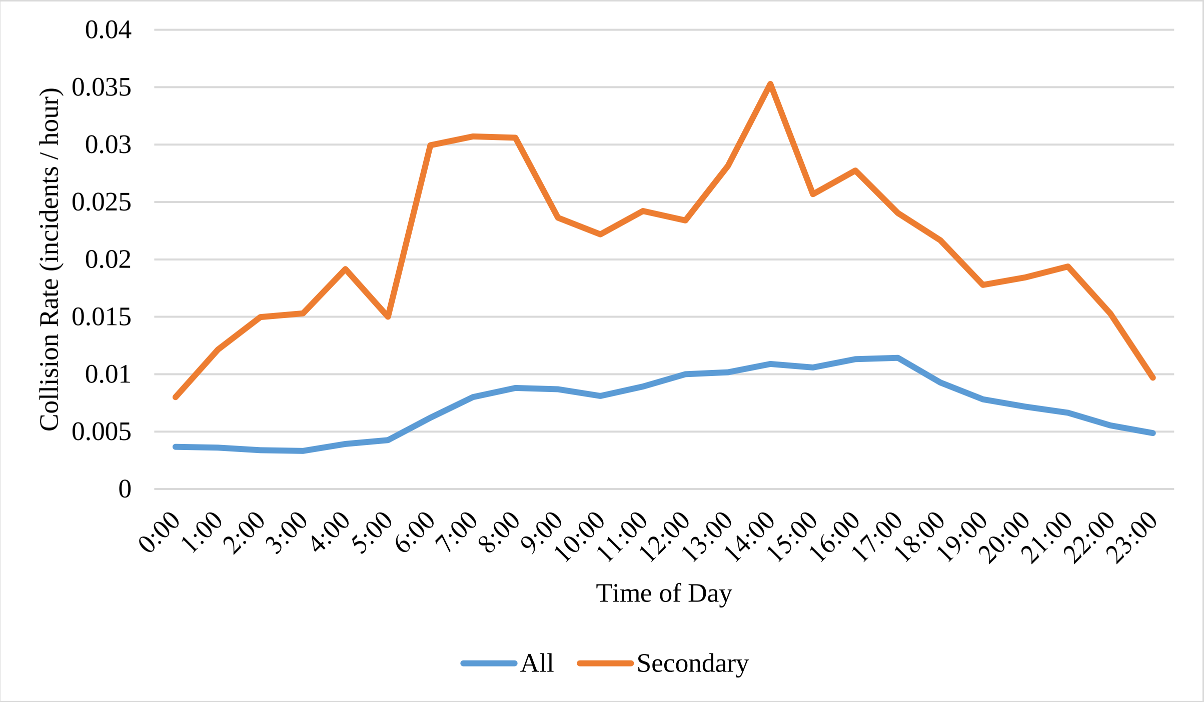


**Figure 4-2**: Secondary and primary incident rates (incidents/hour) vs. hour of day

## 4.2 Adaptive Lighting Strategy

### *4.2.1 Outline*

As discussed in the literature review section, the relationship between roadway lighting and weather, roadway geometry, safety, and operational factors is extremely complicated, and thus, it is very challenging to develop an algorithm that can be generalized to all locations and time periods. Still, enough work on this topic exists as a good foundation upon which to develop some "best practices" guidelines for reducing lighting levels via an adaptive lighting system that can control lighting levels based on observed data. On the basis of the findings in the literature review and our analysis of the incident data, we developed a preliminary strategy for setting appropriate lighting levels for changing traffic conditions, weather, and the presence of objects in the roadway.

As a proof of concept, in this project, we explored our adaptive lighting plan via simulation experiments and revised as needed.

The adaptive lighting principles of this plan, detailed in the following, were based on our conversations with WSDOT lighting engineers, incident analysis, and the literature review, all of which were consistent with FHWA guidance for adaptive lighting systems (Gibbons et al., 2014):

- Dimming lights allows lighting levels to be reduced without impacting other design criteria. Furthermore, maintaining reasonable lighting uniformity in terms of lighting class should be prioritized in setting lighting levels over a corridor.
- Lighting levels can generally be reduced during late night, low volume time periods in areas with historically low collision rates without significant safety or performance impacts.
- Generally, more lighting is needed as the roadway Level of Service decreases (i.e., as traffic gets more congested).
- Design or normal lighting levels should be used in the presence of significantly reduced visibility or surface friction.
- Traffic volumes remained non-negligible throughout the night in all study locations. For this reason, and because of the lag time needed for lights to turn on, an adaptive scenario that allowed lights to be turned on only when a vehicle was detected would not likely be practical (i.e., luminaires will not be turned on/off instantaneously in response to individual vehicle detections).

- In the study area, preliminary analyses of incident data showed there was a significantly elevated risk of traffic collision following a primary event such as a collision, object in the roadway, or traffic stop. Without assuming that increased lighting would have a significant impact on all such secondary incidents, design or normal light levels should be used when a primary incident is detected.
- There is significant interaction among site-specific characteristics, including interchange density, ambient luminance, and guidance quality and the setting of appropriate lighting levels.

Additionally, it is recommended that roadway lighting levels be defined, as described in the FWHA guidance, in discrete classes according to average luminance, maximum uniformity ratio (UR), and veiling luminance ratio. This specification is consistent with accepted design standards and current guidance for adaptive systems (Gibbons et al., 2014; International Commission on Illumination, 2010).

These principles are implemented in three separate parts of the proposed adaptive lighting mechanism, each dependent on specific conditions. First, there is a real-time safety-based component that sets minimum required lighting levels for each road segment if an incident or collision has been detected. This component must be able to respond promptly, allowing light levels to change as soon as the incident or crash has been reported. The second component updates the minimum lighting levels for each road segment periodically (once per hour) based on traffic and weather observations. The final component is the lighting class check, which sets the minimum lighting class for each road segment unit on the basis of overall uniformity requirements. At each time step, the lighting level for each road segment will be set at the maximum level of the recommendations from these three components. Figure 4-3 illustrates the decision process for the first two components.

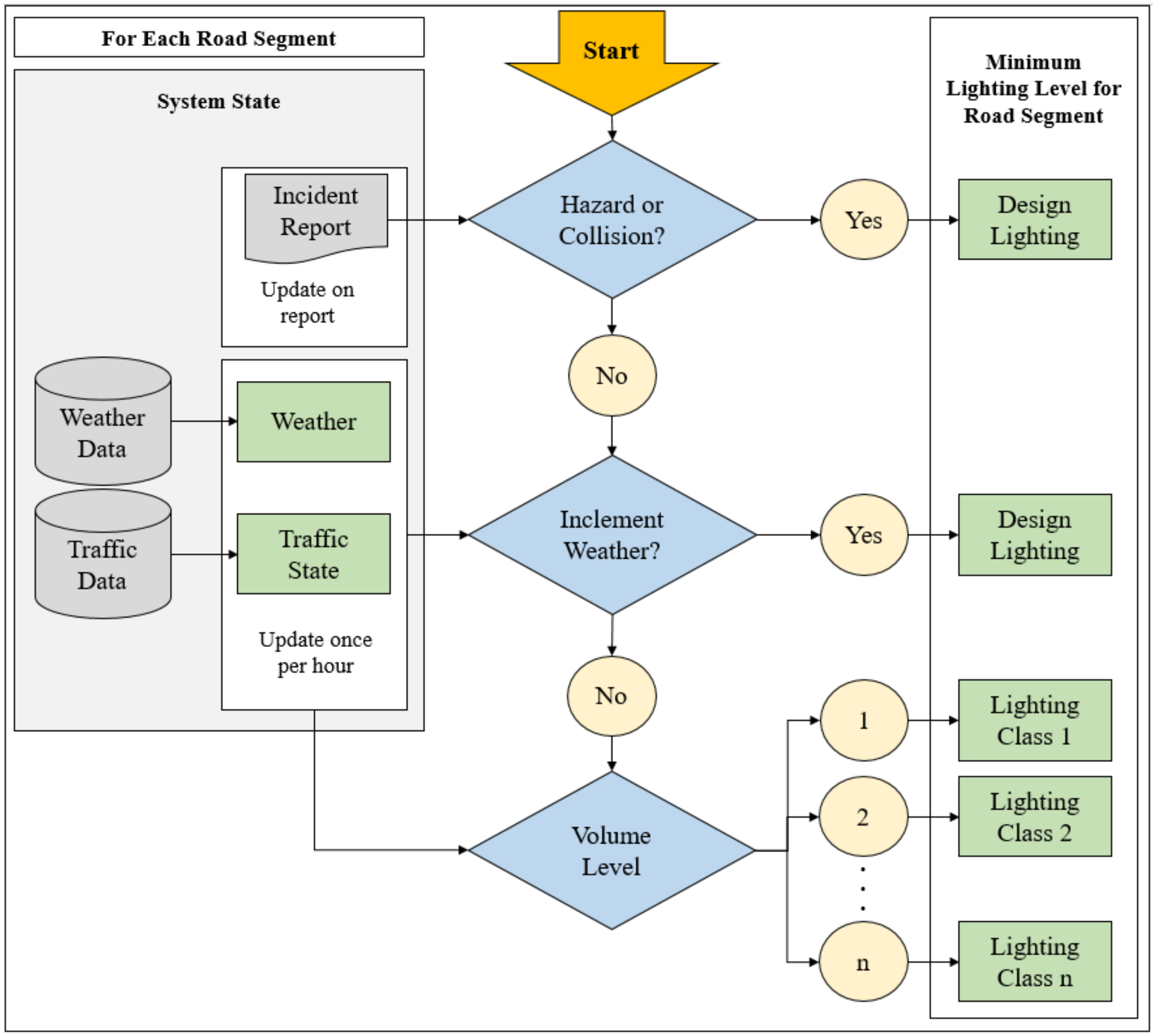


**Figure 4-3**: Flow chart for lighting level setup based on safety, traffic, and weather conditions

Here we set roadway lighting class 1 to be the design lighting level (highest level of illumination) and all subsequent levels to constitute a reduction from that level. For example, if lighting class 2 is selected as shown in Figure 4-3, this means that the minimum *lighting levels* are associated with lighting class 2, and that class 2 is the lowest *lighting class* for that segment. Thus, the lighting class for that segment could be 1 or 2, but not greater than or equal to 3.

In the final component, the lighting class for each road segment must be set to ensure that overall uniformity requirements are satisfied as described in Gibbons et al. (2014). Thus, uniformity checks must be conducted once all segment lighting classes are determined. Following Gibbons et al. (2014), the lighting class difference between any two consecutive segments must be no more than 1. If the determined minimum lighting level for road segment *i* is class 2 and that for its immediate next road segment *i+1* is 4, these two segments' lighting levels do not satisfy the uniformity requirement because the difference is more than 1. Then we need to increase the lighting level of segment *i+1* to 3 to bring the difference within 1 class. Please note that this change may create a new violation of the uniformity requirement and the check needs to be conducted repeatedly until the uniformity requirement is completely satisfied. Also, the way to address the uniformity violation is to bring the lower light level up rather than pushing the higher lighting level down.

### *4.2.2 Collisions and Objects or Distractions in the Roadway*

We considered any roadway event or stationary object in the roadway, incident, or segments with significant roadside distraction to warrant enhanced lighting. To establish the criteria for what constitutes an object in the roadway, incident, or distraction, we looked at the WSP incident classes. As shown in Table 4-1, we defined incident severity codes for each incident type, indicating the expected impact on roadway safety in terms of the risk of secondary incidents. All non-blocking incidents that do not involve pedestrians were categorized as the lowest impact with a severity score of 0. All non-blocking incidents that constitute a significant safety risk, including fire, presence of pedestrians, or other roadway objects, were categorized as moderate impact with a severity code of 1. All blocking incidents that are not categorized as collisions were defined as high impact with a severity code of 2. All collision types were categorized as very high impact with a severity code of 3.

**Table 4-1**: WSP CAD data incident types

| **Incident Type** | **Severity Code** |
|---|---|
| ABANDONED | 0 |
| CLOSE | 0 |
| DISABLED VEHICLE | 0 |
| DISABLED VEHICLE / TOW ENROUTE | 0 |
| OVERPASS | 0 |
| PEDESTRIAN WARRANT | 0 |
| ROAD AND PASS CONDITIONS | 0 |
| ALTERCATION | 1 |
| DISABLED VEH FIRE | 1 |
| FIRE | 1 |
| HAZARDOUS MATERIALS | 1 |
| PEDESTRIAN | 1 |
| PEDESTRIAN EXCITED DELIRIUM | 1 |
| PEDESTRIAN ON BRIDGE/OP | 1 |
| TRAFFIC HAZARD | 1 |
| TRAFFIC HAZARD TRUCK | 1 |
| ABANDONED BLOCKING | 2 |
| DISABLED VEHICLE BLOCKING | 2 |
| TRAFFIC HAZARD BLOCKING | 2 |
| COLLISION ABANDONED | 3 |
| COLLISION INJURY UNKNOWN | 3 |
| COLLISION PERSONAL INJ HIT & RUN | 3 |
| COLLISION PERSONAL INJURY | 3 |
| COLLISION PROP DAMAGE HIT & RUN | 3 |
| COLLISION PROPERTY DAMAGE | 3 |

Using these severity code definitions, any incident type that is of moderate impact or higher warrants enhanced roadway lighting.

### *4.2.3 Traffic State*

The traffic state criteria for roadway lighting were based on general guidance from the literature for controlled access facilities. Specifically, we looked at the guidance provided in Gibbons et al. (2014), which was loosely based on Level of Service. This work considered a weighting scheme for setting design lighting levels and then incorporated real-time traffic data as an additional weighting parameter. The weight values for fixed roadway lighting are shown in Table 4-2. To use this table, the sum of all weight values for a road section are subtracted from the base value for the roadway class, and the result is rounded down to the nearest integer. For controlled access highways, the base value is 5. With the lighting class selected in this way, the on-road light conditions are specified as shown in Table 4-2.

Obviously, the design lighting levels for all road sections in the study had already been established by WSDOT lighting engineers. We discuss this fixed lighting methodology only as a basis for the adjustments made to consider real-time traffic information. For the study area, all segments were classified as high traffic volume, high speed, and high interchange density. No data were available for ambient luminance, so given the surrounding land use, we assumed it to be moderate. Although medians are present along both I-5 and Highway 101, in most cases they are not high enough to block glare. For some segments, there is adequate distance/grade separation between opposing traffic directions to constitute a glare blocking median. Guidance, which refers to road surface markings, was assumed to be in good condition on all road segments in the study area.

**Table 4-2**: Design lighting level weight table (from Gibbons et al., 2014)

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

**Table 4-3**: Lighting levels for limited access roadways (from Gibbons et al., 2014)

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

WSDOT lighting data collected on Highway 101 seems to conform to the prescribed average luminance levels for classes H1 and H2 (which describes all of the road segments in the study area) (Bailey, van Schalkwyk, and Milton, 2015). Therefore, with this general framework, real-time traffic conditions could be incorporated into the weighting scheme by using the values shown in Table 4-4. From this, it is clear that traffic dropping below 1,000 vehicles/lane/hour would result in lowering of one lighting class level, i.e., a reduction in average luminance of approximately 0.2 $cd/m^2$. Likewise, traffic levels reaching 2,000 vehicles/lane/hour would result in an increase in average luminance of approximately 0.2 $cd/m^2$, although most segments in the study area would operate at design levels even under moderate traffic, in which case no further increase would be made.

**Table 4-4**: Weighting values for real-time traffic conditions (from Gibbons et al., 2014)

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

In practice, assuming current design or normal lighting levels are not changed, the methodology prescribed by Gibbons et al. (2014) would only result in a single threshold for adaptive lighting, i.e., a drop in average luminance when traffic dropped below 1,000 vehicles/hour/lane. To further refine this approach, it would be necessary to conduct a thorough audit of lighting levels in order to identify segments where lighting could be reduced under moderate traffic conditions.

### *4.2.4 Weather Conditions*

Weather conditions that warrant enhanced lighting are those that can be expected to result in significantly reduced visibility or surface friction. Thus, heavy rain, fog, and snow were considered in the criteria for setting the maximum lighting class for a road segment. Wet and freezing temperatures alone were not considered because all of the roads in the study area are regularly treated with anti-icing chemicals when conditions warrant. In addition, the criteria had to be based on the fields present in the available weather data, and, because no surface condition information was available, the criteria had to be based on precipitation, temperature, and visibility observations.

The conditions that warrant higher lighting levels were defined in terms of visibility distance and precipitation intensity (as defined in Table 4-5). We selected a visibility threshold of 1 mile, such that enhanced lighting would be warranted when visibility dropped below this value. This is somewhat higher than the values typically used for fog warning systems, which are generally less than 1,000 ft. (Goodwin, 2003). However, as there were no visibility sensors on the roadways of interest, there was a strong chance that on-road visibility would drop well below the observed value at the weather station. In addition, some previous work has shown that there is a significant relationship between visibility and traffic safety even in less severe conditions (Das et al., 2017; Hassan, 2011). Note that, in a number of case studies, street lights were extinguished during extremely low visibility conditions (300 – 400 ft.) (Goodwin, 2003). However, it is not clear that there is a strong basis for this, and such conditions are exceedingly rare in the study area.

For the precipitation threshold, we considered “moderate rain” as defined by the American Meteorological Society (American Meteorological Society., 2012). This threshold was used for both rain and equivalent intensity of snowfall during freezing conditions.

**Table 4-5**: Criteria for inclement weather

| **Criteria** | **Threshold Value** |
|---|---|
| Visibility | 1 mile |
| Precipitation | 0.11 inches / hour |

### *4.2.5 Summary*

Given the traffic incident, traffic volume, and weather criteria for roadway lighting, the adaptive strategy can be summarized as follows:

1. If traffic volumes fall below 1,000 vehicles/lane/hour, reduce lighting levels according to Table 4-4, or reduce average luminance by 0.2 cd/m$^2$.
2. If an incident is present on a road segment, set lighting to the normal or design level.
3. If visibility falls below 1 mile, or if precipitation intensity reaches 0.11 inches/hour, set lighting to the design or normal levels.
4. After considering 1 – 3, increase lighting levels as needed to ensure that the change in lighting class is less than one class between consecutive segments.

As a preliminary evaluation of this strategy, we combined weather, sun angle, incident, and traffic volume data to determine the minimum lighting levels on a single road segment in 2016. We compared minimum lighting levels with the current settings, in which lighting is always at design levels except during the curfew hours of 11:00 PM – 5:00 AM, during which time lighting is reduced. Thus, the current and proposed strategies were considered equivalent when a) the proposed strategy called for reduced lighting during curfew hours or b) when the proposed strategy called for design lighting during non-curfew hours. The two strategies were not equivalent when a) reduced lighting was prescribed by the proposed strategy during non-curfew hours or b) when design lighting was prescribed by the proposed strategy during curfew hours.

Table 4-6 shows a comparison of the proposed adaptive lighting plan and the current curfew plan over the entire year of 2016 for the road segment containing cabinet 005es10792. This table shows all lighting criteria on an hourly basis, and only the time periods when lighting was warranted, that is, after civil dusk and before civil dawn. It is clear that the adaptive scenario would very often prescribe reduced lighting levels during non-curfew hours. This is because, in many cases, traffic volume is below the enhanced lighting threshold during non-curfew time periods. During a small number of curfew hours the adaptive scenario prescribed design lighting, primarily because of the presence of incidents. During the majority of curfew hours the adaptive scenario prescribed reduced lighting.

**Table 4-6**: Comparison of adaptive and current lighting plans

| | | **Curfew** | |
|---|---|---|---|
| | | *Design* | *Reduced* |
| **Adaptive** | *Design* | 331 | 54 |
| | *Reduced* | 1322 | 1790 |

## 4.3 Active Traffic Management for Efficiency Enhancement

Operational efficiency is a secondary focus of the adaptive lighting strategy. With the data obtained for adaptive lighting purposes, it would be possible to communicate with drivers in real time to warn of traffic incidents and slowdowns and provide speed advisories appropriate for conditions. To do this, we proposed an active traffic management (ATM) strategy similar to the approach that has been taken in previous case studies. The literature review made clear that, especially during inclement weather, there is significant interaction among lighting levels, traffic speed, and crash potential.

A number of successful case studies on traffic management strategies to enhance operational efficiency that considered weather and traffic conditions were summarized by Goodwin (2003). In those studies, messages and advisories were communicated to drivers primarily through the use of dynamic message signs (DMS). The approaches used in those studies are briefly summarized below.

- Low visibility warning systems – Display different messages depending on current visibility level, such as "FOG WARNING" when visibility is reduced or "DENSE FOG" alternating with "SLOW, USE LOW BEAMS" under extremely low visibility.
- Speed advisories – Display a speed limit appropriate for conditions based on visibility, rain or snow, or traffic state. Alternatively, advise drivers when downstream traffic speed drops to congested conditions.
- High wind warning – Display warning messages and high-profile vehicle restrictions when high winds are detected.
- Combination – When speed limits are reduced for weather or other reasons, display messages directing drivers to reduce speed as well as the reason for the speed reduction, such as "FOG AHEAD" alternating with "REDUCE SPEED TURN ON LOW BEAMS."

In contrast to much of the work described in Goodwin (2003), we did not have access to a network of on-road weather and surface conditions sensors. In addition, the objective here was to send warnings and advisories to travelers through their mobile phones, using either the mesh network on which the roadway lights would communicate or through the cellular network. In order to avoid overloading drivers with information, the messages should be designed to be easily interpretable. Thus, the strategy pursued here was simplified somewhat in comparison to conventional ATM approaches. We proposed the scenario shown in Table 4-7 which is a synthesis of previous work on ATM simplified for the current study. The snow intensity shown in this table should be interpreted as "rainfall equivalent."

**Table 4-7**: Active traffic management scenario

| Event | Message |
|---|---|
| **Weather** | |
| *Visibility < 0.5 miles* | REDUCE SPEED - LOW VISIBILITY |
| *Rain Intensity > 0.11 inches / hour* | REDUCE SPEED - HEAVY RAIN |
| *Snow intensity > 0.11 inches / hour* | REDUCE SPEED - SNOWY CONDITIONS |
| *Precipitation and temperature < 25$^o$ F* | WATCH FOR ICE |
| **Traffic** | |
| *Traffic Speed < 35 mph* | REDUCE SPEED - SLOW TRAFFIC |
| **Traffic Incident** | |
| *Any incident or object in the roadway* | INCIDENT AHEAD |
| *Lane blocking incident* | LANE BLOCKED - MERGE LEFT / RIGHT |
| *Major collision / fire* | REDUCE SPEED - COLLISION AHEAD |

# 5.0 Simulation Platform

## 5.1 Simulation Set-Up and Background

Once the methodology had been developed, and prior to testing it in the field, simulation was used to study how the adaptive lighting methodology would function in a controlled setting. A variety of potential simulation platforms were investigated before one was chosen. Figure 5-1 shows the overall schema of the different platforms used in the simulation, each of which will be described in depth.

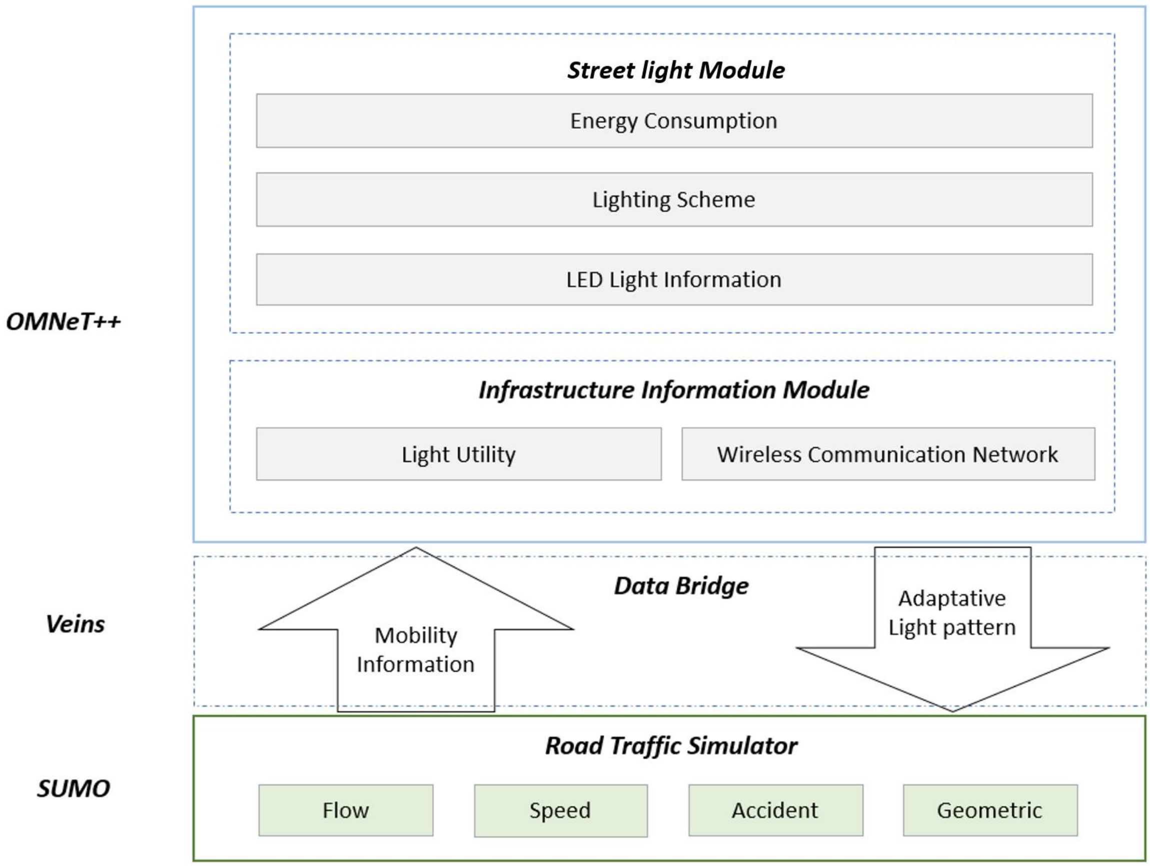


**Figure 5-1**: Schema of different platforms used in simulation

Simulation of Urban MObility (SUMO) is an open source traffic simulation platform designed by the German Aerospace Center (DLR) in 2001. Like other traffic microsimulation platforms, it can be used to simulate the effects of infrastructure changes and policy changes on traffic before their implementations. The key features of SUMO are as follows (Behrisch et al, 2011; ITS, 2016):

- Allows for microscopic simulation - vehicles, pedestrians and public transport are modeled explicitly and at a high resolution with appropriate car-following models, etc.;
- Provides for online/real-time interaction – users can control the simulation with the Traffic Control Interface (TraCI);
- Covers simulation of multimodal traffic, e.g., vehicles, public transport, and pedestrians;
- Enables traffic signal timing plans to be imported or automatically developed within SUMO;
- Does not impose artificial limitations on network size and number of simulated vehicles;
- Supports numerous file import formats: OpenStreetMap (shown in Figure 5-2), VISUM, VISSIM, NavTeq; and
- Is implemented efficiently in C++ and only makes use of portable libraries.

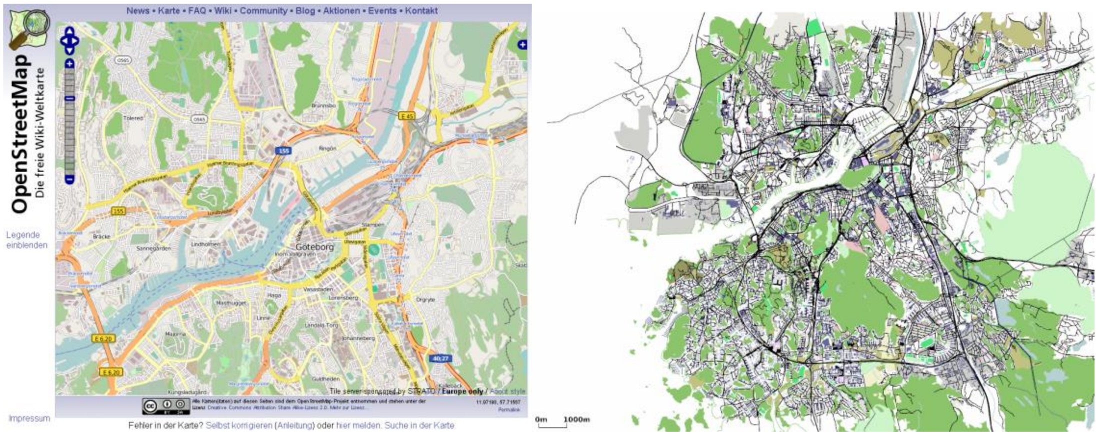


**Figure 5-2**: Screenshot of imported OpenStreetMap (left) data into SUMO (right) (Behrisch et al., 2011)

SUMO has been used in various research projects to study topics such as route choice, communication simulation, automatic driving, and traffic signal timing algorithms. It also provides support for some other common file types such as shapefiles. It is further worth mentioning that SUMO has become very popular for use in simulating V2X (vehicle to everything, including vehicle-to-vehicle, vehicle-to-infrastructure, etc.) communications in a variety of connected vehicle research projects (Behrisch et al, 2011).

OMNet++ (Objective Modular Network Testbed in C++) is an extensible, modular, component-based C++ simulation library and framework for simulation of communications (OpenSim Ltd., 2018). It was developed in 1992 by Andras Varga at the Technical University of Budapest. Since it is an object-oriented discrete event simulator written in C++, it is relatively easy to integrate new modules within the architecture (IRMA, 2010). It has been used in research and teaching because of its non-commercial, open source features. However, OMNet++ simulator does have its weaknesses, including 1) it is slow because of its high memory consumption; and 2) it has a steep learning curve for users inexperienced with communications protocols and a background in electrical engineering. The simulation model ultimately needs to be built in two different applications and written in a text file (IRMA, 2010).

Lau, Merrett, and White (2013) used SUMO and OMNet++ simulation tools to validate an adaptive lighting algorithm based on traffic sensing. Their results showed that their proposed lighting scenario consumed 30 percent less energy than the state-of-the-art benchmark, and it reached the best performance with low traffic volumes that traveled at high speeds. They stated that the previous proposed adaptive lighting simulation systems had problems such as 1) considering only the energy consumption, but ignoring utility; 2) errors in communication systems; and 3) limitations in the communications between users and the lighting system. SUMO provides for detailed simulation settings such as different users travelling at different speeds under various situations, for instance, travel under normal conditions versus conditions under which a crash has occurred.

Other authors have integrated OMNet++ with SUMO (Sommer et al. 2011; Lau et al., 2013). Their component-based architecture can provide for development of more complex and larger components assembled from simple model pieces, i.e., it is scalable (Lau et al., 2013). Figure 5-3 shows the platform interface in which the colors represent different lighting intensities in the work of Lau et al. (2013).

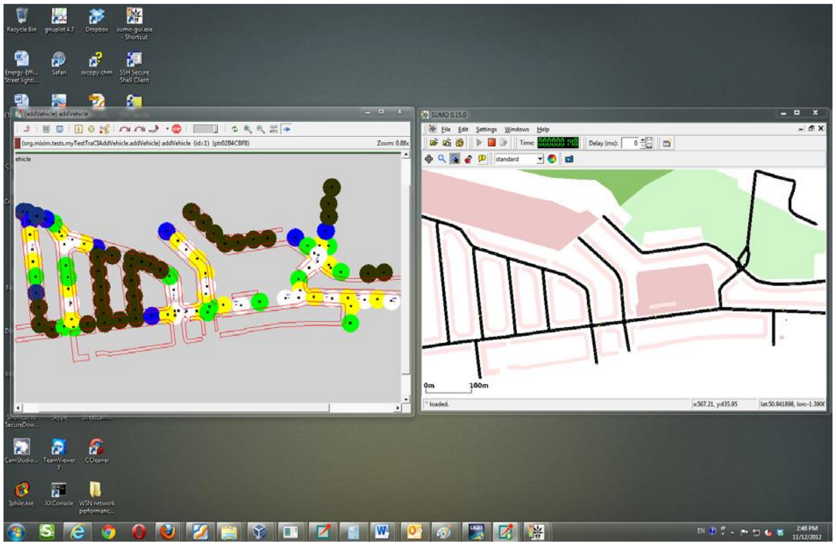


**Figure 5-3**: Screenshot of OMNet++ simulator (left) with corresponding SUMO simulator (right) when simulating adaptive lighting from Lau et al. (2013)

To combine SUMO and OMNet++ together (a necessary task to simultaneously model the transportation and communication networks and their effects on each other), Sommer et al. (2011) created the Vehicle in Network Simulation (Veins) platform in 2011. Veins is an open source framework for running vehicular network simulations based on two well-established simulators: OMNeT and SUMO. This simulation platform has been used by universities, governmental bodies, research institutes, and more. The advantages of Veins include the following (Sommer, 2018):

1. Veins includes a comprehensive suite of models to make vehicular network simulations realistic without sacrificing speed;
2. The graphical user interface (GUI) and interactive development environment (IDE) are easy and quick to set up and make the simulation interactive;

3. The influence of vehicular networks can be modeled, and complex interactions between both domains (i.e., transportation and communications) can be explored; and
4. Domain-specific models provide a comprehensive framework, but still present an easy-to-learn and use platform for beginners.

## 5.2 Quantifying the Lighting Index of Roadway Lighting

From a driver's point of view, street lighting helps to expand the visual horizon. Under normal circumstances, the vehicle's low beam headlights have a line of sight of around 197 ft (or 60 m). Vehicles traveling on the roadway sections along I-5 and US 101, on which the LED lights were installed, generally use low beam lights. Street lights/luminaires provide a clearer view beyond the field of view of the vehicle's headlights. This allows drivers to detect potential dangers and obstacles in the direction of travel farther downstream.

In general, effective street lighting scenarios consider average brightness, brightness mode (also known as uniformity), threshold increment, and surround ratio (Raynham, 2004). Among these factors, average brightness and uniformity affect the ability of the driver to detect potential objects or distractions in the roadway. The effects of various illumination levels and uniformities on object detection have been extensively studied (Wanvik et al., 2009, Güler et al., 2003, Brémond et al., 2012). These studies noted that drivers are better at detecting objects when the levels of brightness and uniformity are within a certain range. Object detection is often associated with risk and proximity of the vehicle at any time or distance to an object; furthermore, it considers where appropriate maneuvers can be made to avoid crashing into the object, thereby reducing the likelihood of injury to drivers or other road users. This distance is considered to be the distance within which the driver can stop without impacting the object after detecting said object (Schreuder, 1998). Usually, depending on the speed of the vehicle, the condition of the road, and the reaction time of the driver, the stopping distance is between 197 ft (60 m) and 645 ft (249 m) from 30 mi/h to 65 mi/h.

In order to design adaptive roadway lighting applications for motorists, it is clear that they will need to have the section(s) of roadway ahead of them illuminated either by their headlights or roadway lighting, thus allowing them to detect objects or conditions within their route and stop their vehicles without incident. Since the stopping distance is usually between 197 ft (60 m) and 525 ft (160 m), our model used a value of 328 ft (100 m) (Schreuder, 1998). In addition to consideration of stopping distance, the level of illumination of each roadway link is important. For the simulation, each road segment was is illuminated at the minimum required illuminance level, as determined on the basis of the methodology presented in Section 4.

As a measure of effectiveness in the simulation, a lighting index (a dimensionless quantity describing the quality of the illuminance provided by the lighting scenario) for a vehicle can be calculated using Equation 5-1 (Lau et al., 2013):

$$LI_{Vehcile} = LC_i * \frac{1}{100}\int_0^{100} \alpha(x,t)dx \tag{5-1}$$

where,

LI$_{\text{Vehicle}}$ is the lighting index for a given vehicle;

$\alpha(x, t)$ is the ratio of illuminance level at x meters ahead of a motorist at time t to the minimum required illuminance level for the road the motorist is travelling on; and

$LC_i$ is the lighting class calculated on the basis of the requirements and methodology presented in Section 4.

And the overall lighting index for all lights can be calculated by the following equation:

$$LI_{all} = \sum_{N,M} LI_{Vehcile} \tag{5-2}$$

In (5-2), $N$ represents the number of vehicles passing the luminaires and $M$ represents the total number of luminaires in the research area.

## 5.3 Wireless Module Description

A key part of the adaptive lighting methodology comprises changes in the illumination levels based on real-time environmental and traffic conditions. Data on such conditions can be gathered in many ways, one being wireless communication between vehicles and the lighting system. The luminaires in this study were assumed to be equipped with a new luminaire controller and an above-the-road sensor developed by the University of Washington Smart Transportation Applications and Research Laboratory (STAR Lab) to enable wireless communications between motorists and the lighting platform. Some popular existing methods described by Huang et al. (2010) and Atıcı, Ozecelebi, and Lukkien (2011) were also implemented in the simulation model. The luminaire controller would modulate the luminaire output to turn the lights on or off, as well as adjust its level of illumination. To allow for a near-instant response to continuously changing illumination requests based on detection of motorists via the road user sensor, each luminaire was assumed to use a dimmable LED luminaire, and its beam pattern was assumed to cover a limited area of a single road segment.

In essence, four steps are used to control this system: Luminaire off, Luminaire on by sensor, Luminaire on by delay, and Luminaire on by neighbor. The system state machine is shown in Figure 5-4. The control cycle would be triggered by the "Luminaire on by sensors" state. When vehicles passed by the luminaire (or were within some detection range dependent on the device used for detection), the luminaire would turn on. Then, if in a certain period of time no additional vehicles passed, the luminaire would change into the "Luminaire on by delay" setting to keep the illumination level at a constant value. At this stage, the luminaires would be triggered to turn on in two additional ways, either by input from the sensors or from other neighboring luminaires. If no vehicle passed, the luminaire would be self-triggered by an active delay timer to maintain the current level of illumination.

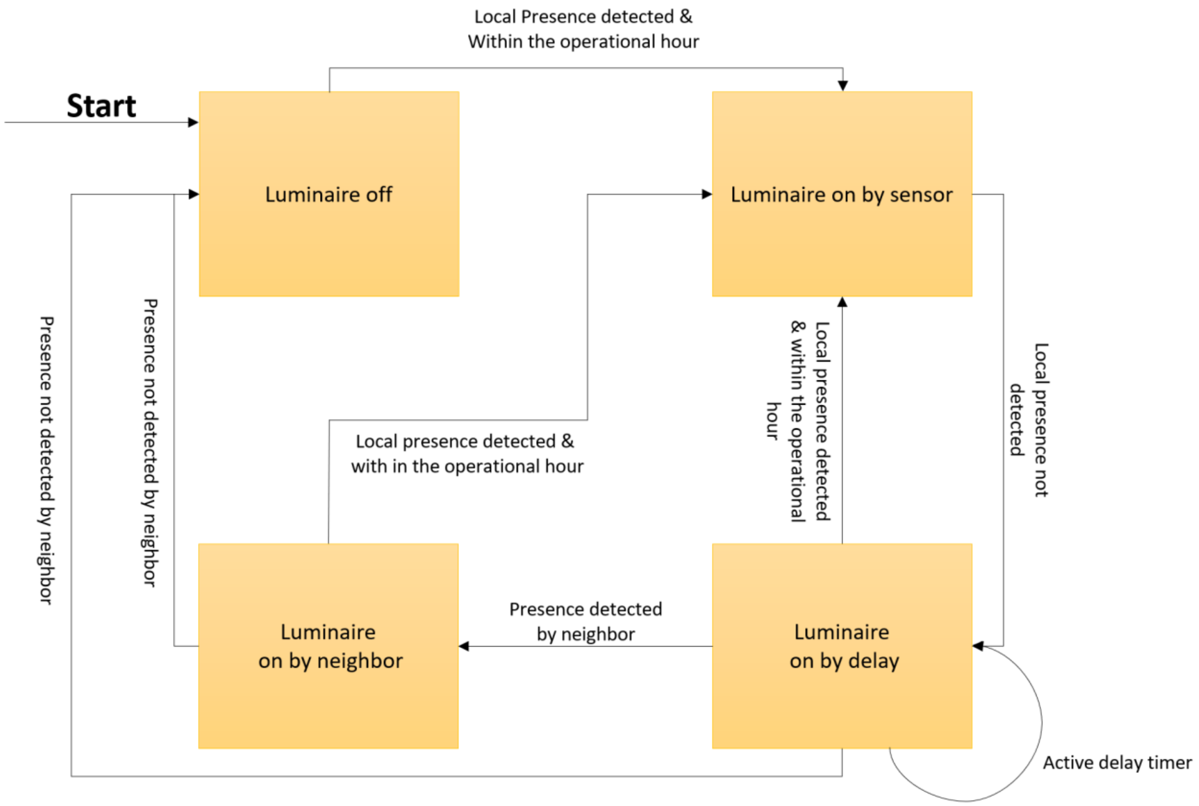


**Figure 5-4**: System state machine of the wireless control module

Typically, in the United States, freeways have a speed limit in the range of 60-70 mph (approximately 27-31 m/s or 96-112 km/h). Usually, the stopping distance is between 197 ft (60 m) to 525 ft (160 m), based on factors including the vehicle's speed, road surface conditions, and the motorist's reaction time; here, we considered the median value to be 328 ft (100 m) in our model. This distance reflects a stopping distance in which a motorist must be able to stop his vehicle safely after a potential object or distraction in the roadway has been detected.

The wireless module in the simulation platform provided the core of the connection between vehicles and the lighting system, and hence it drove the control component of the adaptive lighting methodology. The entire communication and control system consisted of three main parts: LED lighting units (i.e., lights or luminaires), the wireless communication and control center, and the data center. This module connected to the database and control center and was subject to real-time adjustment based on weather and traffic information. At the same time, the module could directly communicate with road users to control the state of the luminaires. Each vehicle had permission to communicate with luminaires to inform the control system of its specific vehicle location. The details of this three-part communication and control system are shown in Figure 5-5.

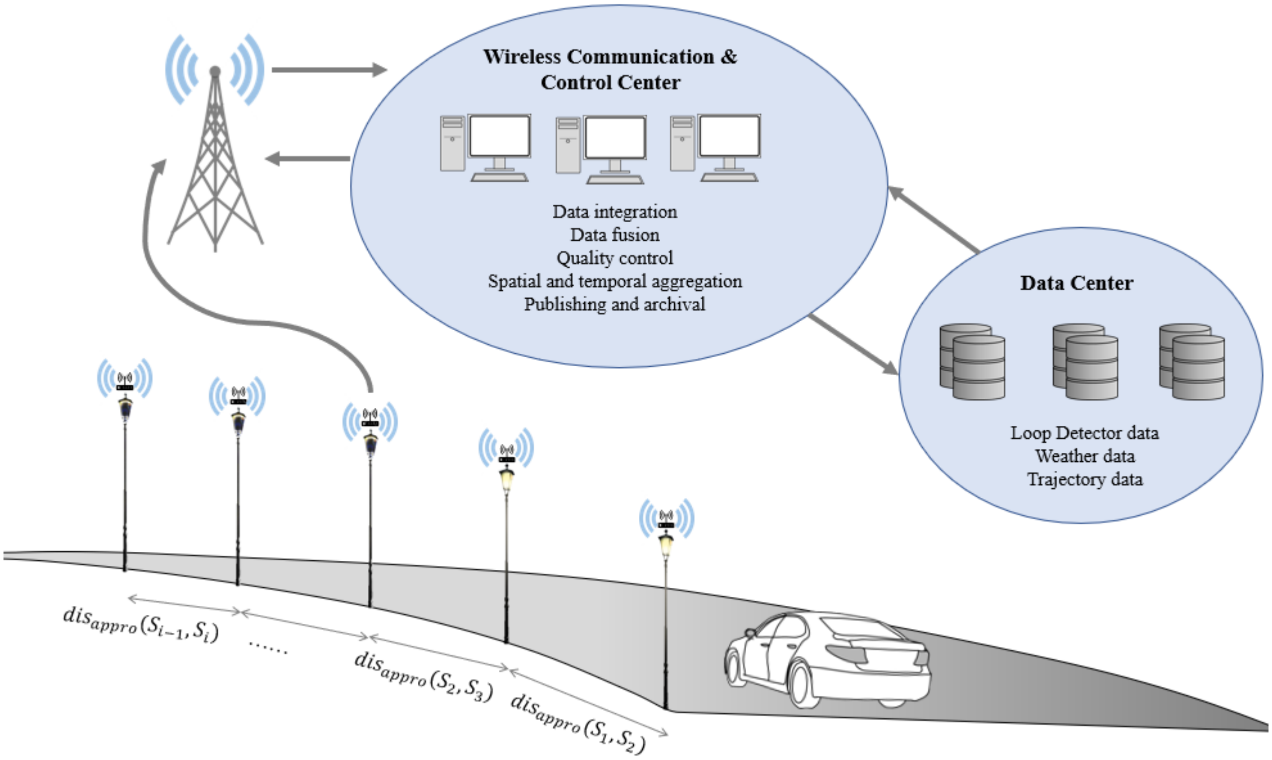


**Figure 5-5**: Three-part communication and control system for adaptive lighting

For the simulation, the illumination light set was calculated as shown in Equation 5-3:

$$ill_{light_{set}} = 1 + \left[\frac{100}{dis_{appro}(s_i,s_{i-1})}\right] \tag{5-3}$$

where,

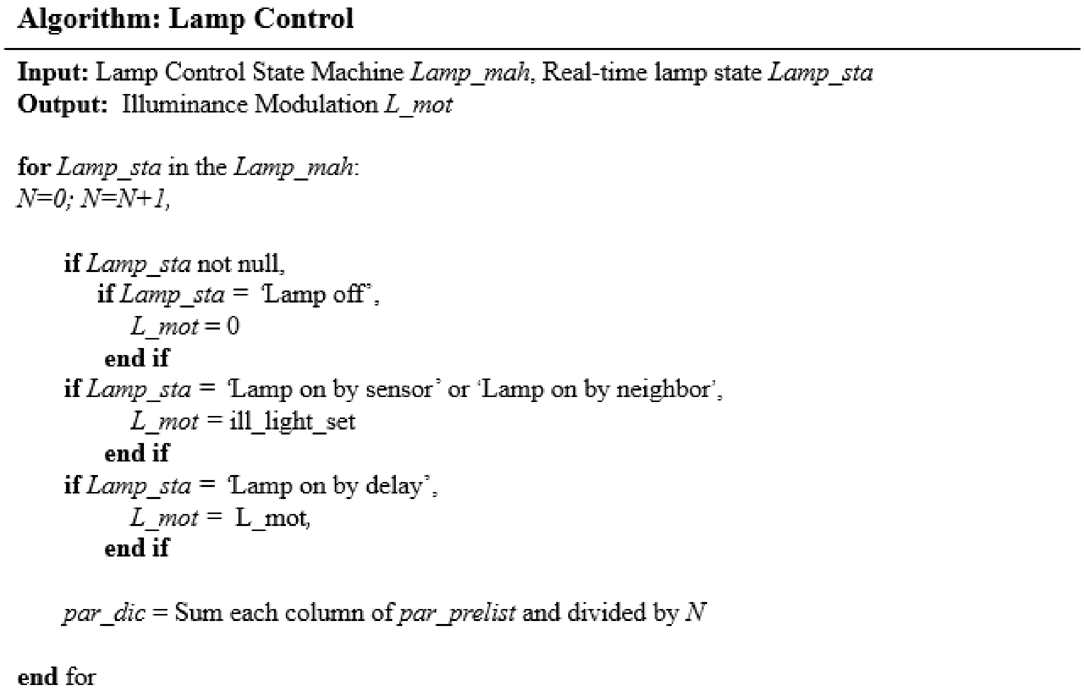
$s_i$ is the $i^{th}$ light in the traffic zone;

$ill_{light_{set}}$ is the set of lights switched on before the $s_{i-1}$, which is equal to a number; and

$dis_{appro}(s_i, s_{i-1})$ is the average distance of a road segment from light $s_i$ to $s_{i-1}$

and the adaptive lighting system control logic process (i.e., pseudocode) is shown in Table 5-1.

**Table 5-1**: Adaptive lighting system control logic process/pseudocode



**Algorithm: Lamp Control**

```
Input: Lamp Control State Machine Lamp_mah, Real-time lamp state Lamp_sta
Output:  Illuminance Modulation L_mot

for Lamp_sta in the Lamp_mah:
N=0; N=N+1,

    if Lamp_sta not null,
        if Lamp_sta = ‘Lamp off’,
            L_mot = 0
        end if
    if Lamp_sta = ‘Lamp on by sensor’ or ‘Lamp on by neighbor’,
            L_mot = ill_light_set
        end if
    if Lamp_sta = ‘Lamp on by delay’,
            L_mot = L_mot,
        end if

    par_dic = Sum each column of par_prelist and divided by N

end for
```

Under normal circumstances, it takes a certain amount of time for the LED luminaire to reach the established requirement from lighting to brightness. In order to ensure the continuous illumination of LED luminaires, the researchers added a separate control state to the control system: “Luminaire on by delay.” This state was used to ensure continuous lighting before the time when the road user was believed to have left the void region and entered the sensing range of the next luminaire. This feature also mitigated the latency of the communication network, which was particularly relevant when neighboring sensor nodes detected the presence of road users simultaneously and competed for the communication channel to disseminate the information. Here, we considered the time delay to be 10 seconds.

The settings of the wireless module parameters that enabled communications for the road user sensor in the simulation platform are shown in Table 5-2. Such sensors can detect vehicle presence and would serve as a link between the vehicles and the wireless communication and control center for the lights. Here, the researchers considered a multi-sensor method achieved by the Mobile Unit for Sensing Traffic (MUST) sensor. The MUST sensor was developed in-house by the STAR Lab as a cost-effective and flexible means for traffic detection. It can detect vehicles and travelers via video image processing and the media access control (MAC) addresses of their mobile devices. Depending on the configuration of MUST devices, data on vehicle presence, speed, etc., can be obtained.

**Table 5-2**: Wireless module parameters summarized in the simulation platform

| Parameter | Value |
|---|---|
| Bit rate | 250 kbps |
| Radio propagation model | Simple path loss model with log-normal shadowing effect |
| Minimum bit error rate | $1 \times 10^{-8}$ |
| Radio transmission power | -3 dBm |
| Sensing range | 30m |
| Sensor sampling rate | 30Hz |
| Sensor method | MUST (Bluetooth and Wi-Fi) + 4G-LTE |

## 5.4 Lighting Scenario Evaluation via Simulation Platform

In this evaluation, lighting index (as defined in Section 5.2) was the only parameter calculated and evaluated in the simulation platform. The lowest lighting level was considered to yield lighting index (equal to 1) and assumed to be at 100 percent energy consumption.

The Conventional/always-on method is generally used for roadway lighting today. It always maintains 100 percent brightness for each light/luminaire at night. Although this lighting effect may seem ideal and provides good uniformity, its efficiency is very low. As a result, it wastes a lot of energy and financial resources. For these reasons, this method needs to be improved.

The Philips Chronosense method proposed by Koninklijke Philips Electronics (Koninklijke Philips Electronics N. V., 2010) saves energy by adjusting the brightness of the luminaires. A typical configuration with a multi-watt 100/150W ballast can achieve a total energy savings of 20 percent per year in comparison to more conventional methods. The specific method of operation is to adjust the brightness to 65 percent from 10:00 PM to 5:00 AM.

The Part-Night method was proposed by the Warwickshire County Council, England (Warwickshire County Council, 2013). The specific implementation method involves turning off the luminaires in a specific area between 12:00 AM and 5:30 AM on weekdays, as well as between 1:00 AM and 6:30 AM on weekends. The Part-Night method is expected to save Warwickshire County approximately £500,000 per year. In addition to saving money, this method also contributes to a reduction in carbon dioxide emissions of approximately 3,000 tons of carbon dioxide per year (about 25 percent of the current street lighting carbon emissions in the county).

The Philips Dynadimmer method proposed by Koninklijke Philips Electronics (Koninklijke Philips Electronics N. V., 2010) maximizes cost savings by employing a method that can make changes in illumination levels such that a luminaire can reach any brightness in any time period; hence it is very flexible. For example, in the evening peak hours when volumes of vehicles are highest, the luminaires can be adjusted to their peak brightness levels, while in the transition period after the peak hours, the brightness level can be adjusted to a lower level based on volume (among other factors). This method can lead to total energy savings of up to 40 percent per year. The Dynadimmer method can allow for establishment of up to five time periods, and users can set different brightness periods according to different brightness levels.

The Multi-Sensor method was proposed by Wu, Shi, and Yang (2010). This method allows for the intelligent roadway light control system to “sleep” and “wake up” and automatically adjust the brightness levels of the luminaires based on the collaborative detection of various sensors. The specific operation method is to adjust the brightness by up to 40 percent over the course of a day.

When there is a vehicle close to the luminaire (i.e., within 66 ft or 20 m), the brightness level is increased to 70 percent. Then, when a vehicle is 33 ft or 10 m from the luminaire, the brightness is further increased up to 100 percent. According to this method, the brightness is adjusted back down to 40 percent when the vehicle leaves the detection area. This method has the potential to save a tremendous amount of electricity (90 percent energy saving) while extending the service life of the luminaire.

## 5.5 Platform Set-Up and Experiment

The following section explains the set-up of the simulation platform, including data sources, as well as the experiment itself. Traffic flow data used in the simulation platform were based upon real data obtained from the study areas on I-5 and US 101 between August 13, 2015, to August 20, 2015. An entire week of traffic volume data was used as the basis of simulation in the study area (shown in Figure 5-6). The study sites to be simulated are discussed in detail in Section 1 and 3 of this report. Through an actual investigation of necessary computing power, the researchers determined that it was not realistic to combine all of the luminaires in the entire study area with actual data in the simulation. The large numbers of calculations and the data volume made the entire simulation platform run too slowly to obtain results.

According to the analysis of the roadway network, the researchers found that the distance between most of the lights/luminaires in the entire road network of the study area was within 312 to 344 ft (95-105 m).

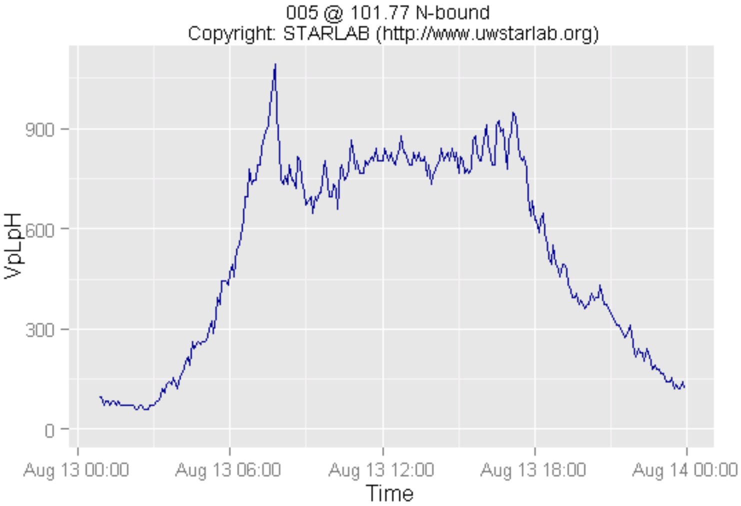


**Figure 5-6**: Sample of traffic volume data in I-5 study area

The roadway luminaires were relatively densely installed in the study area. Specifically, in the entire roadway section being studied, 516 adaptative LED lights were placed. The length of the study section where the luminaires were distributed was approximately 8.96 miles on I-5 and at some discrete points on US 101, approximately 9.3 miles in total. To break down the overall study area network, 15 smaller roadway segments were established from the original segments of I-5 and US 101 (Figure 5-7 shows details). The simulation platform was then used to simulate the 15 different road sections with LED lighting conditions.

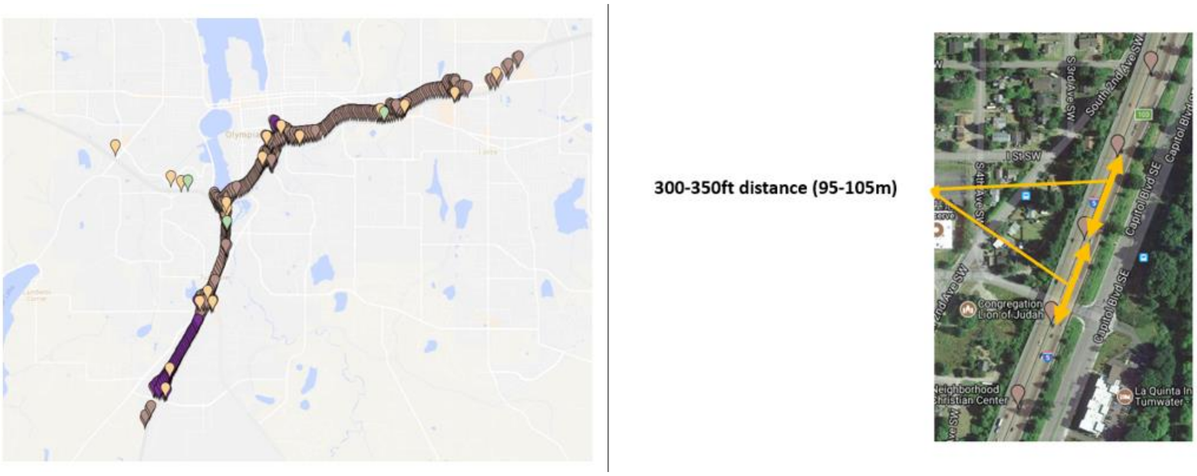


**Figure 5-7**: Research area summary and luminaire location extraction

The locations of the luminaires were identified by using an aerial photograph. The left image in Figure 5-8 shows the topology of the luminaires (represented by dots) in Segment 2 over a 0.8 mile (1.3 km) road section. In total, 13 luminaires were placed in this section. For the purposes of evaluation, each streetlight was assumed to be equipped with an ATBM D 480 R3 4B NL P7 DM LED luminaire, which can illuminate a certain road segment. The luminaires were assumed to start operation at sunset and finish at sunrise the next day (from 16:00 to next day 08:00). The lighting index and energy consumption of the different lighting scenarios is influenced by the duration of their operation. This is dependent upon geographical location, season, weather, and local environment.

As previously discussed, the platform was developed with OMNeT++, Veins, and SUMO 0.15.0. A view of the simulation platform running is shown in Figure 5-9. The top left image in the figure shows the communication states of each luminaire. The top right image shows the 0.8 mile (1.3 km) road segment. The bottom left image shows the simulation status of the whole platform in the OMNet++ information interface, and the bottom right figure shows the detailed package transmission message status and control information.

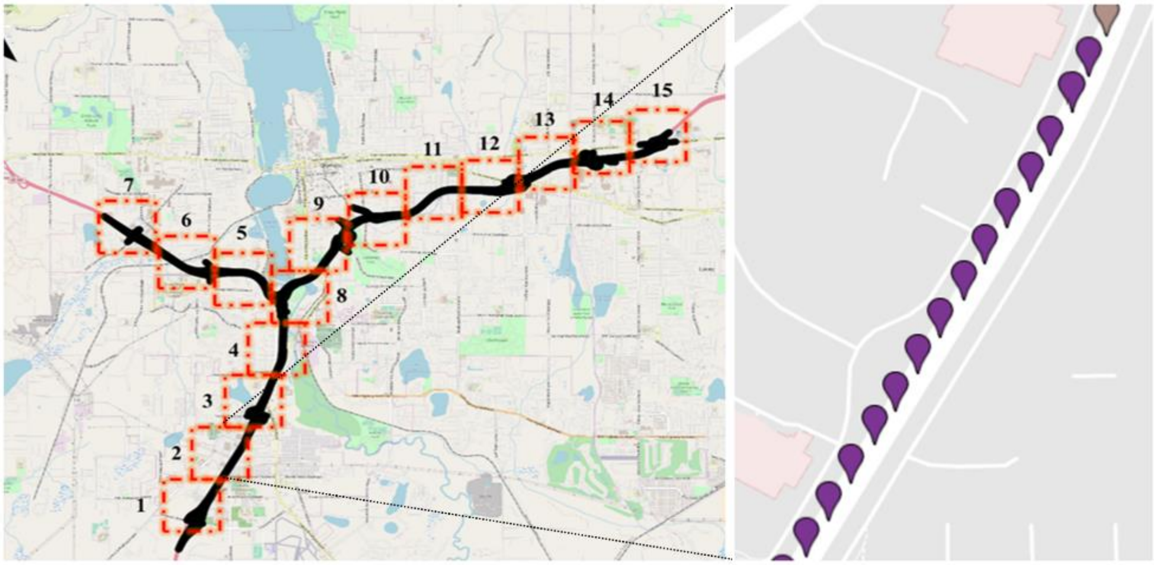
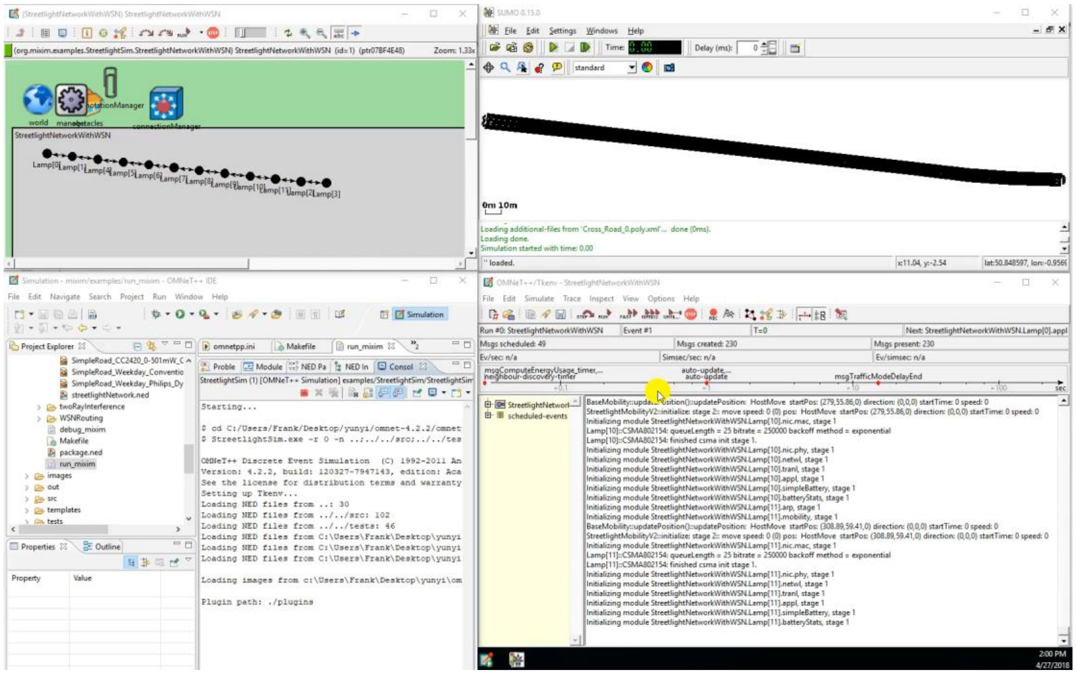


**Figure 5-8**: Locations of the 15 roadway segments in the study area and a detail of Zone 2



```
Loading additional-files from 'Cross_Road_0.poly.xml'... done (0ms).
Loading done.
Simulation started with time: 0.00
```

" loaded.    x:11.04, y:-2.54    lat:50.848597, lon:-0.956

StreetlightSim (1) [OMNeT++ Simulation] examples/StreetlightSim/StreetlightSim

```
Starting...

$ cd C:/Users/Frank/Desktop/yunyi/omnet-4.2.2/omnet
$ StreetlightSim.exe -r 0 -n ..;../../src;../../tes

OMNeT++ Discrete Event Simulation  (C) 1992-2011 An
Version: 4.2.2, build: 120327-7947143, edition: Aca
See the license for distribution terms and warranty
Setting up Tkenv...
Loading NED files from ..: 30
Loading NED files from ../../src: 102
Loading NED files from ../../tests: 46
Loading NED files from C:\Users\Frank\Desktop\yunyi
Loading NED files from C:\Users\Frank\Desktop\yunyi
Loading NED files from C:\Users\Frank\Desktop\yunyi

Loading images from c:\Users\Frank\Desktop\yunyi\om

Plugin path: ./plugins
```

Run #0: StreetlightNetworkWithWSN | Event #1 | T=0 | Next: StreetlightNetworkWithWSN.Lamp[0].appl

Msgs scheduled: 49 | Msgs created: 230 | Msgs present: 230

Ev/sec: n/a | Simsec/sec: n/a | Ev/simsec: n/a

```
BaseMobility::updatePosition()::updatePosition:  HostMove  startPos: (279,55.86,0) direction: (0,0,0) startTime: 0 speed: 0
StreetlightMobilityV2::initialize: stage 2:: move speed: 0 (0) pos:  HostMove  startPos: (279,55.86,0) direction: (0,0,0) startTime: 0 speed: 0
Initializing module StreetlightNetworkWithWSN.Lamp[10].nic.mac, stage 1
Lamp[10]::CSMA802154: queueLength = 25 bitrate = 250000 backoff method = exponential
Lamp[10]::CSMA802154: finished csma init stage 1.
Initializing module StreetlightNetworkWithWSN.Lamp[10].nic.phy, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[10].netwl, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[10].tranl, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[10].appl, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[10].simpleBattery, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[10].batteryStats, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].arp, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].mobility, stage 1
BaseMobility::updatePosition()::updatePosition:  HostMove  startPos: (308.89,59.41,0) direction: (0,0,0) startTime: 0 speed: 0
StreetlightMobilityV2::initialize: stage 2:: move speed: 0 (0) pos:  HostMove  startPos: (308.89,59.41,0) direction: (0,0,0) startTime: 0 speed: 0
Initializing module StreetlightNetworkWithWSN.Lamp[11].nic.mac, stage 1
Lamp[11]::CSMA802154: queueLength = 25 bitrate = 250000 backoff method = exponential
Lamp[11]::CSMA802154: finished csma init stage 1.
Initializing module StreetlightNetworkWithWSN.Lamp[11].nic.phy, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].netwl, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].tranl, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].appl, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].simpleBattery, stage 1
Initializing module StreetlightNetworkWithWSN.Lamp[11].batteryStats, stage 1
```

**Figure 5-9**: An example showing the simulation process for roadway Segment 2

# 6.0 Case Study Results and Discussion

## 6.1 Comparison of Overall Lighting Index among Different Lighting Scenarios

Various tests were conducted using the simulation platform. Figure 6-1 shows the overall lighting index, $LI_{all}$, comparison for the different lighting scenarios as described in Section 5.4. Each lighting index measure for a given lighting scenario at a given time was the average lighting index across all 15 segments that composed the study site. From this figure, we can clearly see that the new adaptive scenario proposed herein provided lighting index comparable to that of the Multi-Sensor scenario from the hours of approximately 21:00 forward. The highest lighting index and in turn energy consumption was provided by the Conventional scenario regardless of time, while the lowest one was provided by the Part-Night scenario during the hours of 00:00 to 04:00. Recall that the Conventional scenario always keeps the luminaires on (so the overall lighting index takes its maximum value, and hence we set the scale to a value of 1.0 for the future comparison), while the Part-Night scenario turns them off during part of the night, hence the portion of time with a zero value of lighting index and in term the maximum possible energy savings during this period. In general, it can be seen that during the late-night hours (e.g., 21:00 to 05:00), lighting indices for most of the lighting algorithms were reduced, a reasonable result, as most algorithms change lighting level in response to traffic volume, which is comparably lower during these hours. As such, energy consumption was also reduced during these hours.

Figure 6-2 presents the lighting index comparison for the different lighting scenarios in a box plot. From the figure, it can be observed that beyond the Conventional scenario, which was the least efficient from a lighting index/energy consumption perspective, the Adaptive lighting methodology proposed herein, as well as the Multi-Sensor scenario, provided higher lighting index in relation to the other methods and also had less variance in their overall lighting index. The similar performance between the proposed Adaptive lighting methodology and the Multi-Sensor scenario is reasonable, as both lighting plans adjust lighting levels on the basis of real-time sensor data related to traffic volumes and vehicle locations. Ultimately, it seems that the new, proposed adaptive lighting methodology could provide comparatively high lighting index and more energy savings than the Conventional scenario.

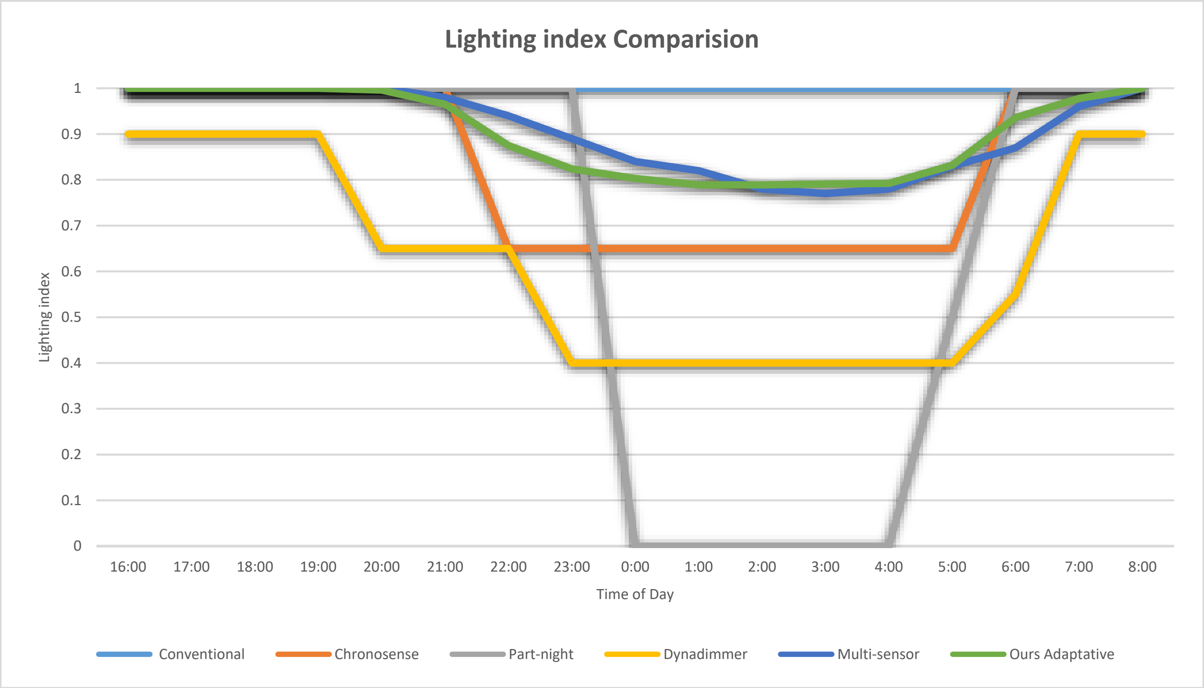


**Figure 6-1**: Average lighting index comparison for different lighting scenarios

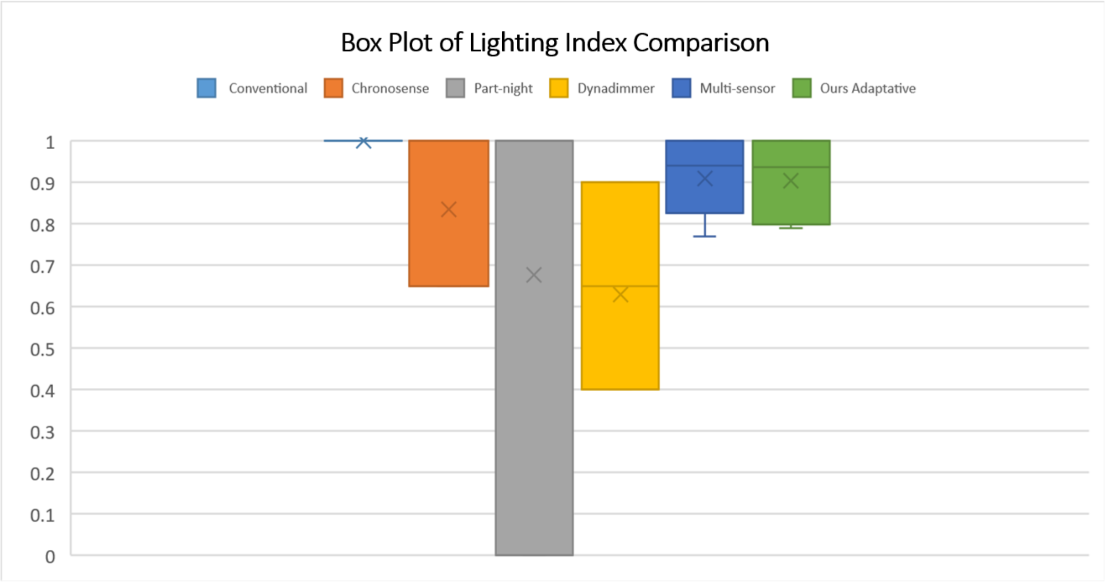


**Figure 6-2**: Box plot of lighting index comparison for different lighting scenarios

## 6.2 Discussion of Lighting Index by Location for Proposed Adaptive Lighting Scenario

This section presents and discusses the simulation results from the proposed adaptive lighting algorithm developed in this project and its performance across all 15 road segments in the study area. Figure 6-3 shows the average lighting index for each of the 15 road segments by time of day under the new adaptive lighting scenario. Each value was computed as the average over the one week of data used in the simulation. From the figure, it can be seen that lighting index generally remained high, very often above 0.85 for most roadway segments at most times of day in which the adaptive roadway lighting scenario was employed. This further emphasizes the new method's strong performance initially shown in Figure 6-1 and Figure 6-2. Figure 6-3 also shows that the lowest lighting index was typically observed between the hours of 03:00 AM to 04:00 AM, an hour when volume is often quite low and hence the MUST sensors would detect few vehicles, and the algorithm would set a correspondingly lower level of illumination. In general, changes in traffic volume would lead to changes in the number of vehicles detected by the MUST sensor. When more vehicles were detected, the adaptive lighting algorithm would select a higher illumination level and the lighting index would thus be higher. That said, since the lighting index was not always 1.0, energy savings were provided by the new adaptive methodology in comparison to the Conventional scenario.

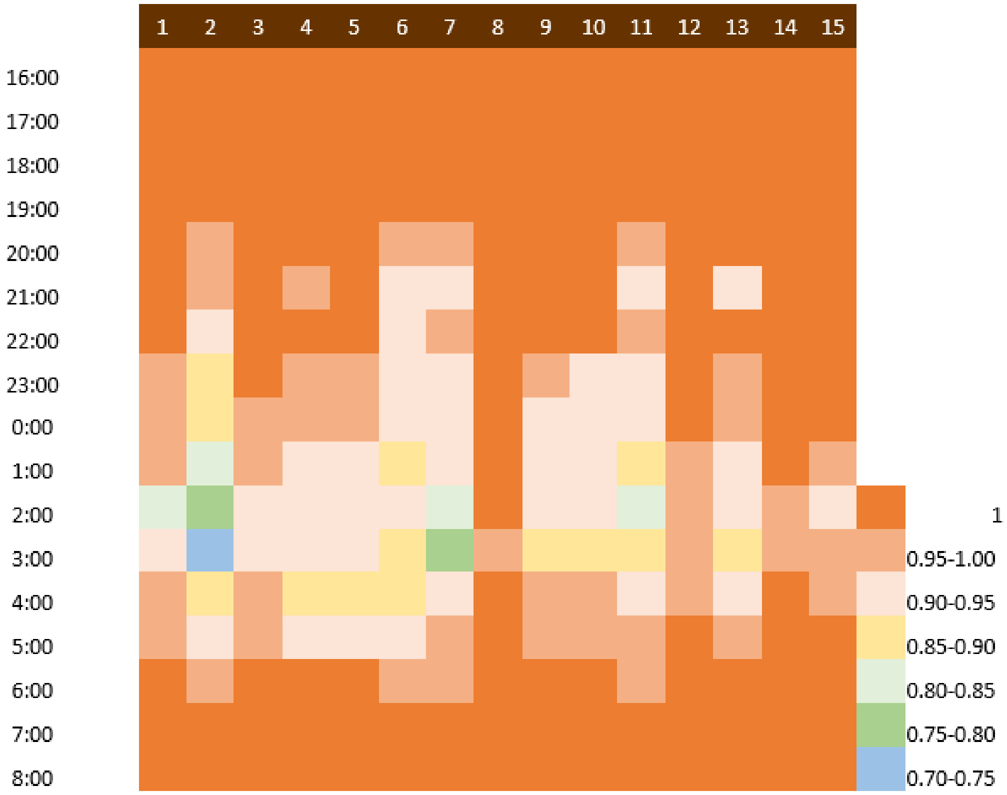


**Figure 6-3**: Lighting index comparison heat map for proposed adaptive lighting scenario by road segment

Further analysis was done to study the lighting index of the new adaptive roadway lighting algorithm in the study area on the basis of crash potential (referred to henceforth simply as potential). On the basis of the historical crash data described in Section 4.2, the roadway segments with the highest historical crash count were designated as high-potential; these segments 8, 12, and 14 (there was a two-way tie). Road segments 2 and 7 were designated as low-potential on the basis of the historical crash records, as they had the lowest observed crash counts. Figures 6-4 and 6-5 show the average lighting index calculated over the one week of data for each hour during which the lights would be used for the high-potential and low-potential road segments, respectively. In each figure, the overall lighting index across all road segments was used to provide a comparison. On the basis of the simulation results, it can be seen that for the low-potential sites especially, the new adaptive lighting methodology provided increased energy savings in comparison to the Conventional lighting scenario. Furthermore, lighting index was often higher on the high-potential segments, as they often experienced higher volumes and hence had higher lighting demands.

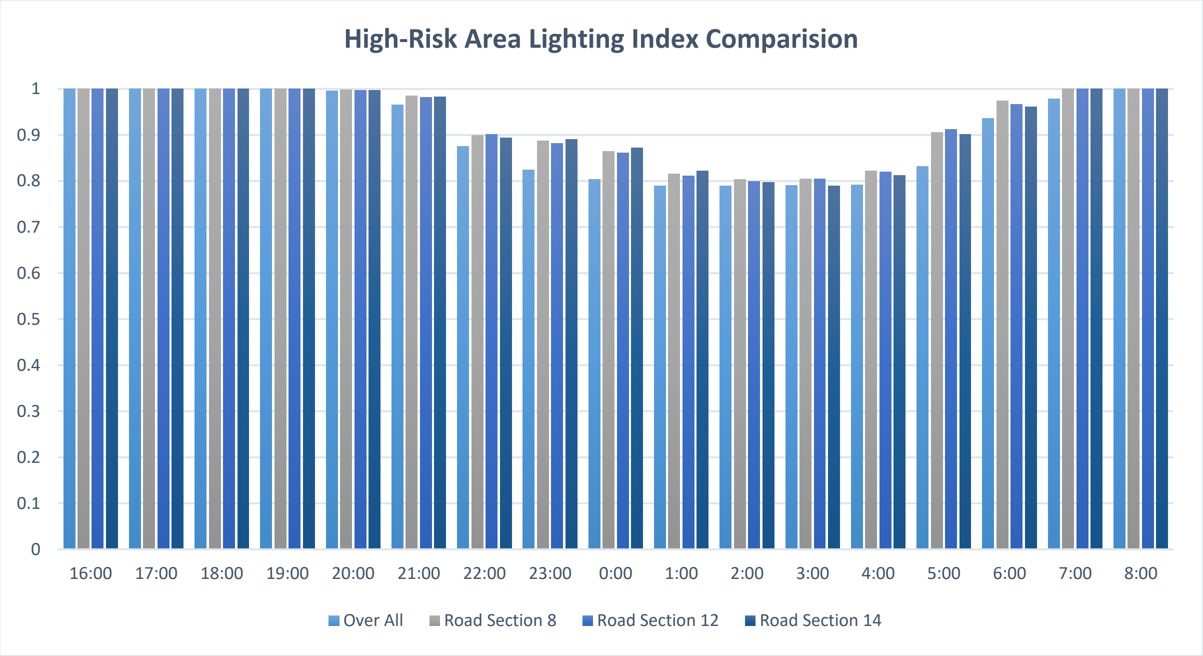


**Figure 6-4**: Lighting index comparison for high risk road segments

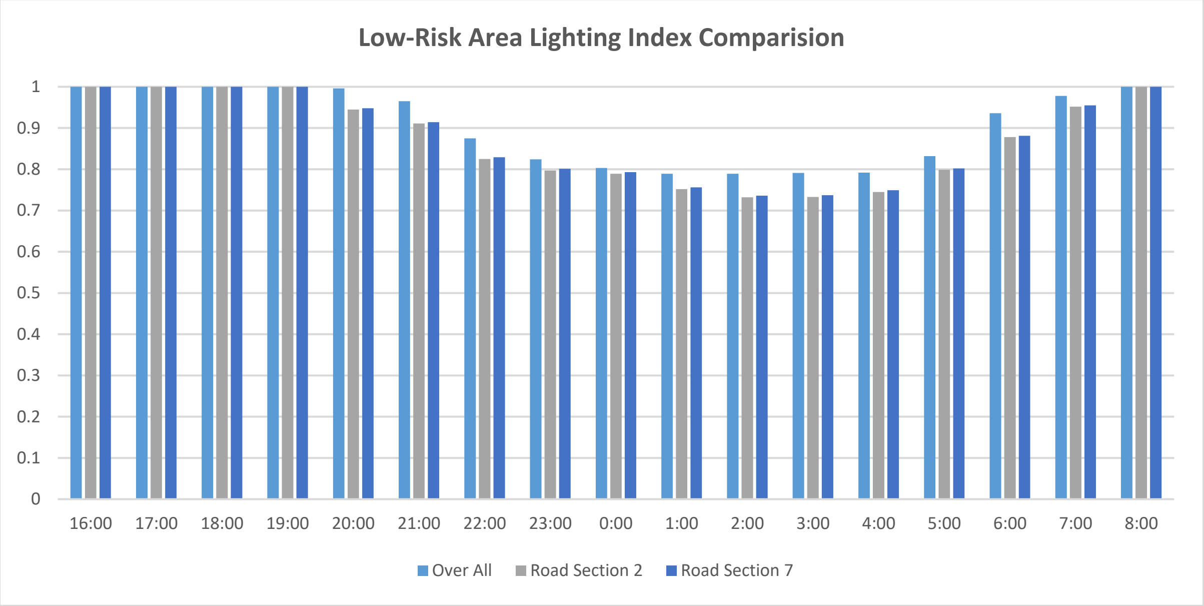


**Figure 6-5**: Lighting index comparison for low risk road segments

# 7.0 Conclusion

Recently, many transportation agencies have begun to employ adaptive roadway lighting methodologies by which illumination levels are established and updated based on real-time traffic and environmental conditions (e.g., weather, crash status, etc.). Such methodologies have a clear and obvious benefit for energy savings, as well as environmental, maintenance, and cost benefits. Many DOTs and other agencies are also switching from conventional, high-pressure sodium roadway lighting systems to LED systems, which are not only more energy-efficient but are also brighter. In this study, an adaptive roadway lighting methodology was developed based on an extensive literature review and a variety of analyses on data collected in Washington state at study locations where WSDOT has installed LED lighting with adaptive capabilities. Such data included traffic flow data, crash data, and weather data, among others. The developed adaptive lighting methodology also had an additional active traffic management component that allowed for provision of advisory messages to travelers based on data inputs used in the adaptive lighting methodology.

In addition to development of the adaptive lighting methodology, a simulation platform was developed to study the effects of the methodology in a controlled setting. SUMO, OMNet++, and Veins were used to develop a system that allowed simulation of traffic, an adaptive roadway lighting system, and communication between travelers and the control system for the lights/luminaires. For the simulation study, the lighting index of the proposed adaptive lighting methodology was compared to that of several other common lighting scenarios (both adaptive and conventional), and trends in lighting index and energy savings were discussed. The results of the simulation showed that the proposed adaptive lighting methodology would provide high lighting index in comparison to existing adaptive lighting methodologies and also provide further energy savings.

It is the research team’s strong desire to implement the algorithm in practice to save energy without degrading safety and mobility. However, further research is needed before we get there. We envision two follow-up studies in the near future. One is to pursue a field implementation of the methodology at a designated site and work with the corresponding transportation agencies to tune and improve the algorithm.  Another topic of future work is to conduct driver behavior data from the field where the algorithm is implemented and try to understand safety implications of the behavior data under various traffic and environmental conditions.

# 8.0 References

Adams, A. C. C. M., and Hamel, B. (2006). *Manual of Dynamic Motorway Lighting*. Rotterdam, the Netherlands: Ministry of Transport, Public Works and Water Management. Retrieved from http://publicaties.minienm.nl/documenten/manual-of-dynamic-motorway-lighting

American Meteorological Society. (2012). *Glossary of Meteorology*. Retrieved from http://glossary.ametsoc.org/wiki/Main_Page

Atıcı, C., Ozcelebi, T. and Lukkien, J.J., 2011. Exploring user-centered intelligent road lighting design: a road map and future research directions. IEEE Transactions on Consumer Electronics, 57(2), pp.788-793.

Bacelar, A. (2005). The Influence of Dimming in Road Lighting on the Visibility of Drivers. *Journal of Light and Visual Environment*, *29*(1), 44–49. https://doi.org/10.2150/jlve.29.44

Bailey, T., van Schalkwyk, I., and Milton, J. (2015). Illumination reform and LED Adaptive Roadway Lighting: WSDOTs Journy on Rethinking Why We Light. Olympia, WA.

Behrisch, M. Bieker, L., Erdmann, J. , and Krajzewicz, D. (2011). "SUMO - Simulation of Urban MObility - an Overview," Proc. 3rd Int. Conf. Adv. Syst. Simul., no. c, pp. 63–68, 2011.

Blake, T. A. (2016). State Routes of Washington State 1:24,000 (2016), Unrouted Lines Metadata. Olympia, WA: Washington State Department of Transportation. Retrieved from http://www.wsdot.wa.gov/mapsdata/geodatacatalog/maps/NOSCALE/DOT_TDO/LRS/24k LRS.htm

Box, P. C. (1976). Effect of Lighting Reduction on an Urban Major Route. *Traffic Engineering*, *46*(10), 26–27. Retrieved from https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_63388_34

Bullough, J. D. (2012). *Guide for Optimizing the Effectiveness and Efficiency of Roadway Lighting*. New York State Energy Research and Development Authority (NYSERDA). Retrieved from https://rosap.ntl.bts.gov/view/dot/24626

Bullough, J. D., Donnell, E. T., and Rea, M. S. (2013). To illuminate or not to illuminate: Roadway lighting as it effects traffic safety at intersections. *Accident Analysis and Prevention*, 53, 65-77. https://doi.org/10.1016/j.aap.2012.12.029

Bullough, J. D., and Radetsky, L. C. (2013). *Analysis of New Highway Lighting Technologies: Final Report (NCHRP 20-7/305)*. National Cooperative Highway Research Program.

Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(305)_FR.pdf

Cai, H. (2015). *Kansas Highway LED Illumination Manual: A Guide for the Use of LED Lighting Systems (K-TRAN: KU-15-6 - FINAL REPORT)*. Kansas Department of Transportation. Retrieved from http://www.ksdot.org/Assets/wwwksdotorg/bureaus/kdotlib/KU156.pdf

Cheung, J. (2019). FHWA - Safety in Roadway Lighting (2019 DOE SSL R&D Workshop). Retrieved from https://www.energy.gov/sites/prod/files/2019/02/f59/cheung-safety_ssl-rd2019.pdf.

Chung, H. S. H., Ho, N. M., Hui, S. Y. R., and Mai, W. Z. (2005). Case study of a highly-reliable dimmable road lighting system with intelligent remote control. In *2005 European Conference on Power Electronics and Applications* (p. 1 pp.-pp.P.10). IEEE. https://doi.org/10.1109/EPE.2005.219632

City of Beverly Hills. (2018). Beverly Hills Staff Report June 19, 2018 - Light Emitting Diode (LED) Street Light Replacement Program. City of Beverly Hills. Retrieved from http://beverlyhills.granicus.com/MetaViewer.php?view_id=49&clip_id=6122&meta_id=367564

City of San José. (2016). *City of San José Public Streetlight Design Guide*. City of San José. Retrieved from https://www.sanjoseca.gov/DocumentCenter/Home/View/242

Clanton & Associates. (2014). *Seattle LED Adaptive Lighting Study*. Northwest Energy Efficiency Alliance. Retrieved from https://neea.org/img/uploads/seattle-led-adaptive-lighting-study.pdf

Collins, A., Thurrell, T., Pink, R., and Feather, J. (1983). Dynamic Dimming: The Future of Motorway Lighting? *Lighting Journal.*, *67*(5). Retrieved from https://trid.trb.org/view.aspx?id=726595

Das, S., Brimley, B. K., Lindheimer, T. E., and Zupancich, M. (2017). Association of reduced visibility with crash outcomes. *IATSS Research*. https://doi.org/10.1016/J.IATSSR.2017.10.003

Denardin, G. W., Barriquello, C. H., Campos, A., Pinto, R. A., Dalla Costa, M. A., and do Prado, R. N. (2011). Control network for modern street lighting systems. In *2011 IEEE International Symposium on Industrial Electronics* (pp. 1282–1289). IEEE. https://doi.org/10.1109/ISIE.2011.5984343

DIAL. (2017) “Lighting design software DIALux,” [Online]. Available: file:///C:/Users/chenc4/Dropbox/PacTrans_lighting_project/Chen_folder/Literature Review/DIALux - DIAL.html.

Gibbons, R., Guo, F., Medina, A., Terry, T., Du, J., Lutkevich, P., and Li, Q. (2014). *Design Criteria for Adaptive Roadway Lighting*. Office of Safety R and D Federal Highway Administration. Retrieved from https://www.fhwa.dot.gov/publications/research/safety/14051/

Golob, T. F., and Recker, W. W. (2003). Relationships Among Urban Freeway Accidents, Traffic Flow, Weather, and Lighting Conditions. *Journal of Transportation Engineering*, *129*(4), 342–353. https://doi.org/10.1061/ASCE0733-947X2003129:4342

Gómez-Lorente, D., Rabaza, O., Esperin Estrella, A., and Peña-García, A. (2013). A new methodology for calculating roadway lighting design based on a multi-objective evolutionary algorithm. *Expert Systems with Applications*, *40*(6), 2156–2164. https://doi.org/10.1016/J.ESWA.2012.10.026

Goodwin, L. C. (2003). *Best Practices for Road Weather Management*. Retrieved from http://www.velocidade.prp.pt/Sites/velocidade/CentroDocumentacao/InvestigacaoEstudos/75 - Best Practices - CaseStudiesFINALv2-RPT.pdf

Griffith, M. S. (1994). *Comparison of the Safety of Lighting Options on Urban Freeways*. *Public Roads* (Vol. 58). Federal Highway Administration. Retrieved from https://trid.trb.org/view.aspx?id=413910

Güler, Ö.  and S. Onaygil. (2003). “The Effect of Luminance Uniformity on Visibility Level in Road Lighting,” Lighting Research and Technology, vol. 35, no. 3, pp. 199-215.

Gupta, H.  Thorve, P., Tripathi, N., Lomte, V. M., (2017). Energy-efficient Intelligent Street Lighting System.  International Research Journal of Engineering and Technology (IRJET). Volume: 04 Issue: 12. e-ISSN: 2395-0056.

Hassan, M. H. R. (2011). *Improving Traffic Safety and Drivers’ Behavior in Reduced Visibility Conditions*. University of Central Florida. Retrieved from http://etd.fcla.edu/CF/CFE0003946/Hassan_Hany_M_201108_PhD.pdf

Huang, B. J., et al. "Development of high-performance solar LED lighting system." Energy Conversion and Management 51.8 (2010): 1669-1675.

International Commission on Illumination. (2010). *CIE - 115 Lighting of Roads for Motor and Pedestrian Traffic*. Retrieved from http://standards.globalspec.com/std/1266107/cie-115

IRMA (Information Resources Management Association), Networking and Telecommunications: Concepts, Methodologies, Tools, and Applications, 2018. Idea Group Inc (IGI); ISBN 978-1-60566-987-8. p. 592.

Isebrands, H. N., Hallmark, S. L., Hans, Z., McDonald, T., Preston, H., and Storm, R. (2006). *Safety Impacts of Street Lighting at Isolated Rural Intersections – Part II*. Retrieved from https://trid.trb.org/view.aspx?id=798668

ITS, Institute of Transportation Systems, "SUMO – Simulation of Urban MObility," 2016. [Online]. Available: http://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883/16931_read-41000/.

Jackett, M., and Frith, W. (2013). Quantifying the impact of road lighting on road safety — A New Zealand Study. *IATSS Research*, *36*(2), 139–145. https://doi.org/10.1016/J.IATSSR.2012.09.001

Jägerbrand, A. K., and Sjöbergh, J. (2016). Effects of weather conditions, light conditions, and road lighting on vehicle speed. *SpringerPlus*, *5*, 505. https://doi.org/10.1186/s40064-016-2124-6

Janoff, M. S., Staplin, L. K., and Arens, J. B. (1986). The potential for reduced lighting on roadways. *Public Roads*, *50*(HS-040 204).

Jing, C., Shu, D., and Gu, D. (2007). Design of Streetlight Monitoring and Control System Based on Wireless Sensor Networks. In *2007 2nd IEEE Conference on Industrial Electronics and Applications* (pp. 57–62). IEEE. https://doi.org/10.1109/ICIEA.2007.4318369

Knobloch, F., and Braunschweig, N. (2017). "A Traffic-Aware Moving Light System Featuring Optimal Energy Efficiency," in *IEEE Sensors Journal*, vol. 17, no. 23, pp. 7731-7740, doi: 10.1109/JSEN.2017.2669398

Koninklijke Philips Electronics N. V., "Different Ways: The Dynadimmer and the Chronosense,"2010.[Online].Available:http://www.docs.lighting.philips.com/en_gb/oem/download/dynadimmer/P_Leaflet_Dynadimmer_V2Finpages.pdf

Kovács, A., Bátai, R., Balázs, C. C., Dudás, P., Háy, B., Pedone, G., … Váncza, J. (2016). Intelligent control for energy-positive street lighting. *Energy, 114,* 40–51. https://doi.org/10.1016/J.ENERGY.2016.07.156

Lamm, R., Kloeckner, J. H., and Choueiri, E. M. (1985). Freeway Lighting and Traffic Safety,— A Long Term Investigation. *Transportation Research Record: Journal of the Transportation Research Board, 1027,* 57–63. Retrieved from https://scholar.google.com/scholar?hl=en&as_sdt=0%2C48&q=Freeway+lighting+and+traffic+safety-a+long-term+investigation&btnG=

Lau, S. P., Merrett, G. V., and White, N. M. (2013). "Energy-Efficient Street Lighting through Embedded Adaptive Intelligence." *Proc., Int. Conf. on Advanced Logistics and Transport*, Sousse, Tunisia, 2013, pp. 53–58.

Li, F., Chen, D., Song, X., and Chen, Y. (2009). LEDs: A Promising Energy-Saving Light Source for Road Lighting. In *2009 Asia-Pacific Power and Energy Engineering Conference* (pp. 1–3). IEEE. https://doi.org/10.1109/APPEEC.2009.4918460

Li, S., Yi, J., Guan, B., Zhao, G., and Thompson, A. (2013). *Cost and Energy-Efficient (LED, Induction and Plasma) Roadway Lighting*. Indiana Department of Transportation. Retrieved from https://rosap.ntl.bts.gov/view/dot/26973/dot_26973_DS1.pdf?

Lyytimäki, J., Tapio, P., and Assmuth, T. (2012). Unawareness in environmental protection: The case of light pollution from traffic. *Land Use Policy*, 29(3), 598-604. https://doi.org/10.1016/j.landusepol.2011.10.002

McLean, D. (2006). Adaptive Roadway Lighting. *IMSA Journal*, *44*(5), 10, 12, 54–48. Retrieved from https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_238007_38

Monsere, C. M., and Fischer, E. L. (2008). Safety effects of reducing freeway illumination for energy conservation. *Accident Analysis and Prevention*, *40*(5), 1773–1780. https://doi.org/10.1016/J.AAP.2008.06.018

Monsere, C. M., Yin, T., and Wolfe, M. (2007). *Understanding the Safety Effects of Roadway Illumination Reductions*. Retrieved from http://pdxscholar.library.pdx.edu/cengin_fac

Nefedov, E., *et al*. (2014). "Energy efficient traffic-based street lighting automation," *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, Istanbul, 2014, pp. 1718-1723. doi: 10.1109/ISIE.2014.6864874

Niaki, M., Saunier, N., Miranda-Moreno, L., Amador, L., and Bruneau, J.-F. (2014). Method for Road Lighting Audit and Safety Screening at Urban Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, *2458*, 27–36. https://doi.org/10.3141/2458-04

OSRAM. (2008). “Step by Step Street Lighting Simulation with OSRAM LEDs in DIALux,” Application Design Center Asia, 2008.

OpenSim Ltd., What is OMUNeT++, 2018. URL: https://www.omnetpp.org/intro. Retrieved by 08/13/2018.

Park, H., Burke, J., and Srivastava, M. B. (2007). Design and Implementation of a Wireless Sensor Network for Intelligent Light Control. In *2007 6th International Symposium on Information Processing in Sensor Networks* (pp. 370–379). IEEE. https://doi.org/10.1109/IPSN.2007.4379697

Raynham, P. (2004). An examination of the fundamentals of road lighting for pedestrians and drivers. Lighting Research and Technology, 36(4), pp.307-313.

Richards, S. H. (1981). Effects of Turning off Selected Roadway Lighting as an Energy Conservation Measure. *Transportation Research Record, Journal of the Transportation Research Board*, *811*, 23–25. Retrieved from https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_485410_38

Roisin, B., Bodart, M., Deneyer, A., and D'Herdt, P. (2007.) "Lighting energy savings in offices using different control systems and their real consumption," Energy Build., vol. 40, no. 4, pp. 514–523.

Schreuder, D.A. (1998). Road Lighting for Safety, London: Thomas Telford Ltd.

Shahzad, G., Yang, H., Ahmad, A. W., and Lee, C. (2016). Energy-Efficient Intelligent Street Lighting System Using Traffic-Adaptive Control. *IEEE Sensors Journal*, *16*(13), 5397–5405. https://doi.org/10.1109/JSEN.2016.2557345

Shu, C. and Gu, D. (2007). Design of streetlight monitoring and control system based on wireless sensor networks[C]//Industrial Electronics and Applications, 2007. ICIEA 2007. 2nd IEEE Conference on. IEEE, 2007: 57-62.

Sommer, C., Yao, Z., German, R., and Dressler, F. (2008). "Simulating the Influence of IVC on Road Traffic using Bidirectionally Coupled Simulators," vol. 00, no. c, 2008.

US Department of Commerce, NOAA, E. S. R. L. (2017). Solar Calculator Glossary. Retrieved November 27, 2017, from https://www.esrl.noaa.gov/gmd/grad/solcalc/glossary.html#azimuthelevation

van Schalkwyk, I., Venkataraman, N., Shankar, V., Milton, J., Bailey, T., and Calais, K. (2016). *Evaluation of the Safety* Performance of Continuous Mainline Roadway Lighting on Freeway

Segments in Washington State. Washington State Department of Transportation. Retrieved from https://www.wsdot.wa.gov/research/reports/fullreports/855.1.pdf.

Venkataraman, N. S., Ulfarsson, G. F., Shankar, V., Oh, J., and Park, M. (2011). " Model of Relationship between Interstate Crash Occurrence and Geometrics: Exploratory Insights from Random Parameter Negative Binomial Approach." *Transportation Research Record: Journal of the Transportation Research Board*, 2236, 41-48.

Venkataraman, N., Shankar, V., and Ulfarsson, G. F. (2013). "Random parameter models of interstate crash frequencies by severity, number of vehicles involved, collision and location type." *Accident Analysis & Prevention*, 59, 309-318.

Venkataraman, N., Shankar, V., Ulfarsson, G. F., and Deptuch, D. (2014). "A heterogeneity-in-means count model for evaluating the effects of interchange type on heterogeneous influences of interstate geometrics on crash frequencies." *Analytic Methods in Accident Research*, 2, 12-20.

Walker, F., and Roberts, S. E. (1974). Influence of Lighting on Accident Frequency at Highway Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, *562*, 73–78. Retrieved from https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_483461_38

Walton, N. E., and Rowan, N. J. (1974). *NCHRP Report 152: Warrants for Highway Lighting*. Retrieved from http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_152.pdf

Wang, Y., Ke, R., Zhang, W., Cui, Z., and Henrickson, K. (2016). *Digital Roadway Interactive Visualization and Evaluation Network Applications to WSDOT Operational Data Usage*. Retrieved from http://www.wsdot.wa.gov/research/reports/fullreports/854.1.pdf

Wanvik, P. O. (2009). Effects of road lighting: An analysis based on Dutch accident statistics 1987–2006. *Accident Analysis and Prevention*, *41*(1), 123–128. https://doi.org/10.1016/J.AAP.2008.10.003

Washington State Department of Licensing et al. (2013). *2013 Annual Collision Report*. Washington State Department of Transportation. Retrieved from https://www.wsdot.wa.gov/mapsdata/crash/pdf/AnnualCollisionSummary2013.pdf

Washington State Department of Licensing et al. (2014). *2014 Annual Collision Report*. Washington State Department of Transportation. Retrieved from https://www.wsdot.wa.gov/mapsdata/crash/pdf/AnnualCollisionSummary2014.pdf

Washington State Department of Licensing et al. (2015). *2015 Annual Collision Report*. Washington State Department of Transportation. Retrieved from https://www.wsdot.wa.gov/mapsdata/crash/pdf/AnnualCollisionSummary2015.pdf

Washington State Department of Transportation. (2013). LED Adaptive lighting and illumination reform. Retrieved from https://www.wsdot.wa.gov/sites/default/files/2017/08/10/PracSol-LEDAdaptiveLightingIllumReform.pdf

Wilken, D., Ananthanarayanan, B., Hasson, P., Lutkevich, P. J., Watson, C. P., Burkett, K., … Avalon Integrated Systems. (2001). *European Road Lighting Technologies*. U.S. Federal Highway Administration, The American Association of State Highways and Transportation Officials, and The National Cooperative Highway Research Program. Retrieved from https://books.google.com/books?hl=en&lr=&id=ppBgBqWIdCgC&oi=fnd&pg=PR8&dq=European+Road+Lighting+Technologies&ots=3yg-9g7uki&sig=g3K2zyJ1eNe_5tLAQruYzKXbffA#v=onepage&q=European Road Lighting Technologies&f=false

Warwickshire County Council, "Part Night Lighting". [Online]. Available: http://www.warwickshire.gov.uk/partnightlighting [Accessed: 11 Nov. 2013].

Wu, Y., C. Shi and W. Yang. (2010). "Study of Acquisition Street lights Background Signal by Multi-sensor Array," in Proc. Int. Conf. Control Automation and Systems (ICCAS), Gyeonggi-do, pp. 1000-1003.