GEORGIA DOT RESEARCH PROJECT 14-32

FINAL REPORT

EVALUATION OF THE COST-EFFECTIVENESS OF ILLUMINATION AS A SAFETY TREATMENT AT RURAL INTERSECTIONS

Georgia Department of Transportation

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Technical Report Documentation Page

1. Report No.: FHWA-GA-16-1432	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Evaluation of the Cost-Effectiveness of Illumination as a Safety Treatment at Rural Intersections		5. Report Date: September 2016 6. Performing Organization Code:
7. Author(s): Angshuman Guin, Ph.D., Michael O. Rodgers, Ph.D., Franklin Gbologah, Ph.D., Roger Purcell, Ph.D.		8. Performing Organization Report No. GTI-2006V60-01
9. Performing Organization Name and Address: Georgia Tech Research Corp., 505 Tenth St., Atlanta, GA. 30318		10. Work Unit No.: 11. Contract or Grant No.: RP 14-32
12. Sponsoring Organization Name and Address: Georgia Department of Transportation, Office of Materials and Research; 15 Kennedy Drive; Forest Park, GA 30297-2534		13. Type of Report & Period Covered: Draft Final; 14. Sponsoring Agency Code:

15. Supplementary Notes:

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract:

This research study seeks to improve current understanding of the relationship between rural intersection safety and different illumination levels. It uses three parallel studies: a survey of rural intersection illumination practices among US state departments of transportation (DOTs), a safety analysis of rural intersection illumination, and a benefit-to-cost analysis of rural intersection illumination. These parallel studies indicate the following:

(a) Most DOTs do not consider cost-effectiveness in rural intersection illumination projects.

(b) There is little or no benefit to rural intersection illumination beyond a threshold of 12 lux.

(c) Illuminance levels lower than the minimum recommended value or 8 lux could provide significant safety benefit.

(d) Any rural intersection that does not require electrification would be cost-effective for illuminances not exceeding 12 lux. The cost-effectiveness of other intersections must be determined based on overall costs, AADT, crash rate, and a target benefit-to-cost ratio that signifies the DOT's required level of cost-effectiveness.

This research study provides a companion benefit-to-cost spreadsheet model to facilitate tradeoff analysis by DOTs.

17. Key Words: Illumination, Roadway Safety, Rural Intersections, Benefit–Cost Analysis, Survey, Georgia		18. Distribution Statement	
19. Security Class (This Report) UNCLASSIFIED	20. Security Class (This Page) UNCLASSIFIED	21. No of Pages 110	22. Price

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

GDOT Research Project No. RP 14-32

Evaluation of the Cost Effectiveness of Illumination as a Safety Treatment at Rural Intersections

Final Report

Safety and Illumination of Rural Conventional Intersections

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Georgia Department of Transportation

In cooperation with

U.S. Department of Transportation
Federal Highway Administration

September 2016

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EXECUTIVE SUMMARY

The major goal this research study is to determine the cost-effectiveness of illumination at uncontrolled and stop-controlled rural intersections in Georgia. This report consolidates three parallel studies that were performed to meet this goal. These three parallel studies are presented in in separate sections of this report.

Section B presents results of a survey of state departments of transportation (DOTs) to help understand current rural intersection illumination practices. The survey results from 24 responding states revealed four key characteristics of rural illumination practices among DOTs:

a) Most DOTs use published illumination guidance and standard. The overwhelming majority use either the guidance from the Illuminating Engineering Society of North America (IESNA) or the standard from the American Association of State Highway and Transportation Officials (AASHTO).

b) Most DOTs currently use standard lighting in rural areas when lighting is deemed necessary.

c) There is limited study going on among DOTs to determine the applicability of published illumination crash modification factors to their local conditions.

d) Most DOTs do not include an actual cost-effectiveness analysis in decision making for rural intersection illumination projects. Most often, DOTs measure cost-effectiveness in terms of either an overall minimization project cost or existence of potential safety benefits.

The results presented in Section C, *Estimation of the Safety Impact of Illumination at Rural Intersections in Georgia*, show overwhelming evidence that lower illumination levels, not included in the existing lighting standards/guidelines, would also provide significant benefits. The existing guidelines prescribe recommended lighting levels ranging from about 8 lux to 34 lux for intersections. However, the findings from this study show that there is little or no benefit to illuminating rural intersections beyond a dose-response range of 0–12 lux.

The third parallel study, *Benefit-to-Cost Analysis of Conventional Rural Intersection Illumination in Georgia*, is presented in Section D. The findings from this study indicate that for rural intersection locations that require no electrification, basically any illumination level within the dose-response range identified in this study will be cost-effective for any entering annual average daily traffic (AADT). However, locations that require electrification need to be evaluated based on the overall costs, entering AADT, existing crash rate, and a target benefit-to-cost ratio that signifies the level of cost-effectiveness required by the state DOT. Consequently, a spreadsheet benefit-to-cost model has been developed as part of the study to facilitate the cost-effectiveness analysis at any rural uncontrolled or stop-controlled intersection.

Generally, the findings support other published studies, which have indicated that lower illumination levels could be used on roads without compromising safety

ACKNOWLEDGEMENT

This work was sponsored by the Georgia Department of Transportation Research Project RP 14-32. The authors thank the Georgia Department of Transportation for its support throughout this research effort. The findings and conclusions presented herein represent the opinion of the authors and not necessarily that of the Georgia Department of Transportation.

INTRODUCTION

Late-night/early-morning driving is associated with significantly higher fatality rates than other periods of the day. According to the National Highway Transportation Safety Administration (NHTSA) [*1*], nighttime driving conditions account for more than 40 percent of fatalities, even though only 27 percent of total crashes occur during nighttime hours. Likewise, road intersections are disproportionately represented among crashes [*2-5*] and are associated with 50 percent of all urban crashes and 25 percent of all rural crashes [*6*], even though they form only a small part of the overall road transportation network. Road intersections thus require effective safety countermeasures to help drivers complete the navigational task, especially during nighttime.

One of the proven nighttime intersection safety countermeasures is the provision of illumination [*7-12*]. According to crash modification factors in the Highway Safety Manual, intersection lighting is expected to reduce 38 percent of nighttime crashes and 42 percent of pedestrian-involved nighttime crashes [*6*]. In a comparative analysis of 376 illuminated and unilluminated rural and near-urban intersections, researchers found that nonstandard lighting and standard lighting can reduce nighttime accident rates by 29 percent and 39 percent, respectively [*12*].

Intersection illumination represents one of the principal contributors to roadway maintenance and operations cost. In an era of constrained resources and increasing demands on state transportation agencies, comprehensive information on the cost-effectiveness of illumination compared to other safety treatments, as well as the relationship between different illumination levels and safety at intersections would be beneficial to transportation planners and other stakeholders.

Overview of Project

The research reported here is for the Georgia Department of Transportation (GDOT)–sponsored research study to evaluate the cost-effectiveness of illumination as a safety treatment at rural intersections. It is designed to improve understanding of (a) the relationship between illumination and safety at rural intersections, and (b) current illumination practices among other state departments of transportation (DOTs).

Project Objectives

This project, *Evaluation of the Cost-Effectiveness of Illumination as a Safety Treatment at Rural Intersections,* was designed to meet the following six major objectives.

- Literature review of safety impacts of different illumination levels at rural intersections
- Comprehensive rural intersection illumination and safety analysis
- Cost-effectiveness analysis of illumination at rural intersections
- Review of North American agencies to determine their current illumination practices
- Synthesis of lighting techniques and technologies that may be applicable for rural areas
- Recommendations for Georgia practice

Report Organization

This final report consolidates different studies that collectively address the project's objectives. These studies have been organized into the following four sections:

- Section A: Literature Review
- Section B: A Review of Rural Intersection Illumination Practices: Survey of US DOTs
- Section C: Estimation of the Safety Impact of Illumination at Rural Conventional Intersections in Georgia
- Section D: Benefit-to-Cost Analysis of Rural Conventional Intersection Illumination in Georgia

There is a separate Microsoft Excel® spreadsheet model the researchers developed to facilitate benefit–cost analysis. The spreadsheet is provided in electronic form along with this report.

SECTION A: LITERATURE REVIEW

A.1 Illumination Impact on Intersection Safety

Review of the literature on illumination and intersection safety shows that most of these studies were conducted using either a before-and-after analysis method or a cross-sectional method comparing intersections with lighting to those without lighting. A few of the studies have been compelled to use other methods because of their inherent data availability limitations.

A.1.1 Before-and-After Studies

In 1976, Walker and Roberts [*13*] analyzed crash data from 47 rural at-grade intersections in Iowa using crash data that spanned 3 years before and after lighting was installed. The study assumed that nighttime traffic volume was 0.27 times the existing daily traffic volume. The results showed a reduced crash rate of 0.91 crashes per million entering vehicles (MEV) in the after period compared to 1.89 crashes per MEV in the before period. That study generally found that the impact of lighting was less for low-volume roads with daily traffic volume lower than 3500 vehicles per day. After that study and in the wake of the 1973 energy crisis, the Iowa Department of Transportation commissioned another study, *Effects of Reduced Intersection Lighting on Nighttime Accident Frequency* [*14*]. The study analyzed crash data from 19 pairs of intersections with similar geometrics. One intersection from each pair had some lights turned off to produce a lighting differential. The results showed that the nighttime crash rate at rural intersections with full lighting was 1.06, while the rate at rural intersections with reduced lighting was 1.01. Based on those results, it was concluded that the lighting level at lighted rural at-grade intersections does not have a significant effect on the accident frequency as long as the conflict area(s) is sufficiently illuminated.

In 1999, Preston and Schoenecker [*15*] undertook a study of 12 rural Minnesota intersections associated with installation of lighting to determine the relative changes in crash frequencies and other crash characteristics. They reported findings of about 40 percent reduction in total nighttime crash rates at the 5 percent significance level and indicated a 20 percent crash severity index reduction at the 10 percent significance level. Crash severity index was estimated as the sum of fatal crashes and personal injury crashes divided by total number of crashes. Also, Green et al. [*16*] investigated the effect of roadway lighting on driver safety using crash data from nine Kentucky intersections. Their study was severely limited by sample size and reported no statistical tests, but the results indicated a 45 percent reduction in nighttime crash frequency after installing lights.

Isebrands et al. [*17*] also used a Poisson regression model to evaluate the change in expected crash frequencies after installation of lighting at 33 rural intersections. They defined *rural intersection* as an intersection that is at least 1 mile away from any development or 1 mile away from a signalized intersection on the same roadway. Both the before and after data had at least 3 years of information, and the Poisson model included intersection-related variables such as night/day (ND), before/after, number of intersection legs, posted speed limits, intersection control, presence of turn lanes, and presence of horizontal or vertical curve. Using a significance threshold of 10 percent, the Poisson regression model revealed a statistically significant reduction in nighttime crash rate of 37 percent after lighting was installed. There was also a reduction in daytime crash rate of 4 percent, but this was not found to be statistically significant.

A.1.2 Cross-sectional Studies

Sometimes it is difficult to identify intersection locations with enough samples of before and after crash data where illumination was the only safety treatment applied during the study period. In such instances a cross-sectional study can be used. Cross-sectional studies compare intersections with a particular attribute (in this case, lighting) to intersections without it.

Wortman and Lipinski [*18*] evaluated the impacts of intersection lighting on crashes at rural highway intersections by analyzing 263 lighted intersection-data-years and 182 unlighted intersection-data-years. Their findings indicate an average night/total crash ratio of 0.25 for lighted intersections and 0.33 for unlighted intersections. This corresponds to a 24 percent reduction in night accidents. Later on, Lipinski and Wortman [*19*] analyzed 445 intersection-data-years and their results show a 22 percent reduction in night/day crash ratio, 45 percent reduction in nighttime total crash rate, and 35 percent reduction in total crash rate at all intersections.

Preston and Schoenecker [*15*] performed a cross-sectional study of over 3400 intersections in Minnesota with crash data from 1995 to 1997. Their results indicate a 25 percent reduction in nighttime total crash rate (0.63 to 0.47 per million entering vehicles) and an 8 percent reduction in injury severity index. Crash severity index was estimated as the sum of fatal crashes and personal injury crashes divided by total number of crashes. Similarly, Bruneau and Morin [*12*] evaluated the safety aspects of roadway lighting at rural and near-urban intersections in Quebec, Canada, by comparing unlit intersections with lit intersections. The lit intersections were those with standard lighting and nonstandard lighting with both three-legged and four-legged intersections included. The study analyzed a total of 376 sites, and the results that were statistically significant at the 5 percent level showed that rural intersection lighting can reduce nighttime total accident rate by 29 percent for nonstandard lighting and by 39 percent for standard lighting.

Isebrands et al. [*20*] evaluated 3622 rural illuminated and unilluminated intersections in Minnesota. Their linear regression model indicated that the relevant variables that affect the ratio of nighttime accidents to total accidents were presence of lighting, volume, and number of intersection legs. Furthermore, the model showed that the expected ratio of nighttime to total crashes was 7 percent higher for unilluminated intersections than for illuminated intersections. Also, Hallmark et al. [*21*] conducted a cross-sectional study of 223 rural intersections using a hierarchical Bayesian model with Poisson distribution. The authors found that the expected mean of nighttime accidents was 2.01 times higher for unlit intersections than for illuminated intersections.

Donnell et al. [*9*] estimated the safety effects of roadway lighting at intersections from Minnesota and California using a cross-sectional approach with 4 years of intersection data. They computed expected night-to-day crash ratios at intersections with and without roadway lighting, and their results indicate 12 and 23 percent reductions in expected night-to-day accident ratios between intersections with and without lighting in Minnesota and California, respectively.

More recently, Donnell [*22*] undertook a study exploring statistical issues in relating lighting to safety. As part of that study, he compared two cross-sectional studies. Each analysis was undertaken with a negative binomial regression, but the input data were treated differently. One analysis incorporated observed crash data while the other analysis used a propensity score–potential outcome framework. Propensity scores are estimated using binary logit regression to determine probability that an entity contains intersection lighting based on site-specific conditions to identify lighted and unlighted sites based on covariates. The results indicate a lighting safety benefit of 11.9 percent and 9.5 percent for the analysis based on observed data and propensity scores, respectively.

A.1.3 Issues with Before-and-After and Cross-sectional Studies

Before-and-after studies are faced with issues that can affect the statistical validity of results. First, such studies can give biased results due to the phenomenon called regression to the mean [*23, 24*]. Usually, it is difficult to find a large sample of data for the before case and the after case. Therefore, before-and-after studies usually use datasets covering a few years on either side of light installation. The mean of such data is easily affected by temporary events, and this can bias the results. On the other hand, if the duration of the before and after samples are increased too much, the study can be influenced by long-term trends that might not continue to be true. Furthermore, a before-and-after study can be faced with selection bias [*8*] or endogeneity bias, as referred to in other studies [*23*]. This bias arises because a traffic safety countermeasure such as lighting is normally applied to a site with a recent or proportionately higher nighttime number of crashes. However, warrants for lighting are usually applied with other operational considerations, so other safety influences may be influencing the results.

Cross-sectional studies attempt to address the regression to the mean bias faced in before-and-after studies. In cross-sectional studies no treatment is applied to a site; rather, sites with particular attributes are compared to those without. However, these studies also face a selection bias issue, so it is difficult to categorically make a case for causation [*8*].

To address these challenges, different approaches have been adopted in previous studies. Hauer [*25*] proposed a before-and-after study in which the observed effect of a treatment is compared to an estimate of the expected number of crashes that would have occurred if the treatment had not been applied. Also, Donnell et al. [*8*] point out that the empirical Bayes (EB) method has been advocated by Hauer [*26*] and Persaud and Lyon [*27*] as a way to address issues of selection bias. Bo et al. [*28*] also developed a full Bayesian empirical approach that addresses issues of selection bias as well as the empirical Bayes method. The empirical Bayes method provides several advantages [*29*]:

- Properly accounts for regression to the mean effects
- Overcomes difficulties in the use of crash rates to normalize for changes in before and after period traffic volumes
- Reduces the level of uncertainty in the estimate of the safety benefit
- Properly accounts for differences in crash experience and crash reporting practice when combining data and results from different jurisdictions

However, the empirical Bayes method also has some drawbacks [*22*]:

- Requires installation dates and time-sequence
- Possible confounding impacts with other "treatments"
- Needs adequate reference and treatment sites for evaluation.

While the first two drawbacks are common to the other methods, the third is the most critical drawback for empirical Bayes in that the method has a much larger data availability requirement that is hard to satisfy in illumination studies. Thus, other researchers such as Donnell et al. [*8*] have used cross-sectional studies with application of multivariate regression models that permit the controlling of other safety influences. The most popular of these multivariate regression models is the negative binomial model because it is suited for count data such as crash data and it is also able to account for both over-dispersion and under-dispersion in count data.

A.2 Evaluation of Roadway Illumination

The performance of roadway illumination can be evaluated by illuminance, luminance, or small target visibility (STV) methods [*30*]. Luminance is a measure of the quantity of light reflected from a surface [*31*-*33*] and it is measured in candela per square meter (cd/m^2). It is what is perceived by the human eye as brightness of the road surface. Illuminance measures the quantity of light falling on the road surface [*31*-*33*] and it is measured in lux or foot candles. STV is a metric used to determine the visibility of an array of targets on the roadway [*33*]. The recommended method for conflict points including intersections is horizontal illuminance [*33*, *34*] Also, vertical illuminance, which helps drivers to see pedestrians and objects in the crosswalk, should be measured at a height of 1.5 meters above the roadway in the crosswalk.

A.2.1 Relationship between Luminance and Illuminance

The two main performance measures for road lighting, luminance and illuminance, are related as shown in Equation 1 [*35*]:

$$L = q * E \cong \frac{\rho}{\pi} * E \ldots\ldots\ldots (\mathbf{1})$$

Where:

L = luminance in cd/m^2

q = luminance coefficient in cd/m^2/lux

E = illuminance in lux

ρ = reflection coefficient

The luminance coefficient varies across different points of the pavement surface [*36*] because it depends on the pavement material, observer position, and the luminaire position relative to the point of interest. Casol et al. [*37*] have shown that for the purposes of simplifying road lighting analysis a road surface can be assumed to be perfectly diffused with a reflection coefficient equal to πQ_0. Many values of this reflection coefficient have been indicated in published studies; Uncu and Kayaku [*38*] found an average value of 0.13 for asphalt roads while Fotios et al. [*36*] found an average value of 0.16 and 0.27 for asphalt and concrete road surfaces, respectively.

A.2.2 Quantity and Quality of Roadway Illumination

Four studies [*39-42*] that evaluated the relationship between illumination parameters (illuminance, luminance, uniformity, and glare) on crashes all concluded that luminance was statistically related to ND crash frequency ratio. One of these four studies [*42*] further estimated that within the luminance range of 0.5–2.0 cd/m^2, an increase in average surface luminance of 1.0 cd/m^2 results in a 35 percent reduction in nighttime crash frequency ratio. Similarly, in a review of 62 studies [*43*] from 15 nations, the International Commission on Illumination (CIE) noted that crashes might increase as uniformity of lighting increases beyond a certain level due to reduction in contrast between an object and its surrounding visual environment.

Oya et al. [*44*] also evaluated illuminance at 18 trunk road intersections, each with at least 10,000 AADT, using 1 year of before data and 4 years of after data. Illuminance data were calculated for each intersection and the results show that illuminance levels of 30 lux or more can positively reduce nighttime crashes. This was found to be significant at the 1 percent level.

Also, the study found that illuminance levels between 20 and 30 lux can reduce nighttime crashes even though the study could not find any statistical significance for this category of lighting level. Subsequently, a Japanese study [*45*] found that an illuminance of 10 lux or more is needed for drivers to have good visibility of pedestrians at an intersection and an illuminance uniformity ratio of 0.4 will make an intersection safer.

Medina et al. [*46*] measured illuminance from three different sets of LEDs and one set of HPS luminaires and compared the measured values to estimates derived from computer analysis with AGi32®, a professional lighting design software. The measurements were taken on dry days and under skies with no full moon, and the results show both close agreement and significant differences between measured values and software estimates. The authors attribute this to luminaire-specific differences, underscoring the need to perform periodic audits to verify if in-situ lighting levels meet the design specifications.

Performing street lighting audits with handheld meters over large sections of the roadway system can pose both a data collection and safety challenge for the data collection personnel. Efforts to overcome this challenge have resulted in the development of automatic mobile reading systems and the use of photography methods that enable quicker data collection from either intersections or road segments. Zhou et al. [*30*] developed a mobile measurement system for collecting illuminance data for Florida DOT. The system employs a vehicle moving at 30 mph that collects data every 17.5 ft. through a computer linked to a lighting meter and a distance measuring instrument. An inverse square method is used to transform measurements made at the top of the moving vehicle to the equivalent measurements at 6 inches above the pavement and the researchers used a Wilcoxon test to compare the measurements. The results showed that the median of differences between the two is not significantly different from zero.

Schmidt et al. [*47*] also explored the feasibility of LED roadway luminaires by analyzing eight LED luminaires produced by different manufacturers and three HPS luminaires with power ratings of 150 W, 250 W, and 400 W. Annualized life cycle costs were used for economic analysis while the technical feasibility was determined by comparing in-situ measurements to recommended IES standards. The study results showed that only one LED luminaire conformed to the IES standard for moderately busy, medium pedestrian-conflict road with R3 (asphalt) pavement. Also, only one of the eight studied LED luminaires economically outperformed the existing HPS in life cycle costs. Therefore, the study concluded that LED luminaires are a promising technology, but more technological advancement would be needed to accurately confirm their feasibility in roadway illumination.

Bullough et al. [*11*] argue that existing installation methods for roundabout illumination, with luminaires hanging from fixed heights on poles, do not necessarily provide the best visibility for drivers and can be energy/cost intensive. Therefore, they evaluated a new lighting method called *ecoluminance* that relies on both illuminance and luminance, using a combination of roadside vegetation to provide visual delineation, lower-level lighting such as landscape lighting to reinforce delineation, pedestrian-level lighting to provide illumination at important safety hazards, and retroreflective elements to provide cues about road geometry. Ecoluminance was tested in New York, and the results show comparable approach speeds and initial costs for ecoluminance and conventional lighting; however, ecoluminance used only a quarter of the energy required by the conventional illumination method.

Niaki et al. [*7*] developed a method for performing illumination audits for intersections using light sensors attached to a handle and a data logger for recording both spot illumination and position via GPS coordinates. The method simplifies the time-consuming spot measurements of illuminance required at intersections by the existing measurement protocols. Measurement can be made by walking across the exit/entrance line of each intersection leg and then averaging to obtain the mean intersection illuminance. The results from a case study of 85 intersections in Montreal indicate that about 59 percent had substandard lighting level. Although this method can simplify the measurements compared to existing protocols, it increases the safety risk for both personnel and equipment since they must be in the active travel lane to collect data. In addition, measurements with this method may lack luminance constancy since onsite voltage can fluctuate before all the intersections are covered.

Jackett and Frith [*48*] studied the relationship between road lighting levels and safety using 5 years of crash data and road lighting measurements from mid-block road sections in New Zealand. The lighting levels were obtained by the photographic method. The authors calibrated sixth-order polynomials for pixel-to-luminance conversions at specific settings of camera exposure. The study included 152 mid-block road sections, and the results showed that the most important performance measure in predicting expected crashes on road sections is average luminance. The authors tried to apply the lighting data to intersections, but the results were not very strong compared to road sections.

Bhagavathula et al. [*49*] investigated the effect of lighting quality and quantity on the ND crash frequency ratios at rural intersections. They used negative binomial regression to model illuminance, luminance, and crash data from 99 lighted and unlighted intersections. The results indicate that a 1 lux increase in the average horizontal illuminance at all rural intersections corresponded to a 7 percent reduction in the ND crash ratio. For the lighted intersections, a 1 lux increase in average horizontal illuminance corresponded to a 9 percent decrease in the ND crash ratio, while for unlighted intersections a 1 lux increase in average horizontal illuminance corresponded to a 21 percent reduction in the ND crash ratio. The findings also showed that stop-controlled intersections experience smaller ND crash ratios than signalized intersections, while intersections with posted speed limit less than or equal to 40 mph also experienced lower ND crash ratios than those with posted speed limit greater than 40 mph.

In another study Gibbons et al. [*50*] investigated the relationship between lighting level and crashes on roadways. Crash data were obtained from select states and the Highway Safety Information System, while lighting measurements were collected in situ with a mobile road lighting measurement system. The results showed there was no benefit to illumination beyond a certain level on an urban interstate, which in the study was about 5 lux. The authors further indicated that there is a potential to reduce lighting requirements on highways and freeways by as much as 50 percent while maintaining traffic safety. Also, the results indicate that the relationship between lighting level and safety was not as strong as that of lighting presence (lit or unlit) and safety.

A.2.3 Roadway Lighting Benefits and Costs

Previous research on the benefits and costs of roadway illumination are few, are mostly dated, and have been focused on either intersections or urban freeway systems. A benefit–cost analysis helps to compare the tradeoff between the costs of a project and its benefits. Benefits are usually estimated as the avoided costs due to reduction in crash occurrence. The costs of implementing road lighting are often estimated as the direct initial costs of installation, maintenance, and repair [*10*]. The incremental benefit–cost ratio of one lighting alternative, j, to another lighting alternative, i, can be estimated as shown in Equation 2.

$$BC_{j-i} = \frac{AC_j - AC_i}{DC_j - DC_i} \quad \dots\dots\dots\dots (\mathbf{2})$$

Where:

BC_{j-i} = the incremental benefit–cost ratio of alternative *j* to alternative *i*

AC = the annualized avoided costs due to the crash reduction

DC = the annualized direct costs of the alternatives

Box [*51*] analyzed benefit–cost ratios for illuminating different multilane urban freeways, and his results indicate benefit–cost ratios of 2.3, 1.4, and 1.7 for lighting four-lane, six-lane, and eight- to ten-lane urban freeways, respectively. In another study on urban freeway systems, Griffith [*52*] evaluated the benefits and cost of lighting. Based on an analysis of 22 miles of urban freeway segments in Minnesota, he identified benefits and costs that yield a ratio of 1.2.

The Federal Highway Administration (FHWA) produces an annual report to Congress on the Highway Safety Improvement Programs (HSIP) in the US. One of the key components of the earlier reports is a benefit–cost ranking of different highway safety improvement programs. The findings in the 1994 report indicated that illumination offered the highest benefit–cost ratio of 21.0 [*53*]. Also, a subsequent report to Congress in 1996 again ranked illumination as the highest out of 20 highway improvements, with a benefit–cost ratio of 26.8 [*10, 54*]. Table 1 presents the benefit–cost ranking of highway safety improvement programs from 1974 to 1995.

Preston and Schoenecker [*15*] evaluated the impacts of street lighting at isolated rural intersections in Minnesota. As part of their evaluation they estimated the avoided costs of crashes and the direct costs of illumination. Their findings show that the benefits outweighed the costs by a ratio of 15.0. The analysis annualized costs and benefits over 10 years at a 5 percent discount rate. Notably, the ratios for road segments (e.g., urban freeway systems) appear to be very small compared to intersections.

Other studies evaluated the benefits and costs of road lighting in terms of its societal benefit from crime reduction. Painter and Farrington [*55*] used official crime valuation data to evaluate the benefits and cost of lighting installation in Dudley and Stoke-on-Trent in the UK. The results for Dudley showed that 1 year after installation of lighting, the benefit–cost ratio was approximately 10:1 and increases to about 121:1 if a 20-year payback is assumed. Similarly, the results for Stoke-on-Trent showed that the benefit–cost ratio after 1 year of lighting installation was 2.4:1 or 24:1 if a 20-year payback is assumed.

Table 1 Highway Safety Improvements with the Highest Benefit–Cost Ratios, 1974–1995

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

(Table data are from Rea et al. 2009 [*10*])

SECTION B: A REVIEW OF RURAL INTERSECTION ILLUMINATION PRACTICES – SURVEY OF STATE TRANSPORTATION AGENCIES

B.1 Introduction

This section presents the results of a survey of rural intersection illumination practices among US DOTs. All 50 state DOTs were contacted to participate in the survey. The research team administered contact mostly through telephone interviews; however, there were a few states that preferred an emailed survey questionnaire. As of the time of writing this report, the survey had been successfully administered to 24 of the 50 state DOTs. The responding states are shown below in Figure 1. The survey questionnaire can be found in the Appendix.

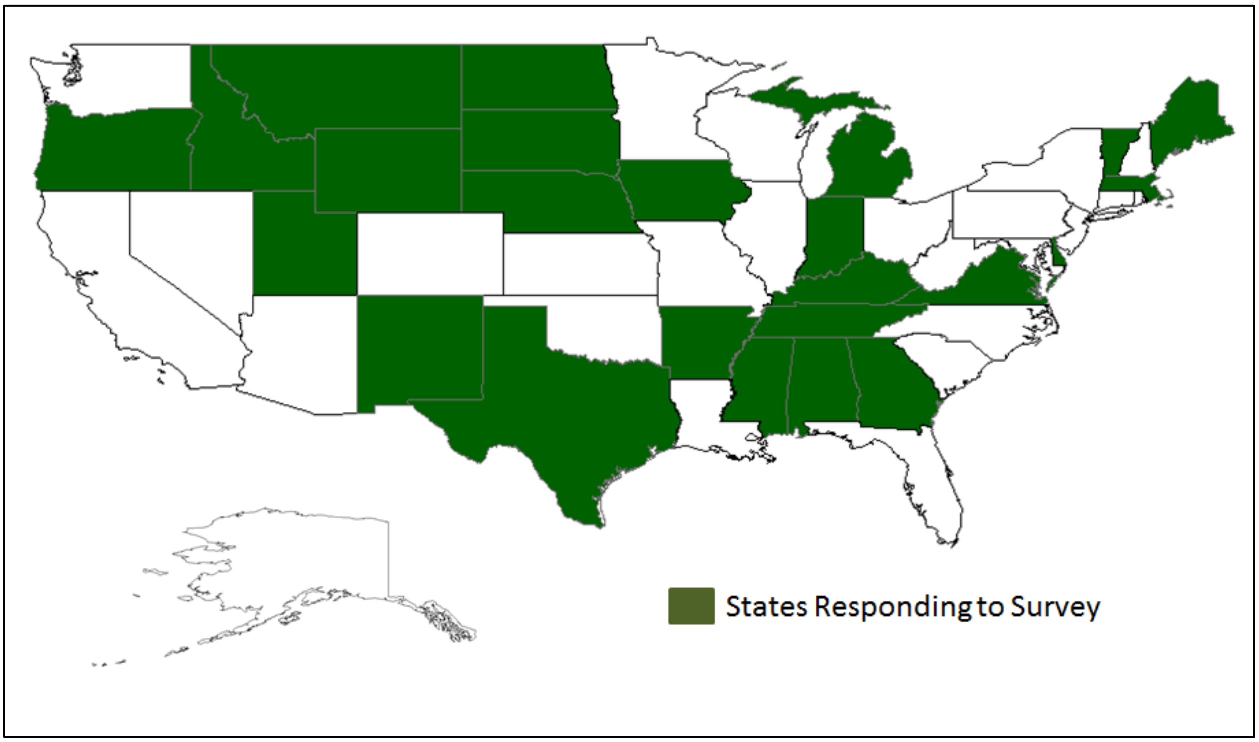


Figure 1 States Responding to Survey

B.2 Survey Results

Of the responding state agencies, 23 indicated that they use developed standards/guidance in illuminating rural intersections. Out of this group, two agencies use only the Illuminating Engineering Society of North America (IESNA) standard; six agencies use only the American Association of State Highway and Transportation Officials (AASHTO) guidelines; four agencies use a state-specific guidelines; four agencies use a combination of IESNA, AASHTO, and state-specific guidelines; six agencies use a combination of IESNA and AASHTO guidelines; and one agency did not give a valid response. Figure 2 shows a graphical representation of this breakdown in percentages.

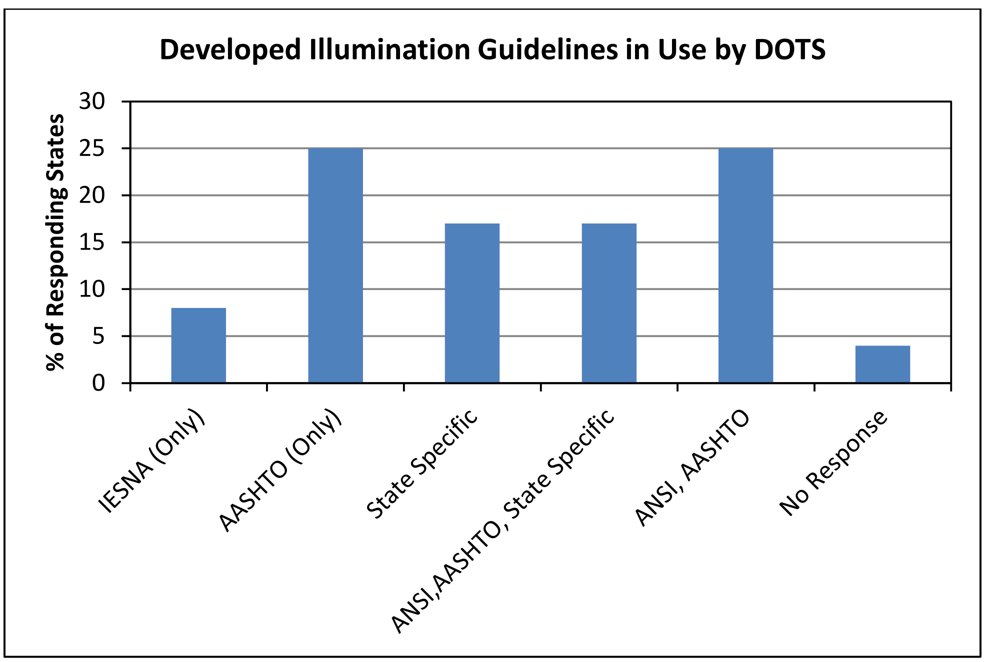


Figure 2 Developed Illumination Guidelines in Use by DOTs

The states were asked about their rural illumination policies. None of the respondents had a systematic rural conventional intersection illumination policy. All 24 states gave a valid response to this question. Their responses break down as follows: three agencies (13 percent) said they illuminate if signalized or requested by local government; one agency (4 percent) indicated that it illuminates an intersection if it is on two US routes, a US route and state route, or two state routes; 13 agencies (54 percent) said they treated illumination on a case-by-case basis with decision falling on warrants or engineering judgment; and five agencies (21 percent) said they had no policy and the decision rests with the local government.

The survey asked the agencies if they sometimes use nonstandard lighting and also how the agencies made decisions to use standard or nonstandard illumination. Nonstandard lighting (i.e., lighting that does not meet the recommended minimum illumination level) can usually be identified as a single pole with one luminaire. The survey results from these questions indicate that nine agencies (38 percent) sometimes use nonstandard lighting while the remaining 15 agencies (62 percent) strictly use standard lighting. Only 10 agencies (58 percent) were unable to give the factors that drive decisions to install standard lighting or nonstandard lighting. Among these 10 agencies, standard lighting is installed according to the following criteria:

- If the intersection is on a state-managed facility (one agency)
- If the location has a history of high crash frequency (two agencies)
- When requested by the local government (one agency)
- On a case-by-case basis (three agencies)
- If funding is from a federal source (one agency)

Also, two agencies indicated that they use nonstandard lighting for destination lighting to give drivers advance warning of the presence of the intersection. Some of the factors that influence the case-by-case decisions include a geometry that can violate driver expectancy, or presence of a raised median on the leg. Figure 3 summarizes the reasons given by the DOTs for illuminating rural intersections with standard lighting.

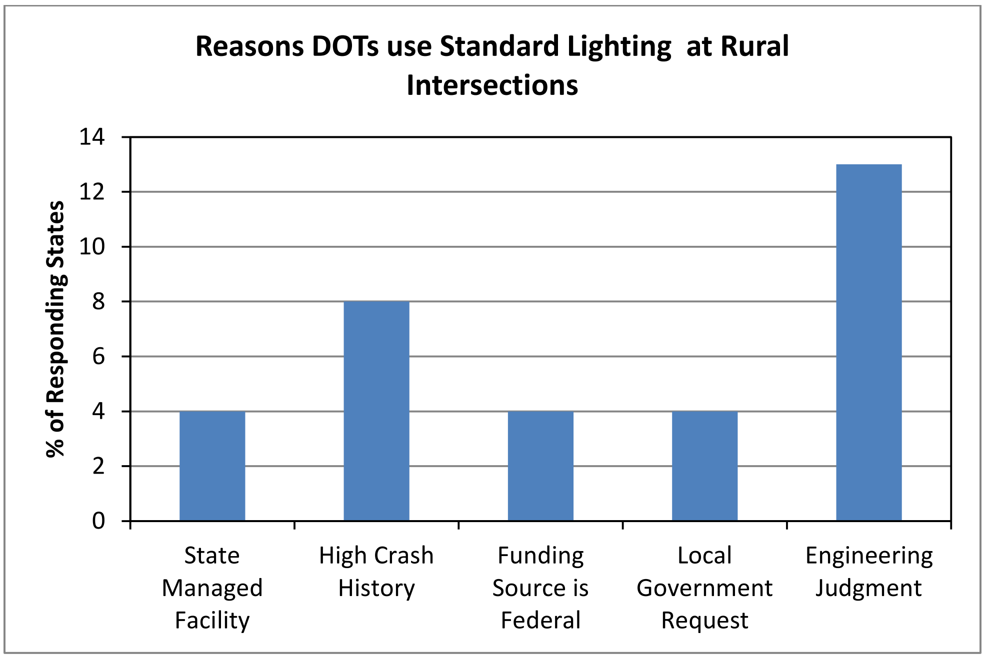


Figure 3 Reasons for Illuminating Rural Intersections

The survey next asked if cost-effectiveness is considered in the design process for rural intersection illumination and, if so, how it is done. The responses to the cost-effectiveness question indicated that about 13 agencies (54 percent of the respondents) consider cost-effectiveness in the design process. However, the latter follow-up question revealed that only a small number actually considered cost-effectiveness: four agencies (17 percent) included a real benefit–cost analysis in the design process, six agencies (25 percent) equated cost-effectiveness to cost minimization through the bidding process or through the use of low-cost technology (e.g., LED vs HPS), and the remaining three agencies (13 percent) considered cost-effectiveness in terms of maximized safety benefit (or crash reduction benefits; i.e., cost is a minor issue). Figure 4 summarizes the indicated strategies used by the DOTs to assess the cost-effectiveness of rural intersection lighting.

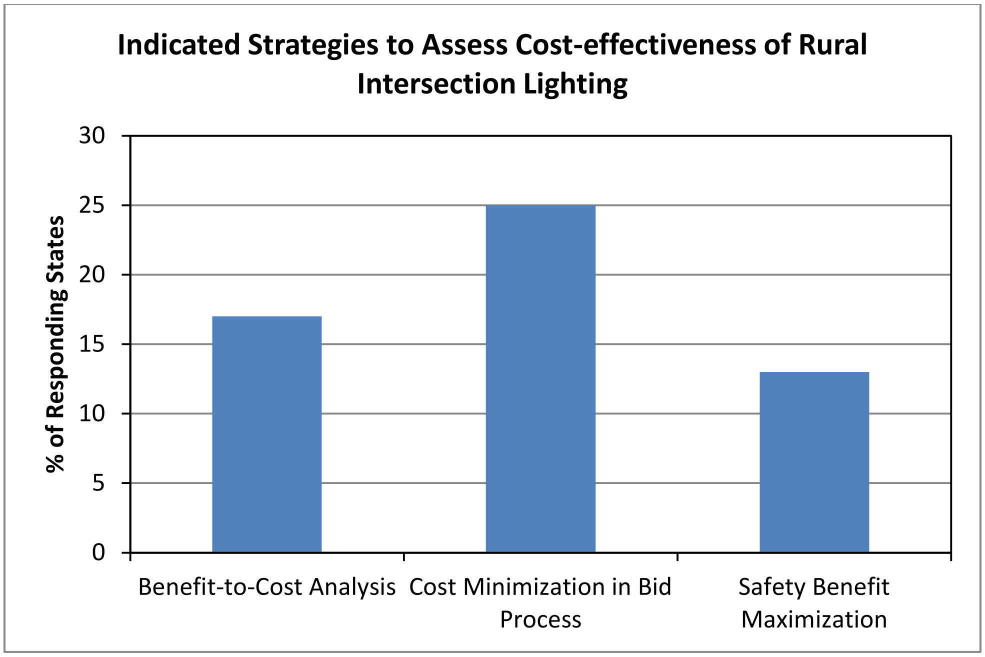


Figure 4 Indicated Strategies used by States to Assess Cost-effectiveness of Rural Intersection Lighting

Also, 12 agencies (50 percent of the responding states) indicated that they use alternatives to illumination for nighttime safety at rural intersections. The alternatives used by these states include retroreflective signage, markings, and stripping to delineate edges. Others also rely on transverse rumble strips, raised pavement markers, and flashing beacons.

The survey results showed that limited comprehensive research is being done by state agencies to see how applicable published national crash modification factors (CMFs) are to their local conditions. When asked if they have found a relationship between illumination levels and observed crashes and/or injury severities at rural intersections, 19 agencies (79 percent of the states) said they have not done any studies to evaluate the effectiveness of lighting. These states rely on only published studies from the federal administration. None of the responding states could provide any published figures or documentation on their illumination costs. This is not surprising since most of the agencies indicated they do not consider cost-effectiveness.

Finally, nine agencies (38 percent of the responding states) said changes to their intersection illumination policy were being considered. These changes seem driven by the need to reduce costs in the form of adopting LED luminaire technologies and using reduced illumination levels.

SECTION C: ESTIMATION OF THE SAFETY IMPACT OF ILLUMINATION AT RURAL CONVENTIONAL INTERSECTIONS IN GEORGIA

C.1 Introduction

The effectiveness of roadway illumination as a crash countermeasure has been well established through previous research studies as outlined in Section A (Literature Review). An overwhelming majority of these studies are based on a binary (i.e., lit or unlit) lighting variable due to a lack of available repositories of quantitative roadway illumination-level data. Consequently, the current version of the Highway Safety Manual is lacking a quantitative illumination crash modification factor. The available CMF is an aggregated value, which is largely uninformative in terms of the crash reduction response/impact of different doses of illumination levels. This implies that transportation agencies are unable to undertake more detailed benefit and cost tradeoff analysis that could maximize the benefit-to-cost ratios of their investments in roadway illumination.

This section presents the methodology and analysis performed in this project on rural conventional intersection crash and illumination data to estimate the safety impact of different quantitative illumination levels. The results from this section form the basis for evaluation of the benefits and costs of providing lighting for rural conventional intersections in Georgia. In this report, rural conventional intersections are referred to as rural intersections.

C.2 Data Requirements and Availability

C.2.1 Minimum Data Requirements

A successful evaluation of the effect of illumination on rural intersection safety requires the simultaneous availability of several types of data: crash data, roadway characteristics, intersection characteristics (including intersection type and presence/absence of purpose-built lighting and illumination levels), and traffic data. Historical sunrise and sunset data are also required to establish times for civil twilight.

The crash data must provide case-by-case information on accidents within the study period. At a minimum it must include the following information:

- Date of accident
- Accident or case ID
- Time of accident
- Location of accident (roadway and milepost or latitude/longitude, rural/urban designation, road segment or intersection)
- Crash severity (fatal, serious, injury, possible injury, and property damage only [PDO]).

The roadway characteristics data must include information that allows the identification of different homogenous segments (e.g., county route name, number of lanes, width of lanes, posted speed limits, beginning milepost, and ending milepost). It must also distinguish between one-way and two-way segments for accurate computation of intersection entering volumes.

Also, there must be information on the intersections of interest within the study area. Information must be available as follows:

- Intersection type
- Traffic control mechanism
- Illumination levels
- Location (rural/urban designation, route, and milepost)
- Traffic volume data or the annual average daily traffic (AADT) for every intersection leg for all the years of the analysis period

Also, historical sunrise and sunset data with adjustments for daylight savings are needed to distinguish nighttime crashes from daytime crashes.

C.2.2 Data Sources

C.2.2.1 Existing Databases

This study uses crash data obtained from the Georgia crash database for accident information. The crash data cover years 2009 to 2014. The study period was selected based on the availability of roadway exposure data that could be computed into daily entry volumes (DEV) for intersections. These exposure (i.e., AADT) data were extracted from the Georgia Department of Transportation RCLINK database for roadway information. The available RCLINK database covers years 2009–2012. Therefore, the researchers projected the exposure data for years 2013 and 2014 by applying a 1 percent growth rate for each year to the known 2012 AADT. The RCLINK database also provided other roadway characteristics information such as one-way designations and rural/urban coding of intersection locations. Also, it includes intersection-level information such as name, type of intersection, traffic control, and layout (four legs or three legs). C.2.2.2 Field Surveys

The RCLINK database lacked information regarding intersection illumination. Therefore, quantitative intersection illumination data were collected from 60 rural intersections in Georgia. The illumination data collected from the rural intersections measure the luminance from the road surface. Luminance refers to reflected light from the pavement surface into the eye of the observer. This is the brightness seen by a driver. The luminance values were converted into the equivalent illuminance values by dividing with the pavement reflection coefficient [*36*, *38*]. Illuminance is the lighting performance value usually recommended for conflict areas such as intersections. Illuminance refers to incident light on the pavement surface.

The field survey collected additional intersection data such as number and width of lanes, presence of horizontal curves, intersection skew angle, and presence of rumble strips on intersection approaches.

C.3 Methodology

This section explains the methodology for selecting the 60 rural intersections where illumination data were collected. The intersections were selected from a pool of rural intersections around Georgia. A quasi-random process was used to ensure that all 60 selected intersections (a) were unsignalized, (b) had all legs paved, (c) had a minimum AADT of 500, (d) had at least one leg on a state or county route, and (e) were not part of an interchange. This section describes the selection of a larger set of rural intersections that were used to establish the applicability of the study results to the bigger population of rural intersection crashes. This larger set of intersections was subjected to the same selection criteria except for the condition that all intersection legs should be paved. The methodologies for computing the intersection daily entry volumes, as well as volume-weighted crash rates, are explained. Finally, this section explains the photographic method of light measurement and the roadway luminance sampling methodology used to make in-situ measurements from the 60 intersections.

C.3.1 Selection of 60 Rural Intersections for Luminance Measurement

The rural intersections were selected from areas around four cities within Georgia: Dalton, Atlanta, Cochran, and Brunswick. The quasi-random selection process for these intersections involved the steps described below. There is currently no intersection inventory database for Georgia; however, the GDOT RCLINK database for road inventory has a companion GIS (Geographic Information System) shapefile that can be spatially analyzed to extract information on the intersections/nodes.

C.3.1.1 GIS Analysis

First, an ArcGIS® file containing nodes within the Georgia road network was used in a spatial intersection analysis of the GDOT RCLINK shapefile to extract node (intersection) information on the names of the connecting links (road segments). Next, duplicate nodes were eliminated and nodes with either less than three or more than four connecting legs were eliminated.

Following this, the research team performed a spatial buffer analysis on the nodes to select all those within 50 miles of the four cities. This buffer analysis was followed by a database analysis on the attribute table to select only the nodes with at least one link/leg on the state or county route. Last, ArcGIS® was used to extract the latitude and longitude of each intersection.

C.3.1.2 Google Earth Analysis

All the latitude and longitude pairs were uploaded into Google Earth® and each of the rural intersections was visually checked to ensure that no interchanges or interchange terminals had been selected. Also, the *streetview* function in Google® Earth was used to check each approach up to about 400 ft upstream of the stop line to collect information on posted speed limits. Additionally, *streetview* was used to identify and omit signalized intersections and intersections where all the legs are not paved. Signalized intersections were omitted because they would complicate the analysis for illumination impact. Also, intersections with unpaved legs were omitted because unpaved roads are associated with low levels of traffic exposure. Also, the *streetview* function was used to identify the layout of luminaires on the approaches as well as the presence of abutting buildings/facilities such as stores and gas stations that might unintentionally serve as other sources of lighting for drivers approaching the intersection.

All the rural intersections were then assigned to one of three illumination groupings based on the identified luminaire layout. The first illumination category is “None” and it refers to a site where there is no purposely built street light on the approaches. Thus, a site with no fixed street lighting but a gas station located at the intersection corner with bright lights that illuminate parts of the intersection would still be considered “None.” The second category is “Partial” and it refers to a site where (a) some of the approaches have no installed lighting, (b) there are luminaires within 400 feet upstream of the intersection on the approach but no luminaire at the intersection itself, or, (c) lighting is provided at the intersection but there is none on the approaches. The “Full” illumination category applies to sites with installed fixed lighting on both its approaches as well as the intersection.

C.3.1.3 Selection of Final 60 Intersections for Luminance Measurement

The daily entering volume was computed for each intersection by summing all the approach AADTs for each analysis year. Those with missing AADTs were omitted from further analysis. The computed annual DEVs were then averaged to obtain a mean for the analysis period. This mean was used to assign each intersection an exposure code of High or Low. Intersections with DEV not exceeding 4000 vehicles were assigned to Low. Also, all locations with DEV less than 500 were omitted. This final filter resulted in a total of 148 candidate intersections.

Each of the 148 intersections had an illumination category code as well as a DEV code. Therefore, there were six unique combinations: None-Low, None-High, Partial-Low, Partial-High, Full-Low, and Full-High. Next, 10 intersections were randomly selected from each of these combination groupings to obtain a final selection of 60 conventional intersections.

Table 2, Table 3, and Table 4 present the list of intersections selected with no dedicated illumination, partial illumination, and full illumination, respectively. Figure 5 and Figure 6 also show maps of Georgia with the intersection locations identified and labeled with the intersection ID on the map.

Table 2 Selected Rural Intersections with No Dedicated Illumination

ID	Area	Illumination Scheme	6-Year AADT	Latitude	Longitude
1	Atlanta	None	12020	33.610942	−84.164771
2	Atlanta	None	12040	33.328946	−84.506553
3	Atlanta	None	8866	33.460053	−85.128609
4	Dalton	None	9979	34.369142	−85.003718
5	Cochran	None	18155	32.551695	−83.610783
6	Dalton	None	9124	34.688607	−84.466841
7	Dalton	None	6377	34.9748	−85.403825
8	Dalton	None	5736	34.4693954	−85.3867744
9	Dalton	None	7740	34.640838	-84.507932
10	Cochran	None	4501	32.1810091	−84.134394
11	Atlanta	None	2471	33.409001	−83.760712
12	Cochran	None	1980	31.692196	−83.113783
13	Cochran	None	1256	31.752663	−83.677117
14	Cochran	None	2447	32.431813	−84.002947
15	Cochran	None	612	32.412943	−83.933468
16	Dalton	None	2112	34.927671	−85.5869896
17	Dalton	None	3938	34.9765363	−85.3667792
18	Cochran	None	3986	31.942601	−83.738504
19	Cochran	None	837	32.123434	−82.863377
20	Cochran	None	2647	32.27341	−82.710022

Table 3 Selected Rural Intersections with Partial Illumination

ID	Area	Illumination Scheme	6-Year AADT	Latitude	Longitude
21	Atlanta	Partial	8145	33.510852	−84.439024
22	Dalton	Partial	7512	34.8936246	−85.1848787
23	Brunswick	Partial	4327	31.743804	−81.439981
24	Dalton	Partial	4079	34.484807	−85.479902
25	Dalton	Partial	9206	34.684957	−84.474753
26	Dalton	Partial	5468	34.8706584	−85.2287353
27	Dalton	Partial	11418	34.9283653	−85.2109702
28	Dalton	Partial	5389	34.977439	−85.415864
29	Cochran	Partial	11042	32.495781	−83.607992
30	Cochran	Partial	6529	32.859922	−83.347219
31	Brunswick	Partial	1630	31.633891	−81.396489
32	Dalton	Partial	1235	34.49462	−84.452927
33	Dalton	Partial	1792	34.978912	−85.433719
34	Dalton	Partial	3676	34.8073337	−85.3892644
35	Dalton	Partial	3441	34.7938924	−85.334694
36	Cochran	Partial	1085	32.204694	−82.668616
37	Cochran	Partial	2630	32.2589	−82.700656
38	Cochran	Partial	1822	32.806965	−82.913333
39	Cochran	Partial	2913	32.810497	−82.757167
40	Cochran	Partial	3480	31.944808	−83.54261

Table 4 Selected Intersections with Full Illumination

ID	Area	Illumination Scheme	6-Year AADT	Latitude	Longitude
41	Dalton	Full	5934	34.69849	−84.481714
42	Cochran	Full	5559	32.541576	−82.903634
43	Dalton	Full	8483	34.694238	−84.481535
44	Dalton	Full	5697	34.689081	−85.30046
45	Dalton	Full	7982	34.69774	−84.481912
46	Atlanta	Full	12176	33.565767	−85.045059
47	Atlanta	Full	16192	31.85	−81.595833
48	Atlanta	Full	15019	33.441022	−84.457578
49	Brunswick	Full	8866	33.46	−85.128611
50	Atlanta	Full	15430	33.368122	−84.779261
51	Dalton	Full	2767	34.696972	−84.480126
52	Cochran	Full	1324	31.807311	−83.487729
53	Cochran	Full	1978	31.948536	−83.456307
54	Cochran	Full	2156	31.949674	−83.454632
55	Cochran	Full	1695	31.946251	−83.456309
56	Cochran	Full	921	32.18756	−82.566154
57	Cochran	Full	1378	32.53928	−82.90251
58	Cochran	Full	1037	31.809023	−83.490021
59	Cochran	Full	2084	31.949702	−83.45626
60	Atlanta	Full	1566	33.791296	−83.596102

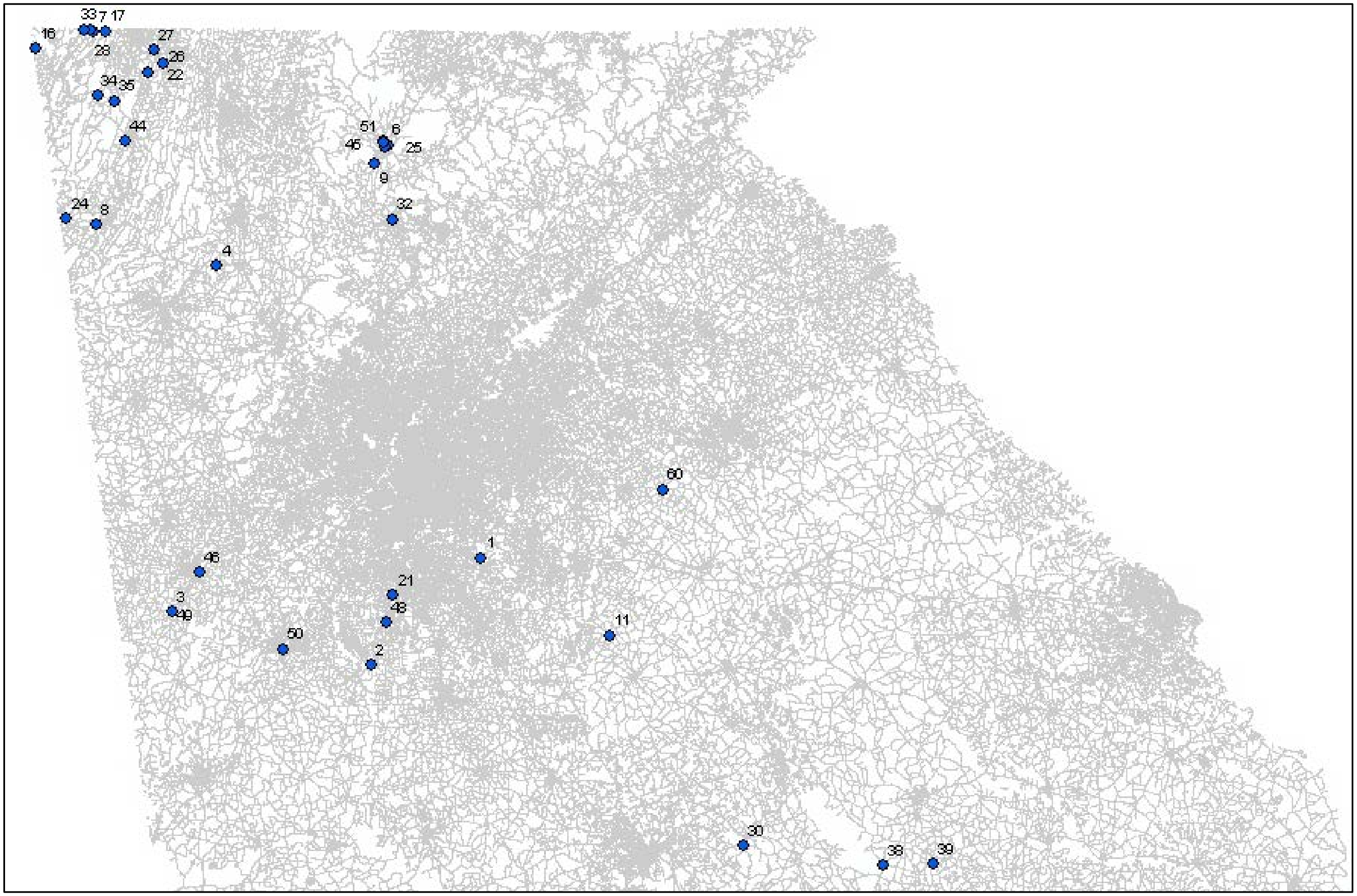


Figure 5 Locations of Intersections in the Northern Half of Georgia

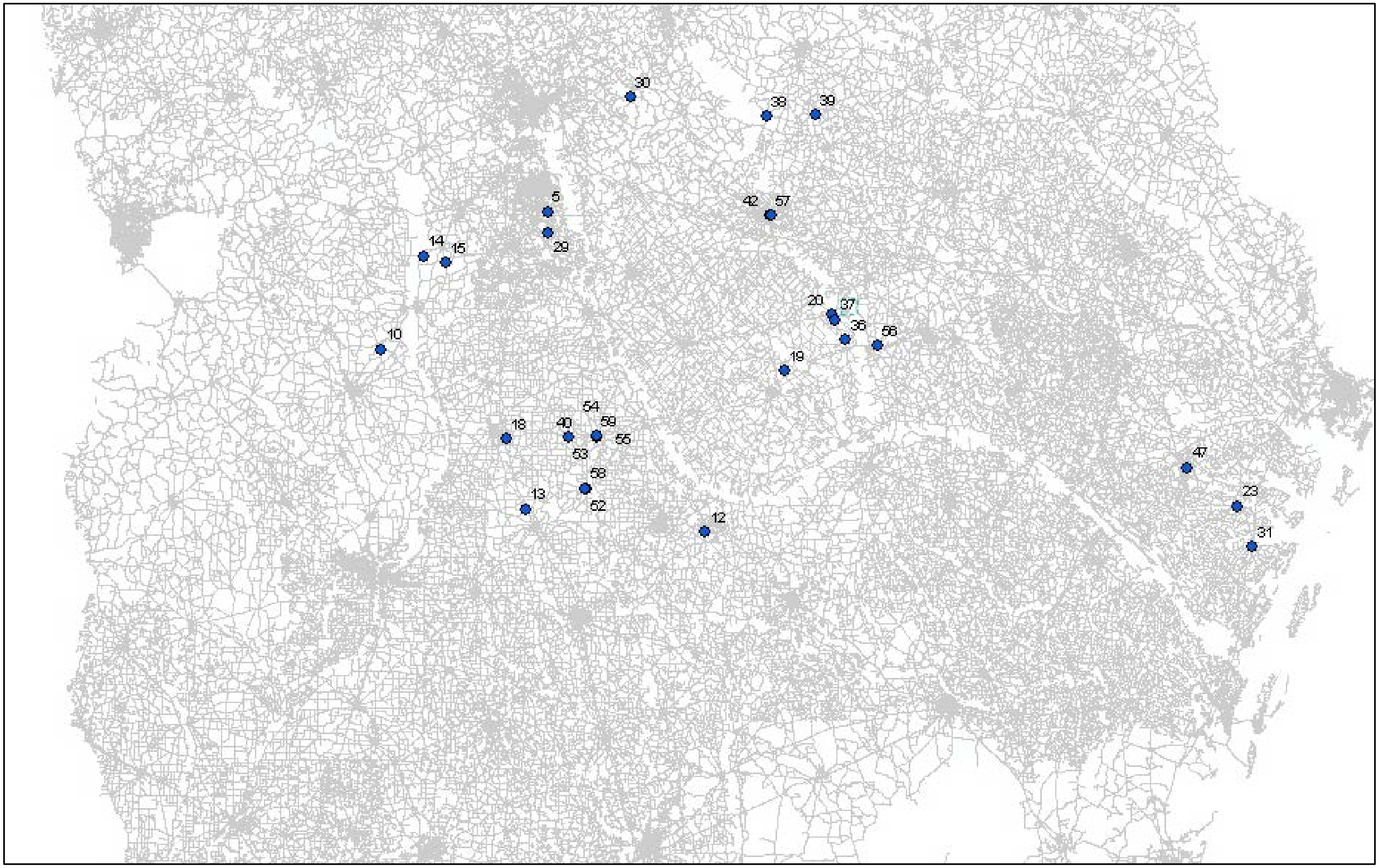


Figure 6 Locations of Intersections in the Southern Half of Georgia

C.3.2 Selection of All Eligible Rural Intersections

It was necessary to develop a separate database of all eligible rural intersections in order to analyze them in comparison with the smaller number of survey intersections. This comparison identified any differences between the two datasets that can hinder a direct application of the findings from the survey intersections to the larger population.

There is currently no intersection inventory database for Georgia. However, the GDOT RCLINK database for road inventory has a companion GIS shapefile that can be spatially analyzed to extract information on the intersections/nodes. Therefore, the selection process started with a GIS spatial analysis of the shapefile and was followed with a regular database analysis of all extracted intersection data.

C.3.2.1 GIS Analysis

A spatial intersect analysis of an ArcGIS® ® shapefile of nodes in the Georgia road network and the GDOT RCLINK road network shapefile was used to obtain the name, traffic exposure, and RCLINK ID for each intersection leg in Georgia. ArcGIS® was used to extract the easting and northing (in feet) of each intersection, and this was later converted into the corresponding decimal degree latitude and longitude values.

The extracted intersection information was analyzed with a filter that selected only three-leg and four-leg rural intersections. This filter identified a total of 306,999 eligible rural intersections. RCLINK IDs of the intersection legs were found in the GDOT RCLINK shapefile under the INVROUTE field. Next, all intersections with no missing RCLINK ID and road name for each leg were selected. This was necessary because while the RCLINK database can be used to identify an intersection leg based on the RCLINK ID, the adjoining intersection legs can only be identified by their names. This filter reduced the number of eligible rural intersections to 251,928.

C.3.2.2 RCLINK Data Analysis

A query was run (using the information on the 251,928 intersections created from the spatial analysis) on each annual RCLINK database (i.e., 2009–2012) to identify the legs of the rural intersections. For each identified intersection leg the AADTs, traffic control, one-way designation, and rural/urban codes were extracted. Next, any intersections with missing leg AADTs for any of the analysis years was filtered out. This further reduced the eligible nodes/intersections as shown in Table 5.

Table 5 Number of Rural Intersections with No Missing AADT Information

Annual Node-RCLINK File	Number of Eligible Nodes/Intersections
2009	75,687
2010	75,687
2011	79,334
2012	71,736

For each annual set shown in Table 5, further analyses were conducted to omit all nodes with a traffic control code other than the RCLINK codes shown in the bullet list below.

- A – Stop sign
- C – Stop sign (all directions)
- O – Stop sign (opposite direction of inventory)
- Y – Yield sign
- W – Yield sign (opposite direction of inventory)

Table 6 shows the total number of identified stop-controlled and uncontrolled intersections in each annual RCLINK database. These intersections were compared across the years and only those available for each year were selected, resulting in 22,431 eligible rural intersections for each year.

Table 6 Number of Available Stop or Yield Control Rural Intersections

Annual Node-RCLINK File	Total	Rural Area	Urban Area
2009	73,402	28,876	44,526
2010	73,402	28,876	44,526
2011	76,987	31,347	45,640
2012	69,400	27,968	41,432

C.3.3 Computation of Intersection Daily Entering Volume

The daily entering volume was computed for each intersection by summing all the approach AADTs. AADTs on one-way legs that exit the intersection were omitted. AADT on two-way approaches were split into two, and only one half was included in the analysis. The assumed 50/50 split was necessary because the actual split of traffic between the two directions on a two-way road was not available in the RCLINK files. Annual entering volumes were calculated by multiplying these DEVs by 365. Also, the nighttime AADT split was assumed to be 24 percent. Next, all intersections with a DEV of less than 500 were omitted from the analysis. This filtering further reduced the number of eligible rural intersections for each analysis year to 18,893.

C.3.4 Treatment of the Georgia Crash Data

GDOT's crash database contains about 46 sub-datasets, which can be electronically merged through the incident ID variable. One of these datasets is the *Incident Table*, which primarily contains information on incident ID; incident date; incident location variables (city, county, latitude, longitude); main road on which crash occurred; nearest intersecting road; distance to nearest intersection; and a variable indicating whether the crash occurred at an intersection, near an intersection, at an interchange, or on a private property. There is also a *Collision Table* that gives further information on each incident (e.g., the type of injury severity and number of people involved).

Similar to most crash databases, the GDOT database has some data quality issues; chief amongst them are missing variable information and possibly wrongly coded location information. Identification of incident records with missing variable information can be easily accomplished with a simple database query. However, deciphering the incident records with wrongly entered data would require a rigorous quality-assurance/quality-control (QA/QC) procedure for the over 1.85 million crash records within the analysis period of 2009–2014. In addition, for each of the 1.85 million crash records, there are 18,893 candidate intersections that must be manually checked before a crash can be assigned to an intersection. This would require an extremely large number of man-hours if the rigorous manual QA/QC approach is adopted.

A possible solution would have been to create a control group out of the 18,893 intersections for use in the analysis. However, the selection of the control group might introduce additional biases if it is not truly representative of the population. Using a control group of intersections also means that some crashes would be unnecessarily excluded from the analysis. Therefore, the research team favored a method that is inclusive of as many intersections and crashes as possible (based on limitations of available data) with a reasonable degree of accuracy. Analysis of the crash data showed that 16.5 percent of crashes had the RCLINK ID of the location coded, while about 71 percent of crashes had the latitude and longitude of the location coded. Therefore, a shortest distance algorithm that makes assignments based on the latitude/longitude of intersections, latitude/longitude of crashes, and a buffer distance of 250 ft was adopted. This method could be limited by the accuracy of the coded latitude and longitude information. However, it offers the most pragmatic approach for this study.

C.3.5 Computation of Crash Rates

A volume-weighted method was used to compute the crash rate for each intersection over the entire analysis period. Equation 3 shows the formula for computing the volume-weighted crash rate. The volume-weighted analysis minimizes the possible effect of trend/temporal effects.

$$crash\ rate = \frac{1000000 * \ sum\ of\ crashes\ in\ analysis\ period}{sum\ of\ annual\ traffic\ volume(s)} \quad (\mathbf{3})$$

C.3.6 Measurement of Intersection Illumination Levels

Like most states, Georgia does not have archived intersection illumination-level data. Therefore, this study undertook a data collection effort whereby actual intersection illumination-level data were measured from 60 rural intersections. Illuminance measurements require in-situ spot measurements, with a hand-held illuminance meter, from an imaginary 6 × 6 ft grid within the intersection area. This procedure requires both data collection personnel and equipment in the active travel lanes, posing increased risk. To mitigate the risks of using this method for all 60 rural intersections, which are located on state routes, would require extensive traffic management and road closures with possible coordination between multiple agencies, including the police. This is likely to increase costs in terms of man-hours and measurement time.

C.3.6.1 Existing Methods for Illuminance Measurement

As discussed in the literature review in Section A, luminance can alternatively be measured and converted into an equivalent illuminance measurement. There are two major existing protocols for roadway luminance measurement. The first protocol is a European standard developed by the CIE [*32*] and the second protocol is a North American standard developed by the Illuminating Engineering Society (IESNA) [*56*]. A third and less common protocol has been developed in New Zealand [*57*] in response to the very time-consuming requirements of the two major protocols.

Even though the protocol developed in New Zealand is more streamlined than the other two, all three methods are time consuming because they require the use of high-precision hand-held light meters to make many spot measurements of luminance from long distances (CIE ≈ 60 meters, IES ≈ 84 meters, New Zealand ≈ 33 meters) and very small observation angles (1° for CIE and IES, and 2° for the New Zealand method). Therefore, they do not seem practical for measuring illumination from a large number of intersections as this study attempts. Additionally, these methods have three major limitations:

a) It is difficult to reproduce measurements.
b) Measurements are usually not made at the same luminance constancy because luminaire output is subject to AC voltage fluctuations.
c) It is impossible to make spot measurements from such long distances as the methods require because actual measurement areas become elliptical, several feet long and wide.

As a result of these limitations, researchers in this study opted to use a photographic method to measure luminance levels at the intersections. The sampling method used is a slight variation of the New Zealand method since it allows measurements to be made at shorter distances with both personnel and equipment on the road shoulder, away from the active travel lanes. Furthermore, the New Zealand method does not require personnel and equipment in the active travel lanes. Therefore, it carries less risk to the data collectors and is also less resource intensive.

C.3.6.2 The Photographic Method

The photographic method of evaluating lighting levels offers an effective solution to the challenges involved with using hand-held illumination meters to evaluate intersection illumination levels. The photographic method is able to achieve luminance constancy that reduces variation in luminance during measurements because the luminance is measured/captured at the same time [*58*]. Also, because the luminance information is captured in an image, the method guarantees repeatability. Uncertainties associated with re-identifying the exact points in the field where measurements were made are eliminated.

The photographic method is an image-analysis approach that can be used to extract pixel-level luminance information from an image taken with a digital camera. A digital camera can effectively serve as a luminance meter because the output from each element of its imaging array is proportional to the luminance of some scene element modified by the optical properties of the lens system and the exposure settings of the camera [*59*]. By calibrating a digital camera, the pixel intensities in an image can be linked to the scene luminance through a specific camera calibration constant [*59*]. The relationship between pixel intensity and scene luminance can be expressed as in Equation 3 [*59*].

$$N_d = K_c \left(\frac{tS}{{f_s}^2}\right) L_s \ \ldots\ldots\ldots \ \mathbf{(4)}$$

Where:

N_d is the digital number or pixel intensity in the image

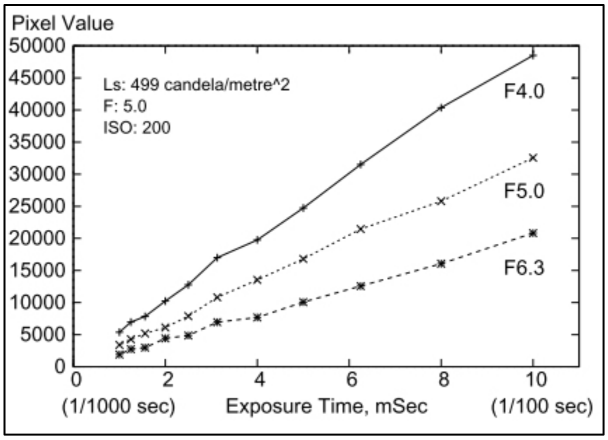
K_c is the calibration constant of the camera t is the exposure time in seconds

f_s is the aperture number (f-stop)

S is the ISO sensitivity of the film

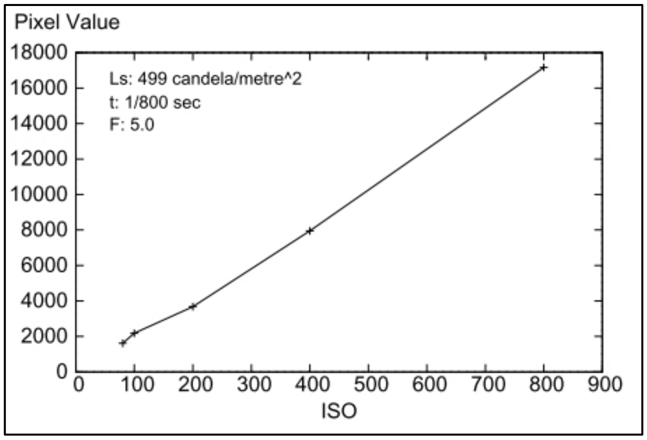
L_s is the luminance of the scene (cd/m^2)

This is essentially an equation of a straight line with slope of K_c and zero intercept, and it implies that under proper exposure conditions (i.e., no saturation in the image) pixel intensity (N_d) will vary linearly with the exposure time, the ISO sensitivity, and the squared inverse of aperture. Hiscocks and Eng [*59*] showed that this relationship holds true for ISO and exposure time at all exposure settings of a digital camera. Figure 7 shows the relationship between pixel intensity and exposure time, while Figure 8 shows the relationship between pixel intensity and ISO. However, they found that at larger apertures (i.e., below f/4.0) the relationship between pixel value and aperture became nonlinear. It is unclear whether the observed threshold between linearity and nonlinearity is device specific since they used a single camera in their study and there is no verification of the phenomenon across other devices. Figure 9 shows the relationship between pixel intensity and aperture size.



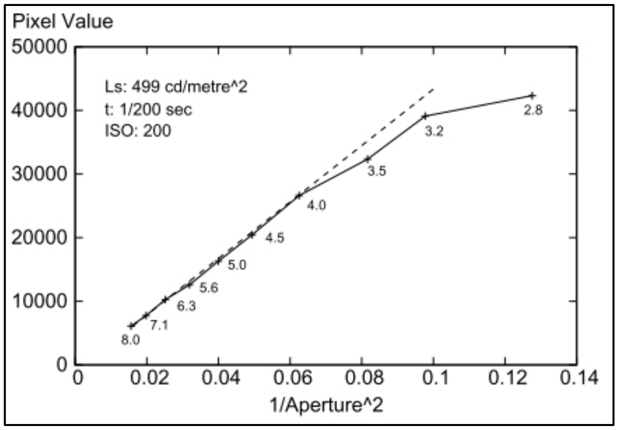
(Source: [*59*])

Figure 7 Exposure Time vs. Pixel Intensity



(Source: [*59*])

Figure 8 Pixel Intensity vs. ISO Sensitivity



(Source: [*59*])

Figure 9 Pixel Intensity vs. Aperture

There are a few minor limitations of the photographic method for illumination measurement. First, it is best to store images in a lossless format such as TIFF rather than a compressed format like JPEG. However, the TIFF format has a downside of putting a constraint on storage space due to very large image files. Next, as pixel intensity in an image increases, the relationship between pixel intensity and luminance becomes nonlinear. Therefore, images should be taken in the underexposed range. Underexposed images are generally dark and, depending on the level of illumination at a site, the images could be too dark to permit easy identification of the intersection's layout later. Therefore, at least one overexposed image of the site must also be taken. Finally, there is often a decrease in light transmission at the ends or periphery of a digital camera lens [*59*]. This is known as vignetting. According to Inanici [*60*], vignetting increases with aperture size. Therefore, smaller apertures should generally be used. Also, intersection images must be centered so that the image has enough room around the intersection and no part of the intersection falls in the vignetting-affected zones.

In this study, researchers calibrated two digital single lens reflex cameras for use in measuring illumination at the intersections. More information on the calibration process is available in Gbologah 2015 [*61*] or Gbologah 2016 [*62*].

C.4 Results and Discussion

The results presented in this section are based on only crashes that were successfully matched to rural intersections with the shortest distance algorithm and a buffer of 250 ft.

C.4.1 Rural Intersection Illumination Levels

All 60 rural intersections were surveyed, but only 43 were eligible for inclusion in the analysis after detailed analysis of the field results. Some intersections had to be omitted for various reasons, including installation of signals during the analysis period or conversion to a roundabout within the analysis period. Figure 10 presents the plot of derived illuminance levels at the 43 rural intersections.

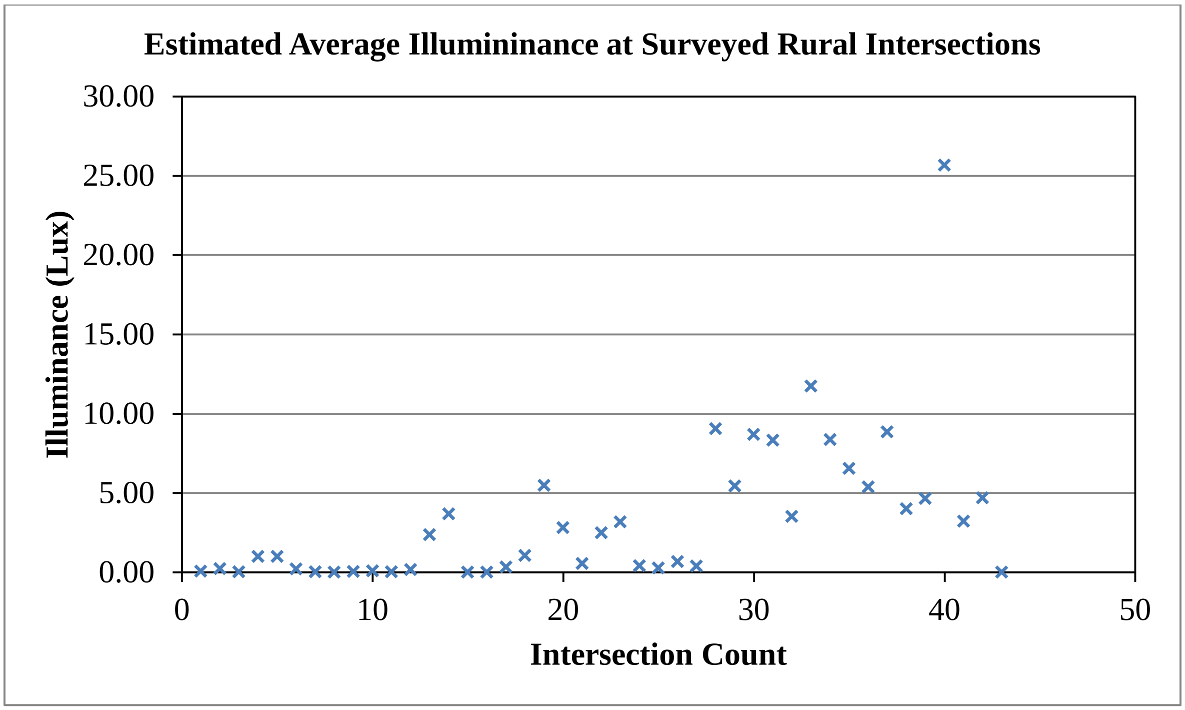


Figure 10 Estimated Rural Intersection Illuminance

C.4.2 Injury Severities

The Georgia crash database categorizes crashes as fatal, injury, or PDO. Table 7 and

Table 8, respectively, present the observed distribution/proportions of these injury severities for nighttime and daytime crashes for three different subsets of the Georgia crash database.

Table 7 Observed Proportions of Nighttime Crash Severity Types

	Proportion of Crash Severities		
Dataset	Fatality	Injury	PDO
Surveyed Intersections	0.02	0.27	0.71
Rural Intersections Only	0.01	0.27	0.72
All Intersections	0.01	0.27	0.72

Table 8 Observed Proportions of Daytime Crash Severity Types

	Proportion of Crash Severities		
Dataset	Fatality	Injury	PDO
Surveyed Intersections	0.02	0.34	0.64
Rural Intersections Only	0.01	0.33	0.66
All Intersections	0.01	0.33	0.66

The proportions of fatal crashes, injury crashes, and PDO crashes in both Table 7 (nighttime crashes) and Table 8 (daytime crashes) show that there isn't much difference between the observed crash occurrence at the surveyed intersections, rural intersections, and all intersections. Therefore, the sample intersections that were surveyed are a good representation of rural intersection.

The "injury" crash severity as shown in Table 7 and Table 8 is usually further broken down into severe crashes, injury crashes, and possible injury crashes. *Severe injury crash* refers to a crash where the victim required transportation to the hospital, *injury crash* refers to a crash where the victim is physically injured but did not require transportation to the hospital, while *possible injury crash* refers to a crash where an injury could not be physically confirmed on-site. Analysis of available (most recent) 2000 to 2006 data from the Georgia Governor's Office of Highway

Safety [*63*] shows that the injury crashes in Georgia break down into 4.5 percent serious injury, 24.1 percent visible injury, and 71.4 percent complaint. This distribution was used to proportionately split the observed 26 percent injury crashes at rural intersections in Table 7 to yield the final crash injury severity distribution shown in Table 9.

Table 9 Distribution of Crash Severity Types within Nighttime Rural Intersection Incidents in Georgia

Injury Severity	Proportion
Fatal	0.02
Severe	0.01
Injury	0.07
Possible Injury	0.19
PDO	0.71

C.4.3 Overview of Observed Crash Experience at the Studied Intersections

Of the 43 available intersections, 26 had neither nighttime nor daytime crashes within the 6-year analysis period. The measured illuminances within this set ranged from 0 to about 25 lux, while AADTs ranged from about 800 to 8100 vehicles per day. The other 17 intersections, which had at least one crash, had measured illuminances ranging from 0 to about 9 lux, while their AADTs ranged from about 612 to 10,000 vehicles per day. Figure 11 shows a comparison of the daytime and nighttime crash rates at all 43 intersections. Both the observed daytime and nighttime crash rates decrease with increasing average intersection nighttime illuminance. However, the reduction is much steeper for nighttime than for daytime. This is an indication that illumination may have an effect on nighttime crashes because it is the only safety influence factor that truly separates nighttime and daytime crash experience. Figure 11 further indicates that part of the observed nighttime crash rate reductions may be unrelated to illumination since daytime crash rates show the same decreasing trend. Therefore, this unrelated component must be estimated and excluded from the estimated crash reductions due to illuminance. Since the main difference between nighttime and daytime conditions is the level of illuminance, this unrelated component can be fairly assumed as the mean daytime crash rate.

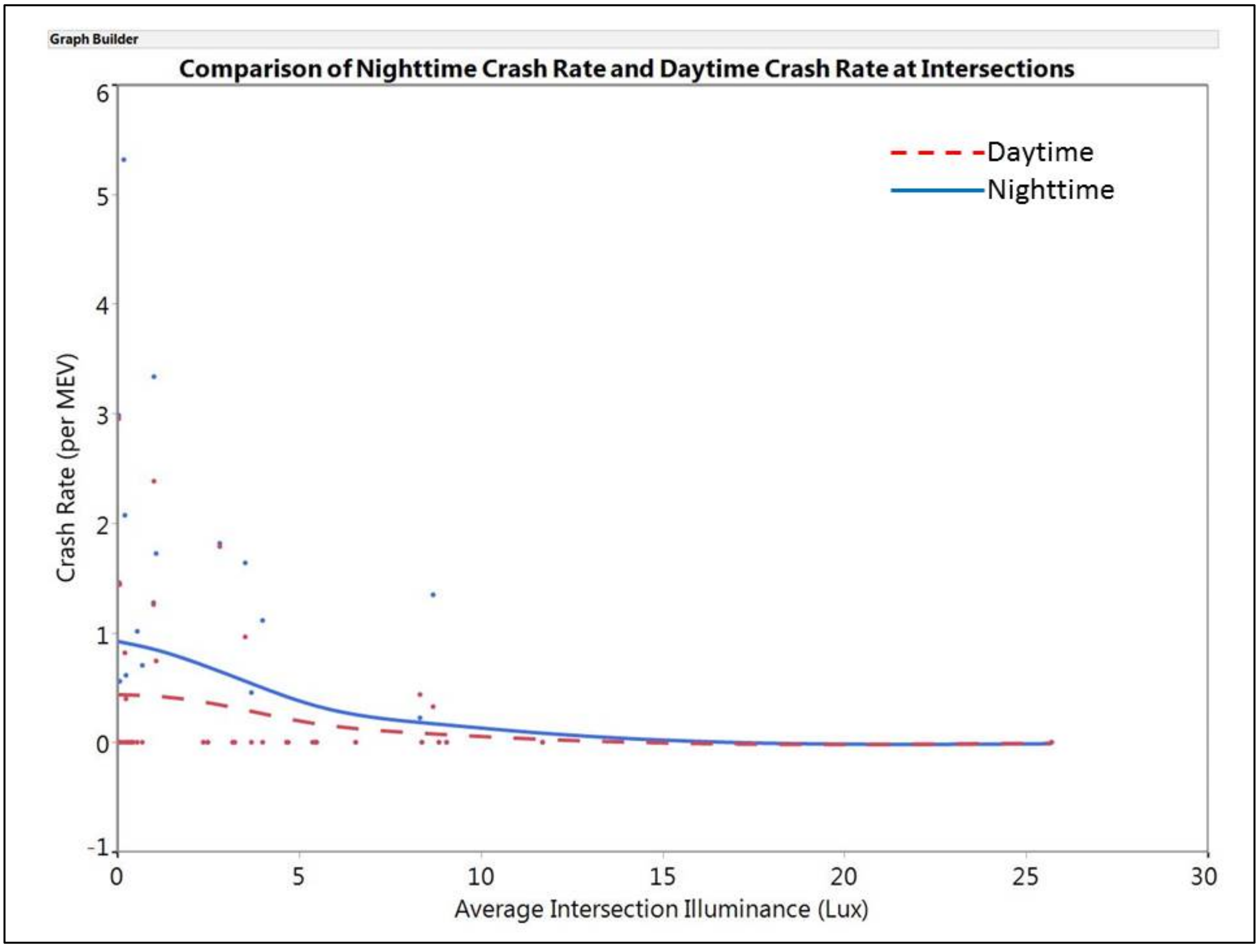


Figure 11 Comparison of Nighttime and Daytime Crash Rate at Intersections

C.4.4 Effect of Illumination Level on Nighttime Total Crash Rates at Rural Intersections

As mentioned in Section C.4.3, more than half (26) of the study's intersections did not experience any crash within the 6-year analysis period of 2009 to 2014. Even though zero crashes were observed, the expected number of crashes at these intersections based on underlying Poisson or negative binomial distribution and the total exposure within the period may not necessarily be zero. It is possible that a single crash may have been observed given a different analysis period. Therefore, treating more than half of the available intersections as zero-crash intersections might lead to erroneous conclusions. Consequently, this study uses a maximum likelihood method to estimate the 95 percent upper bound crash frequency for each intersection based on its exposure level.

Statistical analysis of the annual crashes for each of the other 17 intersections that had at least one observed crash showed that a Poisson crash distribution can be assumed for the intersections. Therefore, the discrete Poisson probability function was used to estimate the 0.95 cumulative probability crash frequency, *n*, given a mean crash frequency, γ, equal to the total crashes observed over the analysis period. Due to the small number of intersections with observed crashes and an even smaller crash frequency at the intersections, it was not possible to estimate *n* for different injury severity types. Equation 5 shows how *n* can be estimated from total crashes.

$$0.95 = \sum_{0}^{n} \frac{e^{-\gamma}\gamma^{n}}{n!} \; \dots\dots\dots..(\mathbf{5})$$

For the other 26 intersections with no observed crashes, *n* was estimated by relaxing the discrete Poisson assumption and assuming a continuous Poisson probability density function as shown in Equation 6.

$$0.05 = \; e^{-n} \dots\dots\dots(\mathbf{6})$$

The estimated 95 percent cumulative crash frequencies were then used to estimate corresponding upper bound crash rates based on entering volumes. Figure 12 shows the log of observed crash rates and estimated upper bound crash rates versus illuminance. Also shown on Figure 12 is the estimated curve of the relationship between illumination level and total crash rate at rural intersections. The curve meets almost all the upper bound crash frequency constraints and also averages between the observed crash rates. It is constrained by the horizontal line representing the mean daytime crash rate. As explained previously, the mean daytime crash rate is assumed in this study to be representative of the proportion of nighttime crash experience, which is unrelated to illumination. A dose-response relationship between illuminance and crash rates at rural intersections is almost non-existent beyond an illuminance level of about 12 lux. Table 10 tabulates the expected percentage reduction in crash rates in response to different illumination levels.

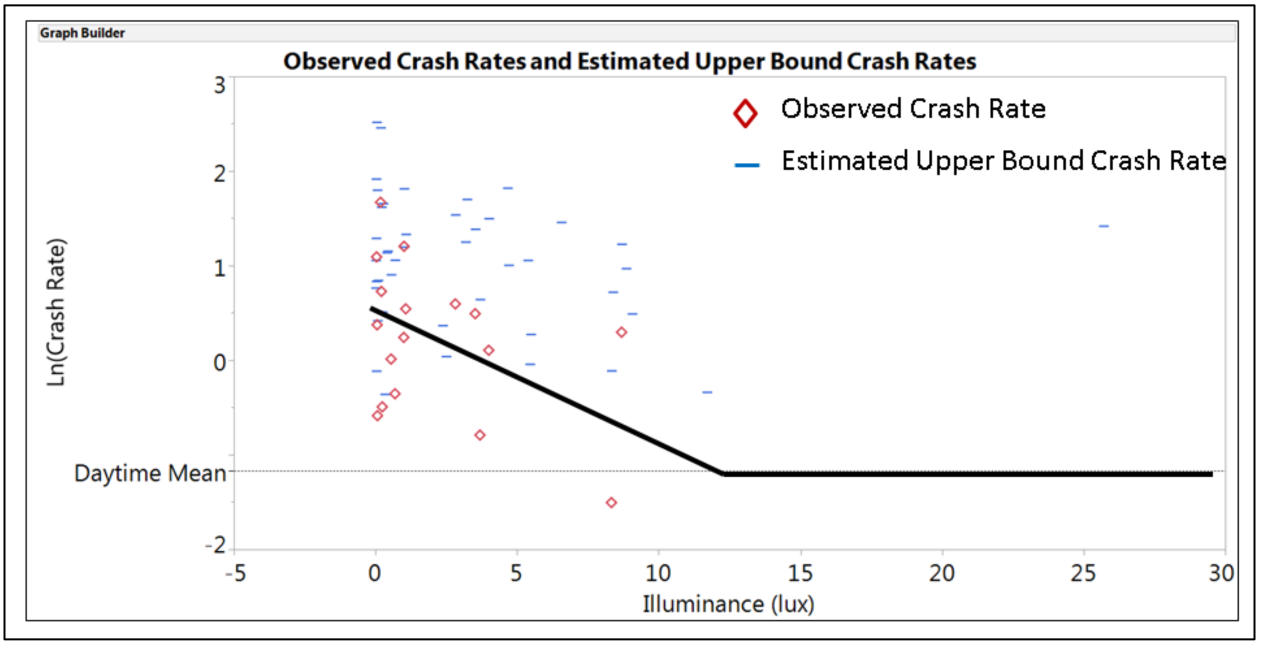


Figure 12 **Observed Effect of Illumination Level on Total Crash Rates at Rural Intersections**

Table 10 Effect of Different Illumination Levels on Observed Nighttime Total Crash Rates at Rural Intersections

Average Intersection Illuminance (Lux)	Expected Reduction in Nighttime Total Crash Rates (%)
0	0.00
0.5	3.38
1.0	6.77
2.0	13.54
3.0	20.31
4.0	27.08
5.0	33.85
6.0	40.62
7.0	47.39
8.0	54.16
10.0	60.93
11.0	67.70
11.5	74.47
≥12.0	81.21

With the estimated crash rate reductions shown in Table 10, the effect of a specific illumination level for different injury severity types can be estimated by breaking down the crash reduction estimate according to the injury severity proportions shown in Table 9.

C.5 Summary Findings for Safety Analysis

This report presents the findings of a rural intersection safety analysis performed with crash data from Georgia. The studied intersections are conventional, non-signalized, and paved four-legged or three-legged intersections with at least one leg on a state or county route.

Crashes were matched to intersections using a minimum distance algorithm and a buffer distance of 250 ft. Distance between intersections and recorded crashes were estimated from their respective latitude and longitude values.

The results show that different illumination levels can provide direct safety benefits compared to the "no light" situation. Also, the study finds that there is an illuminance threshold beyond which the dose-response relationship between nighttime crash rate and illuminance becomes non-existent (i.e., an increase in illuminance does not improve the crash rate any further). This study finds that for rural conventional intersections in Georgia this illuminance threshold is about 12 lux. The minimum recommended intersection illuminance by the Illuminating Engineering Society of North America [*33*] is about 8 lux. This study finds that even lower illuminance levels can provide significant benefits. Table 10 of this report gives the expected reduction in crash rates for different illuminance levels.

It was not possible to directly estimate the impact of illumination levels on different crash severity types due to the relatively small sample of illuminated intersections that could be studied in this analysis within the constraints of the budget and time, and even smaller number of crashes at these intersections. Consequently, the study made a necessary assumption that any observed effect on total crashes will proportionately split among the different crash severities (fatal, serious, injury, possible injury, and PDO) based on their distribution within the larger rural intersection crash dataset.

It is critical in considering these potential benefits of lighting to recall that the impact on frequency of incidents or expected percentage crash rate reductions may not be justified for all intersections depending on the average entering volumes, especially for safety programs where funds may be needed to reduce more substantial risks to the public elsewhere. Making these decisions requires access to additional decision making tools, such as the Benefit to Cost Model provided as part of this study, which utilizes the estimated benefits from this section.

SECTION D: BENEFIT-TO-COST ANALYSIS OF RURAL CONVENTIONAL INTERSECTION ILLUMINATION IN GEORGIA

D.1 Introduction

In this section, the research team presents a limited economic analysis of the costs associated with illuminating rural conventional intersections in Georgia and the safety benefits (cost savings) due to illumination. In the first subsection the researchers present the cost analysis for rural conventional intersection illumination, and in the second subsection they follow up with the steps undertaken to monetize the associated safety benefits to provide a preliminary estimate of the benefit-to-cost ratios associated with various illumination levels. They also discuss results from a spreadsheet model that the research team developed to facilitate the benefit-to-cost analysis.

D.2 Cost Estimation

The cost estimation analysis considered Philips Lumec® Roadstar LED luminaires ranging from 40 watts to 180 watts. These luminaires were selected because they have been recently used in the GDOT-sponsored *Lighting Operation and Maintenance Study* [*64*]. Illumination models for different average intersection illuminance levels were developed to estimate their associated power consumption. The illuminance levels cover the full range of the dose-response relationship of nighttime crash rate and illuminance identified in Section B of this report.

D.2.1 Development of the Illumination Models

The models were developed with DIALux® (www.dial.de/en/dialux/), a professional lighting design software. The lighting models developed are applicable to both three-leg and four-leg intersections with two-way travel directions on each leg and 13-ft-wide travel lanes. Pole heights ranged from 35 ft to 45 ft with each pole mounted on a 2-ft-diameter by 8-ft-deep concrete footing. Luminaires are attached to the poles via 4-ft extension arms. The poles are situated such that the luminaires hang over the road edge with the extension arms aligned to the 45° diagonal through the intersection from the corners. Figure 13 and Figure 14 show the luminaire layouts for four-leg and three-leg intersections, respectively. The modeling also assumed that a photocell located at a central service station is used to switch luminaires on/off for 12 hours a day.

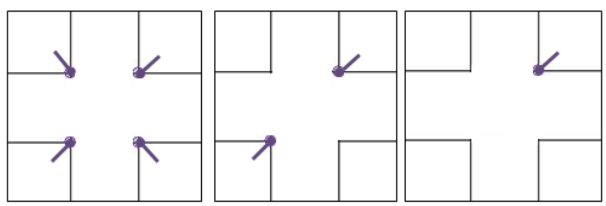


Figure 13 Modeled Luminaire Layouts for Rural Conventional Four-Leg Intersections

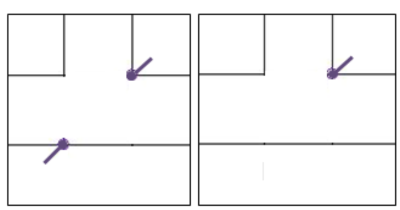


Figure 14 Modeled Luminaire Layouts for Rural Conventional Three-Leg Intersections

Horizontal illuminance was evaluated with a calculation grid covering the entire intersection area bounded by the corners. The calculation grid also extends 5 ft. on each approach/leg. The evaluation points within the calculation grid were arranged as a 6 ft. × 6 ft. grid. There are many intersection-related cost factors that could be considered, but for the purposes of this study only factors that introduce variability were considered. These factors were identified as follows [*64*]:

- Luminaires and associated components
- Luminaire poles and arms (overhangs)
- Foundations for poles
- Cost of replacement parts for maintenance
- Power consumption
- Cost of labor, contractor markup, and other associated fees

All other costs of power distribution and service, such as conduit, conductors, service panels, grounding, etc., are assumed to be similar for all the intersections.

D.2.2 Illumination Modeling Results and Estimated Costs

The results of the intersection illumination modeling have been summarized in Table 11. These are the minimum power consumption and luminaire configurations required to meet the modeled illuminance ranges with the Philips Lumec Roadstar luminaires. The calculated ratios of average horizontal illuminance (E_{avg}) to minimum horizontal illuminance (E_{min}), also called uniformity ratios, are all below the recommended maximums for major, collector, and local roads *[65]*.

The costs for the various luminaire installation components and the price per kilowatt-hour (kWh) were obtained from the *Lighting Operation and Maintenance Study* [*64*], which was conducted by Gresham Smith and Partners for GDOT. The cost estimates in that report were in year 2013 dollars, so they were converted into year 2016 dollars using consumer price index factors [*66*]. The annualized installation costs for these components are shown in Table 12. Table 13 presents the estimated annual maintenance costs for each luminaire type modeled, and Table 14 shows the estimated annual energy costs per luminaire type. Table 15 presents the final estimated costs for each illuminance range and corresponding luminaire configuration/schedule. All cost estimates have been annualized over a 30-year period at a social discount of 3 percent.

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Table 11 Intersection Illuminance, Power Consumption, and Luminaire Configuration Chart

Scenario #	Intersection Illuminance (Lux)	Uniformity Ratio (E_{avg}/E_{min})	Luminaire Schedule	Philips Product #	Mounting Height (ft)	System Power Consumption (Watts)
1	2.58	2.00	1@40W	GPLS-40W49LED4K-ES-LEH3	45	47
2	2.59–3.01	2.15	1@40W	GPLS-40W49LED4K-ES-LEH3	40	47
3	3.02–3.55	2.20	1@40W	GPLS-40W49LED4K-ES-LEH3	35	47
4	3.56–3.98	2.06	1@65W	GPLS-65W49LED4K-ES-LEH3	40	72
5	3.99–4.74	2.20	1@65W	GPLS-65W49LED4K-ES-LEH3	35	72
6	4.75–5.70	2.21	1@90W	GPLS-90W49LED4K-ES-LEH3	35	101.6
7	5.71–7.10	1.43	2@60W	GPLS-60W30LEDEK-ES-LEH3	35	136
8	7.12–9.58	1.44	2@65W	GPLS-65W49LED4K-ES-LEH3	35	144
9	9.59–11.41	1.41	2@90W	GPLS-90W49LED4K-ES-LEH3	35	201.1
10	11.42–12.00	2.24	1@180W	GPLM-180W98LED4K-ES-LEH2	40	204
11	12.28 – 14.32	1.08	4@40W	GPLS-40W49LED4K-ES-LEH3	35	188
12	14.33 -15.39	1.35	2@105W	GPLM-105W79LED4K-ES-LEH3	35	238
13	15.40 – 19.16	1.09	4@65W	GPLS-65W49LED4K-ES-LEH3	35	288
14	19.17 – 22.93	1.08	4@90W	GPLS-90W49LED4K-ES-LEHS	35	406.4
15	22.94 – 30.78	1.11	4@105W	GPLM-105W79LED4K-ES-LEH3	35	476
16	30.79 – 44.13	1.11	4@105W	GPLM-150W79LED4K-ES-LEH3	35	680

Table 12 Estimated Installation Costs per Luminaire Type

#	Luminaire Unit Cost	Photocell at Service Point	Cost of Mounting Pole	2′ × 8′ Pole Footing	4′ Luminaire Arm	Contractor Markup (%)	Installation Charge	Total Cost per Item	Annualized Cost per Luminaire Type
1	$633.12	$69.16	$2,660.16	$316.03	$266.02	15%	$761	$5,297	$270.25
2	$633.12	$69.16	$2,394.15	$316.03	$266.02	15%	$761	$4,991	$254.64
3	$633.12	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,685	$239.03
4	$728.88	$69.16	$2,394.15	$316.03	$266.02	15%	$761	$5,101	$260.26
5	$728.88	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,795	$244.65
6	$728.88	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,795	$244.65
7	$633.12	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,685	$239.03
8	$728.88	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,795	$244.65
9	$728.88	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,795	$244.65
10	$1,165.15	$69.16	$2,394.15	$316.03	$266.02	15%	$761	$5,603	$285.85
11	$633.12	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,685	$239.03
12	$1,058.74	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$5,175	$264.00
13	$728.88	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,795	$244.65
14	$728.88	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$4,795	$244.65
15	$1,058.74	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$5,175	$264.00
16	$1,058.74	$69.16	$2,128.13	$316.03	$266.02	15%	$761	$5,175	$264.00

Table 13 Estimated Annual Maintenance Costs per Luminaire Type

Scenario #	Wattage	Parts	Cost	Service Cost per Unit	Rated Life (Hours)	First Maintenance Occurs (Years)	Second Maintenance Occurs (Years)	Present Value of Costs	Annualized Cost per Item	Annualized Cost per Luminaire Type
1	40	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
2	40	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
3	40	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
4	65	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
5	65	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
6	90	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
7	60	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$16.96
		LED Array	$266	$80	70,000	16.0	32.0	$214.06	$10.92	
8	65	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
9	90	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
10	180	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$28.38
		LED Array	$628	$80	70,000	16.0	32.0	$438.01	$22.34	
11	40	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
12	105	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$26.03
		LED Array	$553	$80	70,000	16.0	32.0	$391.90	$19.99	

13	65	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
14	90	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$19.32
		LED Array	$341	$80	70,000	16.0	32.0	$260.17	$13.27	
15	105	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$26.03
		LED Array	$553	$80	70,000	16.0	32.0	$391.90	$19.99	
16	150	Driver	$112	$80	70,000	16.0	32.0	$118.56	$6.05	$26.03
		LED Array	$553	$80	70,000	16.0	32.0	$391.90	$19.99	

Table 14 Estimated Annual Energy Consumption Costs for Luminaire Configuration

Scenario #	Luminaire Schedule	Total System Power Consumption (Watts)	Daily Hours of Operation	Total kWh per Year	Power Cost per kWh	Power Cost per Year
1	1@40W	47	12	205.86	$0.12	$24.70
2	1@40W	47	12	205.86	$0.12	$24.70
3	1@40W	47	12	205.86	$0.12	$24.70
4	1@65W	72	12	315.36	$0.12	$37.84
5	1@65W	72	12	315.36	$0.12	$37.84
6	1@90W	101.6	12	445.01	$0.12	$53.40
7	2@60W	136	12	595.68	$0.12	$71.48
8	2@65W	144	12	630.72	$0.12	$75.69
9	2@90W	201.1	12	880.82	$0.12	$105.70
10	1@180W	204	12	893.52	$0.12	$107.22
11	4@40W	188	12	823.44	$0.12	$98.81
12	2@105W	238	12	1042.44	$0.12	$125.09
13	4@65W	288	12	1261.44	$0.12	$151.37
14	4@90W	406.4	12	1780.03	$0.12	$213.60
15	4@105W	476	12	2084.88	$0.12	$250.19
16	4@105W	680	12	2978.40	$0.12	$357.41

Table 15 Estimated Total Annual Costs for Different Intersection Illuminance Level Groupings

Intersection Illuminance (Lux)	Luminaire Configuration	Annual Installation Costs	Annual Maintenance Costs	Annual Energy Costs	Total Annual Costs for Luminaire Configuration
2.58	1@40W	$270.25	$19.32	$24.70	$314.26
2.59–3.01	1@40W	$254.64	$19.32	$24.70	$298.66
3.02–3.55	1@40W	$239.03	$19.32	$24.70	$283.05
3.56–3.98	1@65W	$260.26	$19.32	$37.84	$317.42
3.99–4.74	1@65W	$244.65	$19.32	$37.84	$301.81
4.75–5.70	1@90W	$244.65	$19.32	$53.40	$317.37
5.71–7.10	2@60W	$478.06	$33.93	$71.48	$583.47
7.12–9.58	2@65W	$489.30	$38.63	$75.69	$603.62
9.59–11.41	2@90W	$489.30	$38.63	$105.70	$633.63
11.42–12.00	1@180W	$285.85	$28.38	$107.22	$421.46
12.28 – 14.32	4@40W	$956.12	$77.26	$98.81	$1,132.20
14.33 -15.39	2@105W	$528.01	$52.07	$125.09	$705.17
15.40 – 19.16	4@65W	$978.60	$77.26	$151.37	$1,207.23
19.17 – 22.93	4@90W	$978.60	$77.26	$213.60	$1,269.46
22.94 – 30.78	4@105W	$1,056.01	$104.13	$250.19	$1,410.33
30.79 – 44.13	4@105W	$1,056.01	$104.13	$357.41	$1,517.55

D.3 Benefit Analysis

The benefits of illuminating rural conventional intersections in Georgia were estimated from the observed reduction in various injury severity crash rates for different intersection illuminance levels in Georgia.

D.3.1 Estimating Crash Rate Reductions

Section C of this final report, *Estimation of the Safety Impact of Illumination at Rural Conventional Intersections in Georgia*, estimates crash rate reductions for different intersection illuminance levels compared to the unlit situation. The estimates are for only stop-controlled or uncontrolled rural intersections with a daily entry volume of at least 500 vehicles. The illuminance levels used were measured from 43 randomly selected intersections from around Cochran, Brunswick, Atlanta, and Dawsonville, Georgia. The crash records for these rural intersections were obtained from the GDOT crash database. The estimated total crash rate reductions for the different intersection illuminance levels are shown in Table 16. The data in Table 16 show that beyond an illuminance of 12 lux there is little or no benefit to additional illumination for rural conventional intersections in Georgia.

As explained in Section C, the sample size of available illuminated intersections was not enough to permit crash rate reduction analysis for different crash injury severities (fatal, severe, injury, possible injury, and PDO). Therefore, it is assumed that the estimated crash rate reductions for total crashes proportionately splits between the crash injury severity types based on their distribution within the entire Georgia crash database (2009–2014). The Georgia crash database includes three crash injury severity types: fatal, injury, and PDO. Table 17 gives the distribution of those three crash injury severity types in the database.

Table 16 Effect of Different Illumination Levels on Observed Nighttime Total Crash Rates at Rural Conventional Intersections in Georgia

Average Intersection Illuminance (Lux)	Expected Reduction in Nighttime Total Crash Rates Compared to the No Illuminance Condition
0	0.0
0.5	3.4
1.0	6.8
2.0	13.5
3.0	20.3
4.0	27.1
5.0	33.9
6.0	40.6
7.0	47.4
8.0	54.2
10.0	60.9
11.0	67.7
11.5	74.5
≥12.0	81.2

Table 17 Proportion of Crash Severities in Georgia

Injury Severity Type	Surveyed Intersections	All Rural Intersections
Fatal Crashes	0.02	0.01
Injury Crashes	0.27	0.27
PDO	0.71	0.72

The “injury” crashes shown in Table 17 are an aggregate of severe injury, injury, and possible injury severities. *Severe injury* refers to injuries where the victim requires transportation to the hospital. *Injury* refers to crashes where a victim is physically injured but requires no transportation to the hospital. *Possible injury* refers to crashes where no physical injury can be confirmed. Analysis of available crash data from the Georgia Governor’s Office of Highway Safety (www.gahighwaysafety.org/research/crash-injuries/) disaggregates injury crashes as shown in Table 18.

Table 18 Distribution of Injury Crash Severity in Georgia

Type of Injury	Proportion
Serious	**0.045**
Visible	**0.241**
Complaint	**0.714**

It should be noted that "serious injury" is equivalent to severe injury as described above, "visible injury" is equivalent to injury, and "complaint" is equivalent to possible injury. Therefore, the data in Table 17 and Table 18 were combined to yield the final distribution of nighttime injury severities at rural conventional intersections shown in Table 19.

Table 19 Distribution of Crash Severity Types within Nighttime Intersection Incidents in Georgia

Injury Severity	Proportion
Fatal	0.02
Severe	0.01
Injury	0.07
Possible Injury	0.19
PDO	0.71

These crash injury severity proportions will be used to apportion estimated crash reductions for total crashes.

D.3.2 Estimating Crash Injury Severity Costs at Rural Conventional Intersection

The cost for each crash injury severity was obtained from *The Economic and Societal Impact of Motor Vehicle Crashes, 2010 (*Revised), which was published by the National Highway Traffic Safety Administration in 2015 [*67*]. This document gives comprehensive unit costs, in year 2010 dollars, for the maximum abbreviated injury scale (MAIS), PDO, and fatal injuries. Table 20 presents the comprehensive unit costs for the different injury severities. To match the smaller injury severity scale available in the Georgia crash data MAIS 5 and MAIS 4 were combined as severe, MAIS 3 and MAIS 2 were combined as injury, and MAIS 1 and MAIS 0 were combined as possible injury. Since these costs are in year 2010 dollars, they were converted to year 2016 dollars to facilitate comparisons with the illumination costs. The conversion was done using available consumer price index factors [*66*]. Table 21 presents the final comprehensive unit costs for the injury severity scale used in the analysis.

Table 20 Comprehensive Accident Injury Severity Costs

Severity	Descriptor	Cost per Incident (2010 $)
Fatal	Fatal	5,348,855
MAIS 5	Critical	3,335,503
MAIS 4	Severe	1,433,442
MAIS 3	Serious	592,721
MAIS 2	Moderate	229,538
MAIS 1	Minor	29,660
MAIS 0		2,843
PDO	PDO	3,862

Table 21 Accident Severity Costs Applied to Georgia Crashes

Severity	Cost Per Injury (2010 $)	Cost Per Injury (2016 $)
Fatal	5,348,855	6,105,131
Severe	2,384,473	2,721,614
Injury	411,130	469,260
Possible Injury	16,252	18,550
PDO	3,862	4,408

Rural conventional intersection crashes in Georgia were analyzed to determine the number of nighttime fatalities per fatal crash and the number of nighttime injuries per injury crash. These results are shown in Table 22. Also shown in Table 22 is the comparable statistic on number of fatalities per fatal crash obtained from the Fatal Accident Reporting System (FARS). The number of injuries per injury crash was distributed among the three injury severity types based on proportions shown in Table 18.

Table 22 Number of Nighttime Fatalities and Injuries per Related Crash in Georgia

	Georgia Intersections	FARS
Fatalities/Fatality crash	1.1	1.08
Injuries/Injury crash	1.50	

D.3.3 Sample Benefit-to-Cost Analysis Results from Spreadsheet Model

To estimate the benefits and costs associated with illuminating rural conventional intersections in Georgia, the results described earlier were incorporated into a benefit–cost model. The model was encoded into a Microsoft Excel® spreadsheet workbook for ease of use in future work. This accompanying benefit–cost model can be used to compute benefit-to-cost ratios for different combinations of intersection illuminance, daily entering volume, and associated electrification costs (to bring power to the site). The spreadsheet can model up to 20 scenarios at a time. Operating instructions for the model are provided on the "Quick Start" tabs of the spreadsheet.

Figure 15 shows estimated benefit-to-cost ratios for different lighting levels at a typical intersection with a daily entry volume of 4000 vehicles. Various electrification cost scenarios of zero costs (no electrification required), $5,000 costs, $10,000 costs, $15,000 costs, $20,000 costs, $50,000 costs, and $100,000 costs are shown for each illuminance level. As can be expected, the benefit-to-cost ratios increase with decreasing electrification costs as well as increasing intersection illuminance. Also, the benefit to cost ratios are affected by the power consumption rating of the luminaire combination required to achieve a specific illuminance or illuminance range. This effect can be seen as a two-step function for the range of illuminance and luminaire combination represented in the Figure 15. The first step seems to include an illuminance range of 0 – 5 lux while the next step seems to include the illuminance range greater than 5 lux. Also, as stated earlier in *Section C: Estimation of the Safety Impact of Illumination at Rural Conventional Intersections in Georgia* there is no additional benefit to safety beyond an average intersection illuminance of 12 Lux. Consequently, Figure 15 shows decreasing benefit-cost ratios for illuminances higher than 12 Lux.

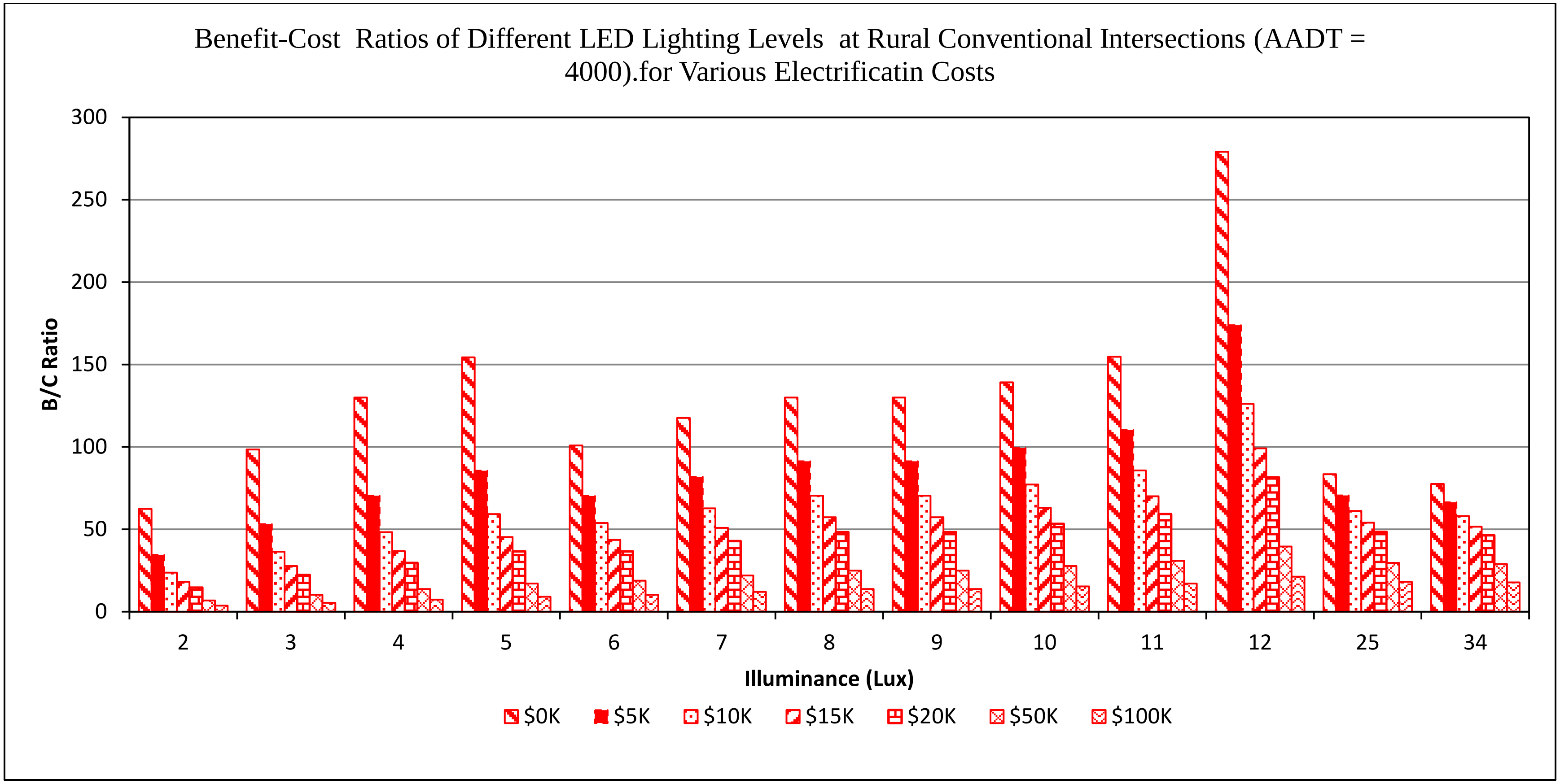

Figure 15 Benefit-Cost Ratios of Different LED Lighting Levels at Rural Conventional Intersections with 4000 AADT for Various Electrification Costs

Next, Figure 16 presents benefit–cost curves for different illuminance levels for an intersection with an assumed electrification cost of $100,000. Such curves and/or their underlying equations can be used to determine an adequate illumination level for an intersection based on its AADT and a target benefit–cost ratio. For example, a minimum benefit–cost ratio of 2.0 is usually accepted as an indication of an economically justified highway project. Table 23 shows the required intersection AADT for various illuminance levels for various electrification cost scenarios based on a target benefit-cost ratio of 2.0. These results show that basically all rural conventional intersections requiring no electrification would be economically justified for the dose-response range of intersection illuminances identified in this study, i.e., 0 – 12 lux. Consequently, for such intersections the decision on the adequate level of illuminance might depend on the agencies preference for either cost minimization or benefit maximization.

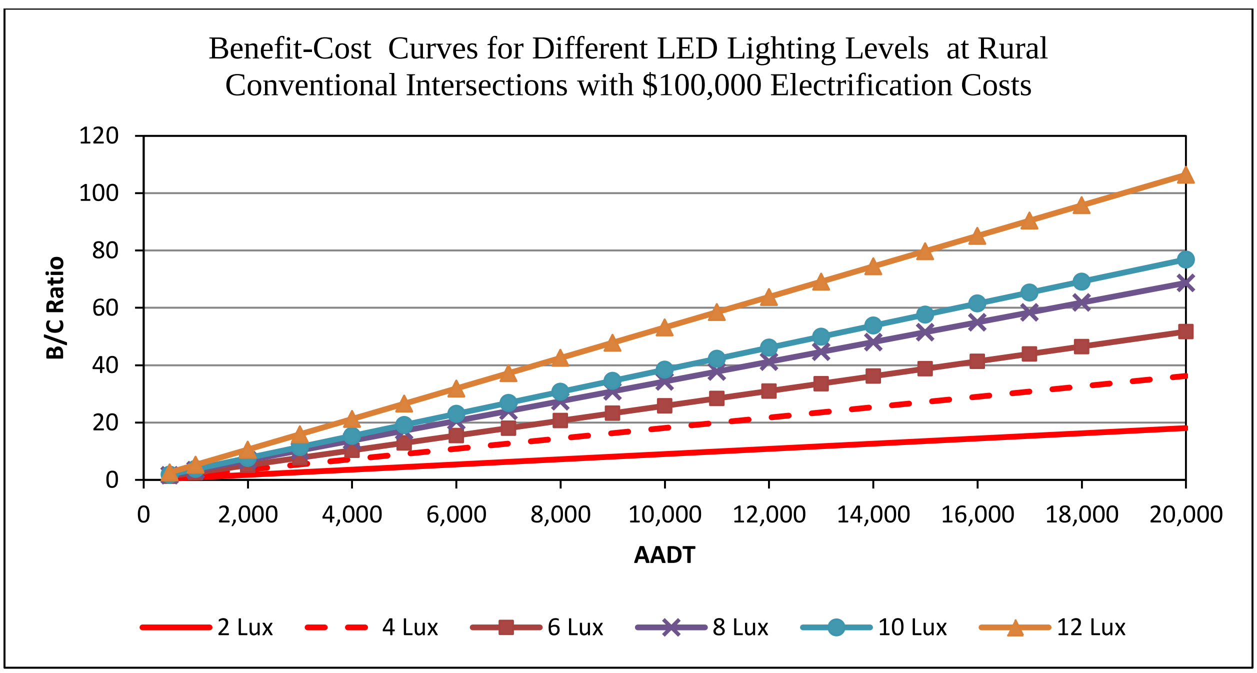

Figure 16 Benefit–Cost Curves for Different LED Lighting Levels at Rural Conventional Intersections with Electrification Costs of $100,000

Table 23 Required AADT at Rural Conventional Intersections for Different Illuminance Levels based on a Target Benefit to Cost Ratio of 2.0

Illuminance (Lux)	Cost of Electrification						No Electrification Needed
	$100K	**$50K**	**$20K**	**$15K**	**$10K**	**$5K**	**$0K**
2	2211	1169	545	441	336	232	128
4	1103	582	270	218	166	114	62
6	773	426	218	183	149	114	79
8	852	322	166	140	114	88	62
10	520	289	150	127	104	81	58
12	376	202	98	81	64	46	29

It is also possible to use the spread sheet to determine the required AADT to meet different economic justification goals (target benefit to cost ratios) for an intersection with a fixed electrification cost. Table 24 shows the required AADT to achieve benefit to cost ratios of 2.0, 5.0, and 20.2 respectively at intersection with an assumed electrification cost of $100,000.

Table 24 Required AADT at Rural Conventional Intersections to Meet Different Economic Justification Goals

Illuminance (Lux)	Economic Justification Goals		
	2.0	5.0	20.0
2	2,211	5,526	22,105
4	1,103	2,757	11,027
6	773	1,934	7,735
8	582	1,455	5,822
10	520	1,301	5,203

12	376	940	3,760

D.4 Summary of Benefit-to-Cost Analysis

This report presents results of analyses performed to determine the benefit-to-cost ratios of rural conventional intersection illumination in Georgia. The analysis uses illumination crash modification factors estimated from Section C: *Estimation of Safety Impact of Illumination at Rural Conventional Intersections in Georgia*. Intersection illumination power consumption and luminaire configuration were determined using DIALux®, a professional lighting design software.

The analysis further considers various electrification cost scenarios; no cost scenario representing an intersection location with ready power, $5,000, $10,000, $15,000, $20,000, $50,000, and a $100,000 electrification cost scenario. Electrification costs are assumed to include actual cost for the electrical equipment and materials to bring power to the site as well as additional costs occurred in the relocation of utilities.

Based on an assumed economic justification criterion, with a benefit-cost ratio of 2.0, the study finds that illumination will generally be cost-effective as a safety treatment at rural conventional intersections requiring no or little electrification costs. This finding is based on the dose-response range of intersection illuminance identified in this study, i.e., 0 - 12 Lux. For locations requiring no electrification, an agency might decide on the adequate illumination level based on either a cost minimization or benefit maximization objective.

In the case of rural conventional intersections requiring electrification, the adequate or cost-effective lighting level is dependent on the AADT. Therefore, intersections must be evaluated on an individual basis.

The analysis for these individual evaluations can be facilitated by the accompanying Microsoft Excel® spreadsheet model. Instructions on how to use the spreadsheet model are provided on the "Quick Start" tabs of the spreadsheet.

PROJECT SUMMARY AND RECOMMENDATIONS

The major goal of this research study is to determine the cost-effectiveness of illumination at uncontrolled and stop-controlled rural intersections in Georgia. This report consolidates three parallel studies that were performed to meet this goal. These three parallel studies have been presented in Sections B, C, and D.

Section B presents results of a survey of DOTs to understand their current rural intersection illumination practices. The survey results from 24 responding states revealed four key characteristics of rural illumination practices among DOTs:

a) Most DOTs use published illumination guidance and standards. The overwhelming majority use either the guidance from the Illuminating Engineering Society of North America or the standard from the American Association of State Highway and Transportation Officials.
b) Most DOTs currently use standard lighting in rural areas when lighting is deemed necessary.
c) There is not much activity among DOTs in terms of studies to determine the applicability of published illumination crash modification factors to their local conditions.
d) Most DOTs do not include an actual cost-effectiveness analysis in decision making for rural intersection illumination projects. Most often, DOTs measure cost-effectiveness in terms of either an overall minimization of project costs or existence of potential safety benefits.

The results of Section C, *Estimation of the Safety Impact of Illumination at Rural Conventional Intersections in Georgia,* show overwhelming evidence that lower illumination levels than those included in the existing lighting standards/guidelines would also provide significant benefits. The existing guidelines prescribe recommended lighting levels ranging from about 8 lux to 34 lux for intersections. However, the findings from this study show that beyond a dose-response range of 0–12 lux there is basically little or no benefit to illuminating rural intersections.

The third parallel study, *Benefit-to-Cost Analysis of Conventional Rural Intersection Illumination in Georgia*, is presented in Section D. The findings from this study indicate that for rural intersection locations that require no electrification, basically any illumination level within the dose-response range identified in this study will be cost-effective for any entering AADT. However, locations that require electrification need to be evaluated based on the overall costs, entering AADT, existing crash rate, and a target benefit-to-cost ratio that signifies the level of cost-effectiveness required by the state DOT. Consequently, a spreadsheet benefit-to-cost model has been developed as part of the study to facilitate the cost-effectiveness analysis at any rural uncontrolled or stop-controlled intersection.

Generally, the findings support other published studies which have indicated that lower illumination levels could be used on roads without compromising safety [*44*, *50*]. However, if researchers are to develop reliable guidance, it will be necessary to include more intersections in the analysis.

There is a strong need to improve both asset management and crash reporting systems to facilitate these important safety studies. There is currently no systematic way of identifying if a particular intersection (both rural and urban) in Georgia is illuminated and, if it is, the type and nature of the lighting devices. A complete and accurate asset management system for road segments and intersections, which is electronically linked to crash data, would help in developing a reliable guidance. At the least, a simplified version in the form of a lighting and intersection database system that gives lighting information (the installation date, luminaire type, mounting height, number of luminaires, luminaire location, and, if available, the illuminance level), as well as intersection characteristics (number of lanes, lane width, presence of horizontal curve on upstream approach, presence of vertical curve on upstream approach, posted speed, skew angle, etc.) would be needed. It is recommended that GDOT partners with other municipal and city transportation agencies to develop a database of measured installed illumination levels at intersections, roundabouts etc.

Also, with the design of this current study it is difficult to control for possible selection bias due to other safety improvements which may have been installed together with illumination. This limitation means that the findings must always be interpreted with caution because the significance of this limitation is unknown. Therefore, it is recommended that a future study be implemented that will ensure that no other safety improvement factor other than illumination is present at study sites. This will require a number of sites without purposely-built illumination to be randomly selected with the same criteria. Half of these sites will then have illumination installed while the other half will serve as a control group. No other safety improvement would be implemented at the study and control intersections within the study years. These two groups would then be studied when at least 3 years of post-deployment crash data are available.

REFERENCES

1. National Highway Traffic Safety Administration. Traffic Safety Facts 2012: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and General Estimates System. DOT HS 812 032. Washington, DC. 2012.

2. Al-Ghamdi, A.S., Analysis of Traffic Accidents at Urban Intersections in Riyadh. In *Accident Analysis & Prevention, No. 35*(5), 2003, p.p 717-724.

3. Montella, A., Identifying Crash Contributory Factors at Urban Roundabouts and Using Association Rules to Explore Their Relationships to Different Crash Types. In *Accident Analysis and Prevention, No. 43*, 2011, p.p 1451-1463.

4. Neuman, T., R. Pfefer, K. Slack, D. Hardwood, I. Potts, D. Torbic and E. Rabbani. Guidance for Implementation of the Aashto Strategic Highway Safety Plan Volume 5: A Guide for Addressing Unsignalized Intersection Collisions. NCHRP Report 500, 2003. Transportation Research Board of the National Academies, Washington DC

5. Retting, R., R. Ulmer and A. Williams, Prevalence and Characteristics of Red Light Running Crashes in the United States. In *Accident Analysis & Prevention, No. 31,* 1999, p.p 687-694.

6. AASHTO, *Highway Safety Manual, 1st Ed. Vol 1*. 2010, American Association of State Highway and Transportation Officials, Washington DC.

7. Niaki, M., N. Saunier, L. Miranda-Moreno, L. Amador and J.-F. Bruneau, Method for Road Lighting Audit and Safety Screening at Urban Intersections. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2458*, 2014, p.p 27-36.

8. Donnell, E.T., R.J. Porter and V.N. Shankar, A Framework for Estimating the Safety Effects of Roadway Lighting at Intersections. In *SAFETY SCIENCE, No. 48*(10), 2010, p.p 1436-1444.

9. Donnell, E., R.J. Porter, V.N. Shankar, F. Gross, W. Hu, M. Gemar and J. Oh. Estimating the Safety Effects of Roadway Lighting at Intersections: A Cross-Sectional Study Approach. *90th Annual Meeting of the Transportation Research Board*. 2011. Washington D.C.: Transportation Research Board.

10. Rea, M., J. Bullough, C. Fay, J. Brons, J. Derlofske and E. Donnell. Review of the Safety Benefits and Other Effects of Roadway Lighting. NCHRP 5-19, 2009. NCHRP, Washington, DC.

11. Bullough, J., J. Snyder, N. Skinner, R. Capo, P. Rizzo and U. Besenecker. Demonstration and Evaluation of New Approaches for Roundabout Lighting. *Transportation Research Board 93rd Annual Meeting*. 2014. Washington, DC.

12. Bruneau, J.F. and D. Morin, Standard and Nonstandard Roadway Lighting Compared with Darkness at Rural Intersections. In *Transportation Research Record: Journal of the Transportation Research Board*, *No*. *1918*, 2005, p.p 116-122.

13. Walker, F.W. and S.E. Roberts, Influence of Lighting on Accident Frequency at Highway Intersections. In *Transportation Research Record*, *No*. (562), 1976, p.p 73-78.

14. Marks, V. Effects of Reduced Intersection Lighting on Nightime Accident Frequency. Project HR-1003A, 1977. Iowa Department of Transportation

15. Preston, H. and T. Schoenecker. Safety Impacts of Street Lighting at Isolated Rural Intersections. 1999-17, 1999. Minnesota Department of Transportation

16. Green, E.R., K.R. Agent, M.L. Barret and J.G. Pigman. Roadway Lighting and Driver Safety. KTC-03-12/SPR247-02-IF, 2003.

17. Isebrands, H., S. Hallmark, W. Li, T. McDonald, R. Storm and H. Preston, Roadway Lighting Shows Safety Benefits at Rural Intersections. In *Journal of Transportation Engineering*, *No*. *136*(11), 2010, p.p 949-955.

18. Wortman, R.H. and M.E. Lipinski. Rural at-Grade Intersection Illumination. 1974.

19. Lipinski, M.E. and R.H. Wortman, Effect of Illumination on Rural at-Grade Intersection Accidents. In *Transportation Research Record*, *No*. (611), 1978, p.p 3.

20. Isebrands, H., S. Hallmark, Z. Hans, T. McDonald, H. Preston and R. Storm. Safety Impacts of Street Lighting at Isolated Rural Intersection - Part 2. MN/RC-2006-35, 2006. Minesota Department of Transportation,

21. Hallmark, S., N. Hawkins, S. Omar, Z. Hans, C. Kinsenbaw, M. Orellano and H. Isebrands. Strategies to Address Nighttime Crashes at Rural, Unsignalized Intersections. 2008. Center for Transportation and Education, Iowa State University

22. Donnell, E. Statistical Issues in Relating Roadway Lighting to Safety. *Transportation Research Board 94th Annual Meeting*. 2015. Washington, DC.

23. Per Ole, W., Effects of Road Lighting: An Analysis Based on Dutch Accident Statistics 1987–2006. In *Accident Analysis and Prevention, No. 41*, 2009, p.p 123-128.

24. Retting, R., B. Persaud, P. Garder and D. Lord, Crash and Injury Reduction Following Installation of Roundabouts in the United States. In *American Journal of Public Health, No. 91*(4), 2001, p.p 628 - 631.

25. Hauer, E. Cause and Effect in Observational Cross-Sectional Studies in Road Safety. *Transportation Research Board Annual Meeting*. 2005.

26. Hauer, E., *Observational before-after Studies in Road Safety*. 1997, Pergamon, , Oxford, OX, U.K. ; Tarrytown, N.Y., U.S.A.

27. Persaud, B. and C. Lyon, Empirical Bayes before–after Safety Studies: Lessons Learned from Two Decades of Experience and Future Directions. In *Accident Analysis & Prevention*, *No. 39*(3), 2007, p.p 546-555.

28. Bo, L., P. Bhagwant, L. Craig and B. Ravi, Validation of a Full Bayes Methodology for Observational before-after Road Safety Studies and Application to Evaluation of Rural Signal Conversions. In *Accident Analysis & Prevention, No. 41*, 2009, p.p 574-580.

29. Gross, F., C. Lyon, B. Persaud and R. Srinivasan, Safety Effectiveness of Converting Signalized Intersections to Roundabouts. In *Accident Analysis and Prevention*, *No. 50*, 2013, p.p 234-241.

30. Zhou, H.G., F. Pirinccioglu and P. Hsu, A New Roadway Lighting Measurement System. In *Transportation Research Part C-Emerging Technologies, No. 17*(3), 2009, p.p 274-284.

31. Illuminating Engineering Society, *Design Guide for Roundabout Lighting*. 2008, Illuminating Engineering Society of North America: New York.

32. International Commission on Illumination, *Cie 115:2010 Lighting of Roads for Motor and Pedestrian Traffic 2nd Edition*. 2010, CIE Central Bureau: Austria.

33. Illuminating Engineering Society, *Roadway Lighting* 2000, Illumination Engineering Society of North America: New York.

34. CEN, Road Lighting - Part 3: Calculation of Performance. In, 2008c.

35. Bassani, M. and G. Mutani, Effects of Environmental Lighting Conditions on Operating Speeds on Urban Arterials. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2298*(-1), 2012, p.p 78-87.

36. Fotios, S., P. Boyce and C. Ellis. The Effect of Pavement Material on Road Lighting Performance. PPAD 9/100/77 2005. UK

37. Casol, M., P. Fiorentin and A. Scroccaro. On Road Measurements of the Luminance Coefficient of Paving. *16th IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements,* . 2008. Florence, Italy.

38. Uncu, I. and M. Kayaku, Analysis of Visibility Level in Road Lighting Using Image Processing Techniques. In *Scientific Research and Essays, No. 5*(18), 2010, p.p 6.

39. Cobb, J., R.A. Hargroves, A.M. Marsden and P. Scott. Road Lighting and Accidents. *Meeting of the International Commision on Illumination (CIE)*. 1979. Kyoto, Japan.

40. Green, J. and R.A. Hargroves, A Mobile Laboratory for Dynamic Road Lighting Measurement. In *Lighting Research & Technology, No*. (11), 1979, p.p 7.

41. Hargroves, R.A. and P. Scott, Measurements of Road Lighting and Accident Results. In *Public Lighting, No*. (44), 1979, p.p 8.

42. Scott, P. The Relationship between Road Lighting Quality and Accident Frequency. LR 929, 1980.

43. International Commission on Illumination. Road Lighting as an Accident Countermeasure. Publication No. 93, 1992. Central Bureau of the CIE, Vienna

44. Oya, H., K. Ando and H. Kanoshima, A Research on Interrelation between Illuminance at Intersections and Reduction in Traffic Accidents. In *Journal of Light & Visual Environment*, *No. 26*(1), 2002, p.p 1_29-1_34.

45. Minoshima, O., K. Oka, K. Ikehara and N. Inukai. Research on Accident Reduction by Intersection Lighting. *Road Engineering Association of Asia and Australia (REAAA)*. 2006. Philippines.

46. Medina, J., K. Avrenli and R. Benekohal, Field and Software Evaluation of Illuminance from Led Luminaires for Roadway Applications. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2384*(-1), 2013, p.p 55-64.

47. Schmidt, S., S. Long and J. Harper. Economic and Technical Feasibility of Led Lighting on State Routes in Missouri. *Transportation Research Board 93rd Annual Meeting*. 2014. Washington, DC: Transportation Research Board.

48. Jackett, M. and W. Frith, Quantifying the Impact of Road Lighting on Road Safety — a New Zealand Study. In *IATSS Research*, *No. 36*(2), 2013, p.p 139-145.

49. Bhagavathula, R., R. Gibbons and C. Edwards, Relationship between Roadway Illumination Level and Nighttime Rural Intersection Safety. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2485*, 2015, p.p 8.

50. Gibbons, R., F. Guo, J. Du, A. Medina, P. Lutkevich, T. Terry and Q. Li. Linking Road Lighting and Crash Safety. *Transportation Research Board 94th Annual Meeting*. 2015. Washington, DC.

51. Box, P. Relationship between Illumination and Freeway Accidents. 1970. Illuminating Research Institute, New York

52. Griffith, M., *Comparison of the Safety of Lighting Options for Urban Freeways*, in *Public Roads*. 1994, Federal Highway Administration: Washington, DC.

53. FHWA. The 1994 Annual Report on Highway Safety Improvement Programs. 1994. O.o.S. U.S. Department of Transportation Federal Highway Administration, Washington, DC

54. FHWA. The 1996 Annual Report on Highway Safety Improvement Programs. 1996. U.S. Department of Transportation Federal Highway Administration Office of Safety, Washington, DC

55. Painter, K. and D. Farrington, The Financial Benefits of Improved Street Light, Based on Crime Reduction. In *Lighting Research & Technology*, *No. 33*(1), 2001, p.p 3 - 12.

56. Illuminating Engineering Society. Lm 5099 - Iesna Guide for Photometric Measurement of Roadway Lighting Installations. 1999.

57. Nicholas, J. A Road Lighting Survey Method for Accidents Sites. Report No. 4, 1991.

58. Wuller, D. and H. Gabele. The Usage of Digital Cameras as Luminance Meters. 2007. Place of Publication: San Jose, CA, USA. Country of Publication: USA.: SPIE - The International Society for Optical Engineering.

59. Hiscocks, P. and P. Eng, Measuring Luminance with a Digital Camera. In, 2011.

60. Inanici, M.N., Evaluation of High Dynamic Range Photography as a Luminance Data Acquisition System. In *Lighting Research and Technology*, *No. 38*(2), 2006, p.p 123-136.

61. Gbologah, F., *The Impacts of Illumination Level on Nighttime Safety at Roundabouts*, in *School of Civil & Environmental Engineering*. 2015, Georgia Institute of Technology: Atlanta, GA. p. 425.

62. Gbologah, F., A. Guin, R. Purcell and M. Rodgers. Calibration of a Digital Camera for Rapid Auditing of in-Situ Intersection Illumination. *95th Annual Meeting of the Transportation Research Board*. 2016. Washington, DC: Transportation Research Board.

63. Georgia Governor's Office of Highway Safety. *Crash Injuries*. http://www.gahighwaysafety.org/research/crash-injuries/ Accessed. 7/14/2014

64. Gresham Smith and Partners. Lighting Operation and Maintenance Study. Project CSSFT-0008(534), 2013. Georgia Department of Transportation,

65. Illuminating Engineering Society. Roadway Lighting Ansi/Ies Rp 8-14. RP 8-14, 2014. I.E. Society,

66. Sahr, R. Consumer Price Index (Cpi) Conversion Factors 1774 to Estimated 2023. 2013. Political Science Department, Oregon State University.

67. Blincoe, L., J. Miller, R. Zaloshnja and B. Lawrence. The Economic and Societal Impact of Motor Vehicle Crashes, 2010. (Revised). Report No. DOT HS 812 013, 2015. N.H.T.S. Administration, Washington, DC

APPENDIX: SURVEY QUESTIONNAIRE

Name of State:..
Name of Safety Engineer interviewedd:...
Phone contact:...
Email:...

A1. Does your state follow developed standards/guidance on the illumination conventional intersections (not roundabouts)?

a) Yes
b) NO

A2. If Yes, what are the standards

a) AASHTO roadway lighting design guide
b) ANSI/IES-RP-8 (Roadway Lighting)
c) State Specific. (Name..)
d) Other. (Name...)

A3. What is your state's policy concerning rural intersection illumination?

....
....
....
....
....
....
....

A4. Do you sometimes use non-standard illumination?

a) Yes
b) No

A5. If Yes, how is the decision for standard and non-standard illumination made?

Standard lighting: ....
....
....

Non-standard lighting: ....
....
....

A6. Is cost-effectiveness considered in the design process for rural intersections illumination?

a) Yes
b) No

A7. If Yes, how is cost-effectiveness considered?

....
....
....
....

....
....

A8. Does your state utilize other alternatives to illumination for nighttime safety at rural intersections?

a) Yes
b) No

A9. If Yes, Can you kindly list these other alternatives (preferably in the order of most effective first) and the conditions where may be used?

a) ....
b) ....
c) ....
d) ....
e) ....

Use a different sheet if there are more than five alternatives

A10. Has you state found any relationship between illumination levels and observed crashes and/or injury severities at rural intersections?

....
....
....
....
....

A11. Does your state have any published figures on costs of illumination or nighttime safety treatment for different types of rural intersections? If Yes, please name the reports/documents

....
....
....
....
....

A12. Do you know if changes to your department's intersection illumination policy are being considered?

a) Yes
b) No