TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle
Minimum Intersection Illumination

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5. Report No.
FHWA/LA. 22/677

6. Report Date
February 2023

7. Performing Organization Code
LTRC Project Number: 20-3SA
SIO Number: DOTLT1000373

8. Type of Report and Period Covered
Final Report
May 2021 – Oct. 2022

9. No. of Pages
113

10. Supplementary Notes
Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

11. Distribution Statement

12. Key Words
Street lighting; traffic safety at nighttime; roundabouts; stop-controlled intersection; rural area; crash data analysis; driving simulator experiment; online national survey

13. Abstract

Numerous prior studies indicated that street lighting improves nighttime traffic safety. However, lighting at unsignalized intersections (e.g., stop-controlled intersections and roundabouts) is not mandatory in some states such as Louisiana. This study aimed to examine whether Louisiana has traffic safety problems due to lack of lighting at its rural and suburban roundabouts and stop-controlled intersections. Underlying this goal, this study set out to (1) record the lessons learned from other states that had implemented partial or full lighting policies or other potentially low-cost countermeasures at their intersections; (2) explore whether the lighting at intersections has a significant impact on the behavior and safety of drivers; and (3) determine the viability of installing lighting at these types of intersections in Louisiana. To achieve these goals, four different approaches were employed: (1) crash data analysis, (2) online national survey among professionals working at the departments of transportation (DOTs) in the US, (3) driving simulator experiment, and (4) cost-benefit analysis.

The results of crash data analysis showed that lighting was not a significant contributing factor to crashes at both types of intersections. In addition, the findings of the survey indicated that lighting at stop-controlled intersections is not mandatory for almost 72% of the participated states; whereas, it is mandatory for roundabouts according to about 67% of the responding states. Furthermore, speeding (22.4%) and driving under the influence (18.8%) were the reported primary reasons for nighttime crashes at roundabouts and stop-controlled intersections, respectively. The reported low-cost countermeasures used in other states to improve safety at unsignalized intersections during nighttime include using reflective pavement markings, reflective pavement markers, larger traffic signs, double signs, blinker signs, and advanced warning. In the driving simulator experiment, participants drove under four different lighting conditions (during daytime, nighttime without lighting, nighttime with partial lighting, and nighttime with full lighting) at both stop-controlled intersections and roundabouts. Several driving behavior measures such as time to collision (TTC) "as a surrogate safety measure," speed, acceleration, and deceleration were collected and analyzed. The results revealed that participants were able to notice pedestrians crossing the intersections and reduce their speed accordingly during daytime, partially and fully lighting conditions at stop-controlled intersection compared to unlighted condition, which is evident by looking at the TTC, 15.5 seconds (s), 5.4s and 5.1s, respectively. However, no significant difference for TTC at different lighting conditions was noticed at the roundabouts. The final approach involved conducting a cost-benefit analysis considering the cost of providing full street lighting and the expected benefits of reduced number and/or severity of crashes. The results showed that providing street lighting at rural and suburban roundabouts in Louisiana is not feasible as none of the nighttime crashes that occurred at those roundabouts during the last 5 years were due to lack of lighting. However, the findings indicated that the expected benefits of installing lighting at stop-controlled intersections in rural and suburban areas outweighed the associated installation and maintenance. The benefits-to-cost ratio (BCR) for stop-controlled intersections was 4.6. The findings of the study indicate that Louisiana does not seem to have a traffic safety problem due to lack of street lighting at its rural and suburban stop-controlled intersections and roundabouts. Therefore, it is concluded that providing street lighting at those type of intersections may be warranted based on traffic safety analysis (e.g., when the intersection has on average at least one nighttime fatal or injury crash per year over a three-year period). However, if lighting is warranted but lighting installation is not feasible due to lack of funding or site constrains, then it is recommended to install other low-cost countermeasures such as reflective pavement markings, reflective pavement markers, larger traffic signs, double signs, blinker signs and, advanced warning.

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Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

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Minimum Intersection Illumination

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LTRC Project No. 20-3SA
SIO No. DOTLT1000373

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

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The results of crash data analysis showed that lighting was not a significant contributing factor to crashes at both types of intersections. In addition, the findings of the survey indicated that lighting at stop-controlled intersections is not mandatory for almost 72% of the participated states; whereas, it is mandatory for roundabouts according to about 67% of the responding states. Furthermore, speeding (22.4%) and driving under the influence (18.8%) were the reported primary reasons for nighttime crashes at roundabouts and stop-controlled intersections, respectively. The reported low-cost countermeasures used in other states to improve safety at unsignalized intersections during nighttime include using reflective pavement markings, reflective pavement markers, larger traffic signs, double signs, blinker signs, and advanced warning. In the driving simulator experiment, participants drove under four different lighting conditions (during daytime, nighttime without lighting, nighttime with partial lighting, and nighttime with full lighting) at both stop-controlled intersections and roundabouts. Several driving behavior measures such as time to collision (TTC) "as a surrogate safety measure," speed, acceleration, and deceleration were collected and analyzed. The final approach involved conducting a cost-benefit analysis considering the cost of providing full street lighting and the expected benefits of reduced number and/or severity of crashes. The results showed that providing street lighting at rural and suburban roundabouts in Louisiana is not feasible as none of the nighttime crashes that occurred at those roundabouts during the last 5 years were due to lack of lighting. However, the findings indicated that the expected benefits of installing

lighting at stop-controlled intersections in rural and suburban areas outweighed the associated installation and maintenance. The benefits-to-cost ratio (BCR) for stop-controlled intersections was 4.6. The findings of the study indicate that Louisiana does not seem to have a traffic safety problem due to lack of street lighting at its rural and suburban stop-controlled intersections and roundabouts. Therefore, it is concluded that providing street lighting at those type of intersections may be warranted based on traffic safety analysis (e.g., when the intersection has on average at least one nighttime fatal or injury crash per year over a three-year period). However, if lighting is warranted but lighting installation is not feasible due to lack of funding or site constrains, then it is recommended to install other low-cost countermeasures such as reflective pavement markings, reflective pavement markers, larger traffic signs, double signs, blinker signs, and advanced warning.

Acknowledgments

The authors would like to thank LTRC and DOTD for supporting this project. We would like to express our special thanks to the Project Review Committee as well as LTRC's Safety Research Manager Elisabeta Mitran, Ph.D., who gave us support and direction throughout the entire project.

In addition, we would also like to acknowledge and appreciate the contribution of DOT professionals who participated in the online survey and individuals who participated in the driving simulator experiment.

Implementation Statement

This study performed an in-depth analysis to investigate the impact of intersection lighting on traffic safety and driving behavior at roundabouts and stop-controlled intersections in rural and suburban areas. This study analyzed different datasets including traffic crashes, national survey, driving simulation experiment, and cost-benefit analysis. The main objectives were to (1) investigate whether Louisiana has a traffic safety problem due to lack of street lighting at stop-controlled intersections and roundabouts in rural and suburban areas, (2) document lessons learned from other states and to determine low-cost countermeasures used to improve safety at those intersections at nighttime, (3) examine the impact of intersections' lighting on drivers' behavior and safety, and (4) evaluate the feasibility of providing street lighting to stop-controlled intersections and roundabouts. The findings from this study provide transportation and traffic safety authorities in Louisiana with valuable insights regarding the performance of its unsignalized intersection in terms of traffic safety. Also, it suggests low-cost countermeasures that can help in improving traffic safety at roundabouts and stop-controlled intersections in rural and suburban areas during nighttime.

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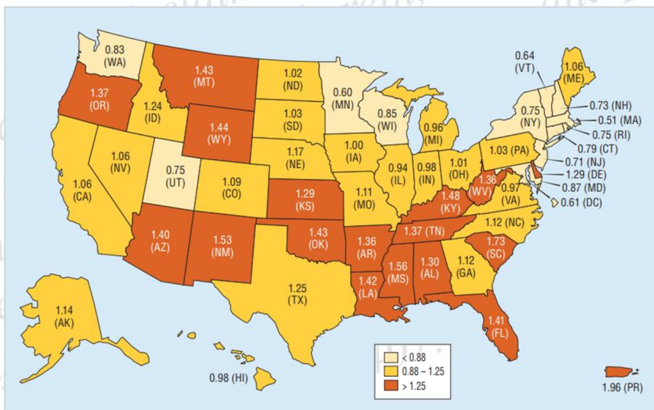
Introduction

Although statistics showed that only 25% of traffic travel occurs at night compared to daytime, the chance of a fatal crash occurring at night is three times higher. Indeed, drivers tend to travel at higher speeds at nighttime due to the low density of traffic, which makes it difficult for them to react appropriately when a hazardous situation suddenly appear specially along dark segments of the road [1]. In Louisiana, a total of 2,275 crashes were recorded at nighttime between 2010 – 2020 [2]. Some of those crashes may be attributed to unlit roadway conditions. Furthermore, the 2019 Facts Sheet by the National Highway Traffic Safety Administration (NHTSA) reported that Louisiana is among the highest fatality rates per 100 million vehicle miles traveled (VMT) in the United States (US) at 1.42 as shown in Figure 1 [3].

Figure 1. Fatality rates per 100 million VMT by state [3]



However, according to the current road design manual of Louisiana, lighting is not mandatory for intersections including roundabouts [4]. Therefore, the main objective of this study was to examine whether Louisiana has traffic safety problems due to lack of lighting at its intersections, particularly at roundabouts and stop-controlled intersections, in rural and suburban areas. Underlying this objective, this study aimed to investigate if intersections' lighting has significant impact on drivers' behavior and to document lessons learned from states who have adopted partial or full lighting policies or other potentially low-cost countermeasures at their intersections. To better achieve these objectives, four different approaches were employed in this study: (1) document lessons learned from other states through a national survey study conducted among professionals working at US DOTs, (2) conduct a crash data analysis (3) design and undertake a driving simulator experiment, and (4) conduct a cost-benefits analysis.

The next section of this report presents the outcomes of the review of previous studies related to street lighting and its impact on nighttime traffic safety. In addition, this report discusses the outcomes of the online survey that was designed and conducted among a sample of professionals working at roadway lighting and traffic safety departments in various US state DOTs to gather their feedback and insights regarding the adopted lighting schemes and the low-cost countermeasures applied at their states to reduce crash rates at nighttime due to lack of lighting.

Furthermore, this report describes the methodology that was followed to conduct crash data analysis on the sample of traffic collisions that occurred in Louisiana in the five years period from 2016 – 2020 along with the results and conclusions. The main purpose of the crash data analysis was to investigate whether Louisiana has a traffic safety problem due lack of lighting at its intersections as well as to identify the contributing factors affecting the occurrence and severity of traffic crashes at night. The analysis included conducting summary statistics, cross sectional analysis comparing crashes occurring at both lit and unlit intersections, multivariate analysis (MVA) including Poisson regression, and negative binomial models.

This report also presents the outcome of a driving simulator study that was conducted at LSU's driving simulator lab. The experiment consisted of two parts: part one included roadway environment consisting of several stop-controlled intersections while part two included roadway environment consisting of several roundabouts. The surrounding environment was built in a rural setting as will be discussed later in more detail. Participants drove through the experiments at different street lighting conditions (intersections had full lighting, partial lighting, and no lighting at all). Several events were introduced to participants at these different conditions (e.g., pedestrians crossing the intersections). Acceleration, deceleration, speed, and time to collision (TTC) data of all participants were collected and analyzed to examine whether street lighting had an impact on drivers' behavior.

Moreover, a cost-benefit analysis was conducted to assess the feasibility of installing street lighting at stop-controlled intersections and roundabouts located in rural and suburban areas. Considering previous studies, the research team compared the costs of providing street lighting with the expected benefits (in monetary value) of reduced crash frequencies and/or severity. Accordingly, the benefit-cost ratios were estimated using different street lighting costs reported by other states in the national survey.

Literature Review

In this task, the research team conducted a comprehensive literature review of the most relevant studies and manuals to street lighting. Some of the reviewed studies were conducted using crash data analysis while others were performed using driving simulation and field experiments. In addition, few studies were conducted using cost-benefit analysis. This section discusses the outcomes of this task and is divided into the following four sections:

- Section 1: discusses the evaluation of street lighting on traffic safety at night,
- Section 2: discusses the specifications and guidelines of different state DOTs,
- Section 3: discusses previous driving simulations and field experiments research on the impact of intersections' lighting on driver behaviors, and
- Section 4: discusses the outcomes of previous cost - benefit analysis related to intersections' lighting

Section 1: Evaluation of Street Lighting on Traffic Safety at Night

Li et al. (2020) explained the benefits of lighting intersections in increasing the safety of the roadway. The objective of that study was to establish more specific lighting guidelines in order to better apply lighting at intersections where it would help reduce crashes the most. Crash data and lighting data were obtained from 242 intersections. To find which variables were most responsible for decreasing the crash rates, a negative binomial regression was used. Three-parameter exponential curves were then utilized to determine the ideal lighting level at a particular intersection. The three-parameter exponential function supported the fact that as lighting levels increase, the nighttime crashes reduce. However, this is only up to a certain point. Once the lighting reached a certain brightness, the number of nighttime crashes stayed stagnant. Therefore, determining this ideal brightness helps decision makers save energy costs while also maintaining the safety of the intersection. Accordingly, it was determined that signalized intersections that were unlighted had a 69% higher night-to-day crash ratio than lighted intersections. Likewise, unsignalized intersections that were unlighted had 27% higher night-to-day crash ratios than their lighted counterparts. Further, it was deduced that a 1 lux increase in lighting decreased the night-to-day crash ratio by 2.9%; however, this relationship was only valid from the values of 0 lux to 27 lux. It was found also that a 1 unit increase in the illuminance uniformity at the intersection is correlated to a 1.9% increase in the night-to-day crash ratio. The result suggests that as the uniformity increases, the average illuminance decreases, which as expected raises the night-to-day crash ratio. These findings further support the claim that lighting is pivotal in increasing the safety of intersections at night. The authors also recommended that VDOT adopt the guidelines obtained from this study in order to decrease the number of nighttime crashes at intersections [5].

Wang and Zou (2016) conducted a study on highway illumination to determine the effectiveness of other sources of light on state highways. The main objective was to outline Washington State DOT (WSDOT) guidelines on illumination and provide information on current and potentially better illumination solutions in order to have better lighting design guidelines for highway illumination that is also cost effective. Data for this study was obtained through literature review of other sources on illumination guidelines and standards. The study summarized the requirements for lighting according to different state lighting guidelines then explored the current illumination technology to better understand the effectiveness of other lighting solutions. It was found that newer light-emitting diode (LED) lights greatly reduced energy and maintenance costs compared to something like high-pressured sodium (HPS) lamps. For example, Carrollton, Georgia partnered with cooper Lighting to replace old HPS lamps with newer LEDs. After the replacement, it was estimated that $2,600 would be saved annually. Further, on a much larger scale, the 4,342 metal-halide fixtures in Hartsfield-Jackson Atlanta international airport were swapped with newer Cooper LEDs. This led to an estimated savings of $500,000 annually. Further, the authors note that when comparing LED lighting to HPS lighting, LED is not only cost effective but also provides a more uniform light that is safer [6].

Edwards (2015) examined the relationship between lighting levels and road safety. Lighting levels at selected rural intersections were measured and compared with other potential variables that could have influenced the crash data. Initially 244 intersections in Minnesota rural areas were selected for the analysis but further insight into the information available for these intersections narrowed this number to 63. The crash data that was used in the analysis of all 63 rural intersections was acquired through MnDOT crash database. Poisson distribution and regression along with negative binomial distribution models were used to draw correlations between lighting levels and nighttime crash rate. The results showed that in general when average illuminance was increased by

1 lux, the nighttime crash ratio decreased by 9%. More specifically, when it was increased by 1 lux for intersections that contained roadway lighting, the result was a 20% decrease in crash ratio. Further, for unlighted intersections when lighting was increased by a unit of 1 lux, the crash ratio plummeted 94%. Therefore, the authors suggested that increasing the average illuminance was a successful crash reduction strategy and should be utilized to improve overall road safety. It was advised that further research should be done to confirm the minimum average illuminance of 5 lux as suggested in the study. Potentially the largest limitation to this study was the low number of intersections taken into consideration. Had a larger number of intersections been considered, the data would have been more representative of all intersections in Minnesota. Further, only horizontal illuminance data was collected in this study. In subsequent studies, it was suggested that vertical illuminance data should be collected in order to better understand the role lighting plays on road safety [7].

Rodgers et al. (2014) conducted a two-phase research program to evaluate the relationship between street lighting and traffic safety specially at roundabouts in rural areas. The main objective of phase I was to assess the feasibility of using partial lighting at roundabouts in rural areas. The authors found that it isn't necessary to install full lighting at rural roundabouts as followed by many other developed countries such as France. They indicated that converting an unlit rural stop-controlled intersection to an unlit roundabout has similar effect on crash rates as to installing standard lighting at the stop-controlled intersection. It was found that roundabouts with partial lighting have higher traffic safety performance than stop-controlled intersections with full lighting. [8]

Gibbons et al. (2014) described some strategies to reduce illumination levels on roadways via adaptive lighting tactics without compromising safety measures. The objective of this study was to provide more insights regarding when it would be appropriate to reduce lighting levels on roadways, the philosophy behind adaptive lighting, the potential benefits of using adaptive lighting, the system requirements to implement adaptive lighting, the legal implications of using adaptive lighting, and the cost-benefit analysis of using such system. The guidelines for recommended lighting levels on roadways was compiled after analyzing crash data obtained from seven states, where each crash was linked to the lighting levels at that crash's location. Adaptive lighting consists of a light that may decrease its luminescence, provided there is a decrease or complete stop in vehicle and/or pedestrian traffic. This feature would allow the systems owners, in most cases the government, to save money on energy and maintenance costs because the light would have a longer life. The proper luminescence of a light can be calculated from the equation: base value minus the sum of the weighted values for the roadway. This corresponds to a class 1-4 on roadways, 1-5 on streets, and 1-5 on residential/pedestrian roads, which then correlates to a design luminescence. Weighted values were determined from factors such as speed, traffic volume, median, intersection/interchange density, ambient luminance, guidance, pedestrian/bicycle interaction, and parked vehicles, depending on which class (roadway, street, or residential/pedestrian) is being analyzed. A drawback of the adaptive lighting system is that even though the system can be programed to sense weather changes, the guidelines do not recommend using it during adverse weather conditions (e.g., during rain, snow, or fog). Some studies found that there is inverse relationship between reduced illumination and visibility during adverse weather conditions. However, further research is still ongoing [9].

Bullough et al. (2013) examined the relationship between roadway lighting and reduction of nighttime crashes while also accounting for as many variables as possible. Statistical modeling and visual performance modeling were employed. The statistical modeling used a with-without comparison of 6,464 intersections, which included 22,058 sample observations over the period of 1999 – 2002. This data was obtained from FHWA's Highway Safety Information System. The data was analyzed via the method of maximum likelihood along with a negative binomial regression model and a random parameter count regression model. When analyzing the statistically modeled data using the negative binomial regression with no yearly indicator variables, it was noticed that there was a difference of 12% between intersections with lights and intersections without lights, with the lighted intersections having the lower night-to-day crash ratio. When yearly indicator variables were accounted for in the same regression, the percentages' difference in the night-to-day crash ratios became -11.9%. However, the authors recommended using a before-and-after analysis and with-or-without studies such as the one they conducted; however, emphasis should be placed on applying suitable control conditions [10].

Jackett and Frith (2013) investigated the relationship between road lighting and ratio of nighttime to daytime crashes. The objective of this study was to draw correlations between lighting levels and traffic collisions to better understand how to improve nighttime traffic safety. The authors used relation methodology and generalized linear models to explore the data, which was acquired via the New Zealand Transport Agency Crash Analysis System. Furthermore, regression models were also used to determine which predictor variables were the most important. These variables were average luminance, overall uniformity, longitudinal uniformity, threshold increment, and color of light. Considering the results of the regression, the given variables were then ranked as to which of them affected the crash rates the most, allowing for the DOT to make the roads safer in the most effective way. It was found that average luminance was the most effective factor in improving road safety. Once this correlation was made, the night-to-day crash ratio was plotted against the average luminescence on an exponential plot. Out of the 7,944 total crashes plotted, the exponential regression was almost perfect, which was mathematically confirmed as $r^2 = 0.99$. Therefore, as the average luminance for a road increase, the night-to-day crash ratio on that road decreases. Moreover, in order to verify that there was not a lurking variable related to the reduction in crashes, such as traffic volume, the night-to-day crash ratios were plotted against the average luminance of the roadways, but the data was separated into three groups based on traffic volume. The plot confirmed that the previous result was not a function of traffic volume but of average luminance because the plot separated into traffic volume groups still showed the same trend as the original plot based on the total number of crashes. Crashes were also divided into crashes at major and minor intersections as well as crashes on wet and dry roads. Similarly, even when divided into different categories, the plots followed the same trend as the original, confirming that the reduction in night-to-day crash rate is a result of average luminance and not another lurking variable. Therefore, it becomes apparent that average luminance of a road greatly improves its safety. Based on this conclusion, the authors recommended reevaluating New Zealand lighting guidelines according to the results of this study in order to make improve traffic safety at night. The authors also recommended that more future research should be carried out involving the relationship between intersection lighting and car crashes to better understand the relationship and to confirm their results [11].

Sasidharan and Donnell (2013) explored the application of propensity scores and potential outcomes to estimate the effectiveness of traffic safety countermeasures, more specifically areas with lighting versus areas without lighting. The objective of this research was to apply propensity scores to crash data to analyze the results differently than most studies to see if it yielded a different outcome. This paper used crash data that was analyzed using a logit model to estimate linear predications propensity scores. To estimate daytime and nighttime crash frequencies, Poisson regressions and negative binomial regressions were utilized. In general, the results showed a reduction in nighttime crashes when there are lights at the intersections. However, in the daytime there was a minuscule increase in crashes. This is believed to be because of the pole on the side of the road that could act as an obstruction in the driver's line of sight. The findings also showed a 4.7% decrease in nighttime crash frequency when lighting is present. In addition, when night-to day crash ratios were analyzed using the nearest neighbor matching method, the night-to-day crash ratios were 9.5% lower at lighted intersections than unlighted intersections. It was also discovered that at night for lighted intersections, when the lighting was turned off there was a 11% increase in nighttime crashes. Also, it was found that a 9.4% decrease in nighttime crashes when unlighted intersections were illuminated. These results indicated that lighting is an effective strategy in reducing the number of nighttime traffic collisions at intersections. One limitation of this study was that specific variables about the lights at the intersections were not taken into consideration (e.g., pole spacing, luminescence, mounting height, etc.). The authors recommend that a database be set up containing all specific information about the lights pertaining to their given intersection locations [12].

Rea et al. (2009) examined a list of studies to determine what conclusions other experts have drawn about the correlation between road safety at night and street lighting. A survey that targeted government employees in transportation agencies was conducted. The survey objectives were to find out the sources for data used in analyzing safety impacts of street lighting and to identify the information used by decision makers to decide whether to implement street lighting or not. The results of the literature review estimated that road safety could be improved between 20% and 30% just with the implementation of lighting; however, there is a limitation. This limitation was that in areas where there is a low chance of vehicle collision with stationary objects, or other vehicles, lighting is not beneficial. The results of the online survey showed that 59% of respondents used high nighttime crash rate as criteria for installing lights. In addition, the findings indicated that lighting is helpful in increasing the safety of a roadway [13].

Hallmark et al. (2008) examined the most effective ways to lower the number of nighttime crashes at unsignalized intersections at rural areas in Iowa. Crash data analysis was analyzed to determine the warrants for street lighting that can reduce the number of nighttime crashes. Cross-sectional analysis of 223 intersections in the state of Iowa over the time period of October 2005 through September 2006 were developed. As the data for these intersections was collected, the location of the intersection was pinpointed in the Geographic Information Systems (GIS) database. Of these intersections, 137 intersections had street lighting (either partial or full street lighting) and 86 intersections had no lighting. A Poisson distribution was used to fit a hierarchical Bayesian model to the data. By using this approach, it was determined that at high crash intersections, unlighted intersections were likely to have two times more crashes than lighted intersections at nighttime. One limitation of this study was that some of the intersections had little to no accidents over the specified time period [14].

Isebrands et al. (2006) analyzed the relationship between lighting at rural intersection and safety. This study was meant to follow up the previous "Street Lighting at Isolated Rural Intersections – Part 1," which was conducted by Preston et al. in 1999. This study had a similar objective as the first study – to analyze the safety benefits of lighting isolated rural intersections specifically in Minnesota. For the comparative analysis, both linear regression models and Poisson regression models were used in analyzing the data. Additionally, for the before-and-after analysis, linear regression and Poisson regression models were used as well. The authors obtained the crash data and the intersection data from the Minnesota Department of Transportation (MnDOT). The results of this study were pivotal in justifying adding lighting to rural intersections. The comparative analysis showed that intersections with no lighting had 27% more crashes than intersections with lighting. Likewise, the before-and-after analysis on the 48 intersections demonstrated that once lighting was installed, there was a 19% decrease in crash rate and a 21% drop in the ratio of nighttime to total crashes. The authors recommend accordingly that it would be beneficial to install lighting at rural intersections as a safety precaution because the data showed that it could greatly reduce risk of traffic accidents [15].

Green et al. (2003) explored how roadway lighting can affect roads' safety and how the proper lighting could be achieved through different lighting fixture placements in relation to the intersection. Data for this study was obtained from two sources. First, crash data was compiled from Kentucky's Collision Report Analysis for Safer Highways (CRASH) database over the period of 1999 – 2001. The second source of data was obtained through a survey sent out to other state department of transportations to examine how their lighting guidelines compared to those of Kentucky's. The data pulled from the CRASH database was analyzed via critical numbers and by the calculation of a critical rate factor. The analysis indicated that roughly 30% of rural area accidents happen at nighttime and 22% of accidents in urban areas. Using a before-and-after crash analysis, it was concluded that roadway lighting could cutback the number of nighttime crashes by up to 50%; however, actual results of the study showed it only being reduced by 45%. The author recommended that for future studies, the critical rate factor method should be used to find sites with a high number of crashes. Further, it is also recommended that AASHTO lighting design guidelines be used as warrants when determining which sites to illuminate [16].

Preston and Schoenecker (1999) examined the impacts of lighting isolated rural intersections within the state of Minnesota on safety. They conducted two types of analyses to achieve the study's objective. The first one was the crash data comparative analysis for over 3,400 isolated rural intersections. While the second one was the before-and-after analysis of 12 intersections in which accident frequency and severity were compared before (unlit condition) and after (lit condition) at each of the 12 intersections. Due to the small sample size of data, being just 12 intersections, a Poisson distribution model was used to analyze the before vs. after crash frequency. The findings indicated that there was a 25% decrease in crash rate at lit intersections. Furthermore, lit intersections had a 34% lower off-road crash rate than their counterpart. When analyzing the before vs. after crash data, intersections that had street lighting installed saw a 29% reduction in single vehicle nighttime crash rate and a 63% reduction in multi-vehicle nighttime crash rate. Also, after street lighting was installed, crash severity dropped by 20% [17].

Section 2: Specifications and Guidelines of Different State DOTs

Different states have different specifications and guidelines about lighting warrants. For example, Kansas Department of Transportation (KDOT) lighting guideline emphasizes that lighting is mandatory for roundabouts in the Kansas highway system. KDOT uses the Illuminating Engineering Society (IES) RP-8-00 specification. For the illumination of a roundabout, it is recommended that the illumination level of the roundabout itself be equivalent to the sum of the illumination levels of the approaching roadways. According to KDOT, the roundabout lighting can be installed at either the interior of the roundabout island or around the perimeter of the outside of the roundabout. Furthermore, when installing the lighting on rural or local roads a clear zone width of 10 ft. should be used. On collector roads and arterial roads with a curb, a clear zone width of 1.5 ft. should be used measured from the curb. Lastly, a minimum width of 3 ft. is required at roundabout approaches where parts of large trucks could hang over the road and strike a light pole [18].

The Delaware Department of Transportation (DelDOT) guidelines dictates that warrant analysis is not required for roundabouts and that all roundabouts shall be illuminated except for roundabouts that are within commercial or residential developments. The lighting level should be 1.3 to 2 times the value on the best lit approach. However, and contrary to KDOT, roundabouts in Delaware should be lit from the outer edge of the road. It must not be lit from the central island [19].

New Hampshire Department of Transportation (NHDOT) lighting design manual follows the American Association of State Highway and Transportation Officials (AASHTO) roadway lighting design guidelines. NHDOT manual states that adequate lighting should be provided to all roundabouts. The overall illumination of the roundabout should not be less than the sum of the illumination levels of the intersecting roadways. The lighting level should be 1.3 – 2 times the value in the best lit approach. However, in the case of rural settings, lighting at roundabouts is recommended but not mandatory as providing lighting may be costly if no power supply is available near the roundabout. Still, the manual emphasize that adequate signs and markers should be used if lighting is not provided so that drivers can safely perceive the roundabout during the night [20].

The New Jersey Department of Transportation (NJDOT) roadway design manual demonstrates all the warrants necessary to provide illumination to intersections and roundabouts in the state of New Jersey. The most basic rule is that all signalized intersections must be illuminated. However, for unsignalized intersections, specific criteria is needed to warrant illumination. In the hours between dusk and dawn, illumination of intersections is warranted if: the highway is a four-lane highway, any right turn motion on the highway exceeds 75 vehicles per hour (VPH), any left turn movement on the highway exceeds 25 VPH/Leg, or the through for either leg exceeds 50 VPH. If lighting is warranted, NJDOT refers to the IES-DG-19-08 design guide [21].

The North Dakota Department of Transportation (NDDOT) lighting warrants policy states that the following criteria should be met to warrant for intersection illumination: signalized intersections, roundabouts, U-turns, presence of raised channelizing island/median, segment of the road is lit, and rural and suburban intersections where traffic volume cross product [major and minor annual average daily traffic (AADT)] is equivalent to 10,000,000 or higher, recommended based on traffic study or cost of installation, operation and maintenance is covered by a local government agency. Whenever lighting is warranted, NDDOT follows the AASHTO's Roadway Lighting Design Guide [22].

The Vermont Agency of Transportation (VTRANS) relies on both AASHTO's Roadway Lighting Design Guide and the Transportation Association of Canada (TAC), which is used whenever AASHTO's guide required a more detailed evaluation. VTRANS uses warrant analysis to determine the lighting scheme to be adopted at an intersection. However, there are some general rules such that: signalized intersections warrant full lighting (without conducting the analysis), roundabouts also warrant full lighting due to the road geometry at roundabouts, and the limitations of fixed headlights of vehicles. Whereas the warrant for lighting at unsignalized intersections depends on the total point-score of the warrant analysis [23].

The Wisconsin Department of Transportation (WisDOT) Traffic Engineering, Operations & Safety Manual mandates that all DOT owned roundabouts shall be illuminated using LED. WisDOT also follows AASHTO's Roadway Lighting Design Guide. However, IES Design Guide for Roundabout Lighting is used as a reference as well [24].

The Tennessee Department of Transportation (TDOT) described in chapter 15 of their traffic design manual the conditions for warranting street lighting at an intersection in rural area that include: 2.4 or more crashes per million vehicles in the last three years, 2.0 or more crashes per million vehicles per year and at least 4 crashes in each year, 3 or more crashes per million vehicles in the last two years, and at least 7 crashes in each year, the intersection is signalized, high nighttime pedestrian volumes, the intersection has an unusual design that requires complex maneuvers, illumination at surrounding area which distracts drivers, or recurrent fog or smog in the area. The manual specified that roundabout illumination should follow the IES Design Guide for Roundabout Lighting [25].

The Oregon Department of Transportation (ODOT) adhere to AASHTO's Roadway Lighting Design Guide as specified in the Lighting Policy and Guidelines. However, there are no specific warrants that ODOT follow to determine the necessity of street lighting instead, ODOT conducts investigation that depends on engineering judgement, traffic volume, crash data, road characteristics, and availability of funds. There are some general warranting conditions, for example, unsignalized intersections may be considered for lighting if at least 30% of crashes occur during nighttime and the total crash rate for the section exceeds the critical crash rate, or if crash data show that nighttime crashes involve a high number of pedestrians or bicyclists. However, ODOT is not obligated to provide lighting even if the conditions were met; the decision for implementing street lighting is at the discretion of ODOT. In case lighting was to be implemented, ODOT prefers LED luminaire [26].

The South Carolina Department of Transportation (SCDOT) roadway design manual clearly states that all roundabouts must be lit including roundabouts in rural areas. In case lighting was not provided, sufficient delineation should be provided for entry islands and splitter islands. In case only the roundabout is lighted, then any raised right channelization or curbs should be lighted. Furthermore, a transition zone for gradual illumination should be provided after each exit in accordance with NCHRP Report 672 (which was discussed earlier) [27].

The Florida Department of Transportation (FDOT) follows AASHTO's Roadway Lighting Design Guide and IES Design Guide for Roundabout Lighting. FDOT uses vertical illuminance as the main design value to measure visibility of pedestrians, which is a function of background illuminance, luminaire location, height, distance to crosswalk, and its photometrics [28].

VDOT underlines in their roadway lighting memorandum a no lighting policy unless safety analysis showed strong justification for it. VDOT recommends using the FHWA Design Criteria for Adaptive Lighting's Design Criteria for Streets (S-Class). In addition, VDOT developed some guidelines for roundabout and intersection lighting. For example, for intersections with pedestrian accommodations, the intersection should include illumination if the light can be fixed on top of the signal pole, so extra utility pole does not have to be added, causing an unnecessary hazard. Also, the VDOT emphasizes the lighting at roundabouts is not required, and each roundabout should be looked at on an individual basis based on sight distances and expected pedestrian activity. Further, the VDOT states that for unsignalized intersections lighting is not mandatory; however, it should be considered as a safety countermeasure to reduce the rate of nighttime crashes [29].

Colorado Department of Transportation (CODOT) utilize both AASHTO's and IES's Design Guidelines for Lighting; however, the justification for warranting street lighting is based on the AASHTO guideline. According to CODOT, all roundabouts with pedestrian activity and a nearby electrical service should be considered for lighting except if the roundabouts are in remote rural areas (pedestrian activity is minimal) where power is not available and speed limit is below 30 miles per hour (mph), then it is not feasible to provide lighting. As for general design specifications, it is recommended that the lighting is not installed in the center of the roundabout, approach lighting should be for at least 400 ft. and lighting feature should be at least 4 ft. away from the edge of the curb to minimize risk of crashing the pole foundation [30].

Louisiana Department of Transportation and Development (DOTD) emphasized in its Roadway Design Manual that lighting is not mandatory in its intersections. However, if lighting is installed, it should comply with the IES Design Guide. Moreover, a permit from DOTD must be obtained to install street lighting. The responsibility, liability, and cost of maintaining the street lighting is that of the permit applicant [4].

Washington State Department of Transportation (WSDOT) Design Manual indicates situations where illumination is warranted. For example, signalized intersections and roundabouts should have sufficient illumination to enhance visual perception during nighttime. The manual also provides standard specification (Exhibit 1040-14) to be followed during the design of roundabout illumination [31].

Jones and Abdul Majeed (2015) documented in the Alabama Department of Transportation (ALDOT) roundabout manual the requirements for roundabout lighting. It is stated that lighting should provide clear visibility for drivers to safely navigate a roundabout and that lighting should highlight the key features of roundabouts such as pedestrian crosswalks and the circulating lanes within the roundabouts. Lighting levels at the roundabout should be uniform with the lighting levels at the intersecting roads. The manual also states that if pedestrian activity is not expected then retro reflectorized signs and markings may be used [32].

Lutkevich et al. (2012) prepared the Federal Highway Administration (FHWA) lighting handbook to serve as a guidance for lighting engineers and decision makers to evaluate potential lighting needs. The handbook supplements the guidelines made by AASHTO, IES, and the Commission Internationale de l'Eclairage (CIE). To assist older drivers, Lutkevich recommends fixed street lighting (whenever feasible) at intersections where potential for movement in the wrong direction is expected based on prior crash experience, high pedestrian movement at night, or shifting lane alignment near or at the intersection. The handbook documents factors that determine the necessity of lighting such as traffic volume at the cross street, availability of crosswalks, nighttime crashes caused by lack of lighting, availability of raised median, and other factors. However, signalized intersections should be fully lighted while unsignalized intersections such as stop-controlled intersections or roundabouts are assessed using warrant analysis. The handbook defines partial lighting as "the illumination of key decision areas, potential – conflict points, and/or hazards in and on the approach to an intersection.", [33].

Robinson (2000) aimed to outline the design guidelines for roundabouts. The authors emphasized that for a roundabout to be considered satisfactory, the vehicle must be able to enter and exit traffic in the roundabout safely and efficiently [34]. Thus, the criterion for roundabout illumination is based on this point. For urban roundabouts, the authors recommended that lighting be utilized if most approaches are illuminated and/or if illumination is needed to improve driver visibility. On the other hand, for suburban roundabouts, illumination is recommended if: one or more approaches contains illumination, other nearby illumination could distract the driver, or if a large volume of nighttime traffic is expected. Another important recommendation is that the illumination of a roundabout should be equal to the sum of the illumination of its intersecting roadways. One limitation of the illumination of roundabouts is the need for clear zones, which are zones around the roundabout with no obstructions. These clear zones are needed due to the high rate of single vehicle crashes at roundabouts which is caused by the driver losing control of their vehicle. The authors recommended that for more specific guidelines, AASHTO Roadside Design Guide should be consulted for more information on clear zones [34].

An overview of the National Cooperative Highway Research Program (NCHRP) Report 672 (2010) shows that all roundabouts should be adequately lit. The report that recommends using the IES design guide as the main resource for lighting design at roundabouts indicates that there are two main reasons for providing lighting to roundabouts, first visibility in advance for road users entering the roundabout and the second is visibility of key conflict areas. The report suggests that the geometry of roundabouts (constrained curve radius) limits the effectiveness of auto headlights thus reducing the driver visibility of obstructions and hazards. The report also suggests providing a transition zone with gradual illumination after each exit of the roundabouts in case the lighting scheme was not continuous between the roadway segment and the roundabout [35].

Section 3: Previous Driving Simulations and Field Experiments

Chakraborty et al. (2022) conducted a simulation study to investigate whether the color temperature of different street lighting sources had an impact of driver's ability to detect objects at night [36]. A total of 20 participants participated in this experiment who were healthy neurologically and physiologically as the results could be impacted by the health conditions of the participants. The scenarios were conducted using two different types of lighting, each scenario was repeated four times corresponding to four different color temperatures, and the reaction time of the participants was recorded every time. The results indicated that the color temperature does have an impact of the reaction time to notice an object at night [36].

Bhagavathula et al. (2017) examined the effect of lighting at rural Virginia intersections with regards to the safety of the intersections. The objective of this study was to obtain lighting data from rural Virginia intersections and quantify its effect on the number of nighttime crashes at those intersections. Lighting data for this study was collected via a Roadway Lighting Mobile Measurement System (RLMMS) mounted to the top of a car. The RLMMS consisted of an illuminance measurement device and a Global Positioning

System (GPS) system. This allowed the location of the measured illuminance to be tracked so an illuminance database created for all intersections driven through. Only 99 out of 131 of the intersections driven through had practical data. The crash data used in the study was obtained from the Virginia Crash Database, courtesy of Virginia Department of Transportation (VDOT). Then, the crash data was analyzed using a negative binomial analysis. Overall, the results of the study showed that the night-to-day crash ratio decreased by 9% for every 1-lux increase in horizontal illuminance at lighted intersections. While the night-to-day crash ratio decreased 21% for every 1-lux increase in horizontal illuminance at unlighted intersections. All intersections combined showed a 7% decrease in the night-to-day crash ratio for a 1-lux increase in average horizontal illuminance. The results concluded that not only do lighted intersections have fewer nighttime crashes than unlighted intersections, but lighted intersections also have a lower night-to-day crash ratio than their counterparts. The authors also pointed out that intersections that followed recommended IES lighting guidelines had lower night-to-day crash ratios. Therefore, it should be noted that IES lighting guidelines should be followed. One limitation of this study was that annual average daily traffic data was not available for the intersections, thus the night-to-day crash ratios had to be indirectly computed. Had these values have been provided, the results of the study would have been more accurate [37].

Bullough et al. (2013) also conducted a visual performance modeling method, the data were obtained through the aid of a computer model and subject participation [10]. AGi32 and Lighting Analyst software was utilized to create realistic driver settings for various conditions. Participants were tested for their Relative Visual Performance (RVP). The results from these tests were then correlated to the visibility level at the given simulated user conditions, which then allowed the authors to draw a conclusion on whether lighting effected the safety of the roadway intersection. The visual performance modeling was analyzed and turned into comparable data using an RVP score. Different age groups were tested and given an RVP score at each intersection with the changing variable being the location of the oncoming traffic in reference to the intersection. The difference in RVP scores at a particular location based on whether the intersection was lighted or unlighted was then averaged for the four groups of intersections: urban/suburban signalized, urban/suburban unsignalized, rural signalized, and rural unsignalized. The results for the difference in RVP scores for these same groups were 0.73, 1.86, 0.27, and 0.21, respectively. The results indicated that there is a positive relationship between installation of lighting at intersections and driver crash reduction ($r^2 = 0.93$) [10].

While Akashi et al. (2007) conducted a field study to examine the impact of street lighting on driver behavior [38]. Participants were required to drive along a lighted street when they observe a pedestrian walking towards or away from the street. They had to brake if the target was moving towards them and accelerate if the target was moving away from them. Two different lighting sources were used. The results showed that both braking and acceleration response times decreased as unified luminance increased, suggesting that unified luminance is a suitable rectifying variable for characterizing light levels for different light sources [38].

Section 4: Outcomes of Previous Cost – Benefit Analysis

Li et al. (2020) conducted a cost-benefit analysis to evaluate the feasibility of intersections' lighting [5]. It was found that lighting for intersections that only sustained property damage in their accident would not be beneficial, as the cost would outweigh the benefit. One limitation of the cost-benefit analysis was that it did not take into consideration environmental and health factors. When accounted for, these factors could affect the cost-benefit analysis greatly. The authors recommended that crash data be the primary basis on which lighting needs should be examined, where the intersection has on average at least one nighttime fatal or injury crash per year over a three-year period [5].

Gbologah et al. (2019) used a benefit-to-cost analysis to determine whether it would be worth installing lighting at some Georgia intersections [39]. The objective of this research was to gain statistical evidence of the benefit of lighting intersections to improve traffic safety at night. To achieve this goal, intersection data needed to be collected. However, because no such database existed, the intersection lighting set up had to be modeled. Previous Georgia Department of Transportation (GDOT) projects concluded that for rural, conventional intersections any illuminance exceeding 12 lux provided no additional safety when used at intersections. Therefore, the effective range of lighting for a conventional, rural Georgia intersection was determined to be between 0 lux and 12 lux. Using this range of illuminance in conjunction with the benefit-to-cost analysis, it was determined that all rural, conventional Georgia intersections without need of further electrification were justified to install lighting. One limitation of this study was that because a database did not exist for all of the intersections, the lighting parameters for each intersection had to be modeled. Therefore, these parameters are not an exact representation of the intersection lighting itself [39].

Zhao et al. (2016) studied the safety and cost effectiveness of intersection lighting [40]. The objective of this study was to investigate the effect intersection lighting had on the overall safety of an intersection. Crash data was used in correlation with a Poisson distribution and a negative binomial distribution to analyze the data. The crash data were obtained from the Fatality Analysis Reporting System (FARS), the General Estimates System (GES), and the Automated Reporting Information Exchange System (ARIES). Using this data, a before-and-after analysis and a cross-sectional analysis was conducted to evaluate the effectiveness of lighting an intersection. The results of these analyses yielded these crash modification factors (CMF): 0.88, 0.9, and 0.84, for overall intersection lighting, four-leg intersection lighting, and three-leg intersection lighting, respectively. Overall, if the CMF was equivalent to 0.88, this means when lighting was introduced, there was a crash reduction factor (CRF) of 0.12, which corresponds to a 12% reduction in crashes. Therefore, the three-leg intersection had the largest improvement when lighting was taken into consideration because there was a 16% reduction in crashes. In contrast, four-leg intersections only had a 10% reduction in crashes when lighting was considered. The authors state that these results are helpful in developing new guidelines for lighting practices. One limitation of this study was the small number of intersections in the before and after study (14 intersections) [40].

Preston and Schoenecker (1999) also assessed the cost effectiveness of using lighting at isolated rural intersections within the state of Minnesota [17]. From a financial point of view, cost-benefit analysis ratio of installing street lighting at rural intersection was around 15:1. Therefore, the benefits of lighting rural intersections far outweigh the cost of installing the lighting system. It was suggested that lighting intersections will have positive effect on the safety of road users at rural intersections compared to other methods of improving road safety such as rumble tracks and overhead flashing beacons, thus the method of illumination of intersections should be tried first before any of the other options. One of the limitations of this study was the samples of crash data collected at lit intersections may be biased due to the state district's practice of essentially including the crash data of intersections with poor safety history [17].

Objective

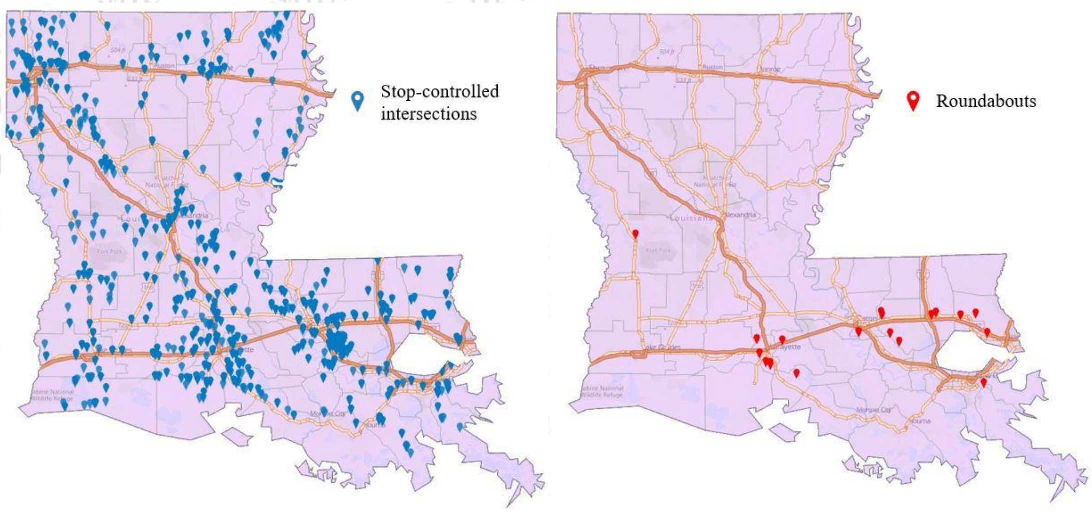
The primary objective of this study was to examine whether Louisiana has a traffic safety problem due to lack of lighting at its intersections, particularly at roundabouts and stop-controlled intersections in rural and suburban areas. Underlying this objective, this study also aimed to:

1. Investigate if an intersection's lighting has significant impact on the drivers' behavior and their ability to safely perform the driving task at unsignalized intersections.
2. Determine which states have adopted a partial/full lighting policy, guidelines, or other potentially low-cost countermeasures for lighting their intersections.
3. Explore how states construct and maintain the lighting equipment at their intersections.
4. Assess the benefits from providing full lighting at stop-controlled intersections and roundabouts considering the costs required to provide this countermeasure and the expected savings due to the expected reduction of the number and/or severity of traffic crashes due to lack of lighting.
5. Provide recommendations regarding whether DOTD should adopt a partial or full lighting policy considering the results of all previous tasks.

Scope

The project scope includes stop-controlled intersections and roundabouts located in rural and suburban areas in Louisiana. As shown in Figure 2, the study area included a total of 577 stop-controlled intersections and 19 roundabouts in rural and suburban areas in Louisiana.

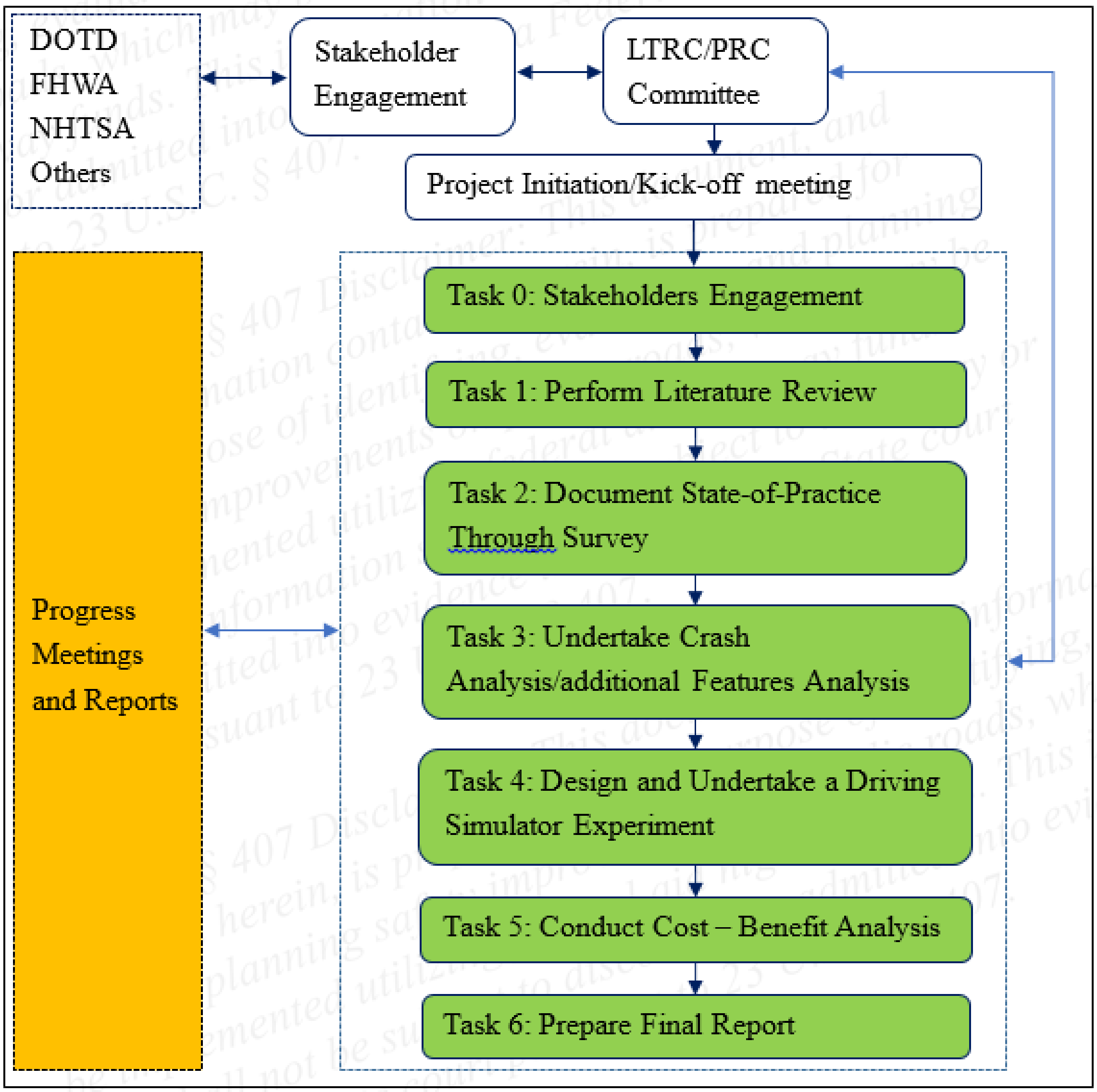
Figure 2. GIS map of stop-controlled intersections (L) and roundabouts (R)



Methodology

This section summarizes the overall methodology that was carried out in this project and discusses each task that was completed to achieve the project objectives. Figure 3 illustrates the overall approach and tasks implemented in this project.

Figure 3. Overall research approach and tasks



Task 0 – Stakeholders Engagement

This task started by conducting a kick-off meeting with Louisiana Transportation Research Center (LTRC) and the project review committee (PRC) to introduce the project objectives, initial research plan and get their feedback.

In addition, this task included several engagement activities with stakeholders such DOTD obtain the required crash data set. In this regard, LTRC played a key role in helping the research team obtain the required information and get all required feedback from PRC throughout the project's phases.

Task 1 – Perform Literature Review

During this task, an in-depth literature review was conducted (as shown in Section 2 of this report) to identify the most relevant studies, best practices relevant to the scope of this research, as well as state DOTs guidelines on lighting requirements in rural areas.

Task 2 – Document State-of-Practice through Survey

To better achieve this task, a national survey targeting professionals working at the safety and lighting departments at state DOTs in the 50 states within the US was conducted. The survey was designed to provide useful insights regarding the challenges and needs of improving the traffic safety at roundabouts and stop-controlled intersections in rural and suburban areas when it comes to intersection lighting according to different states' guidelines within the US. In addition, the survey aimed to assess the effectiveness of different lighting methods such as partial, full, or other lighting schemes used by different states to reduce the number and severity of traffic crashes during nighttime. Finally, the survey aimed to provide low-cost recommendations that can improve traffic safety at unlet intersections based on identified best practices that other state DOTs adopted.

Task 3 – Undertake Crash Analysis/Additional Features Analysis

During this task, the research team obtained the crash data of all the crashes that occurred at roundabout and stop-controlled intersections in rural and suburban areas within Louisiana in the five years between 2016 and 2020. After data preparation and coding, several analytical techniques including descriptive summary statistics, cross sectional analysis, and multivariate analysis (MVA) (Poisson regression and negative binomial models) were performed on the crash data to investigate the primary factors that affected crash occurrence and severity, compare crash frequency and rates at lit and unlit intersections as well as to conclude if Louisiana has a traffic safety problem due lack of lighting at its intersections.

Task 4 – Design and Undertake a Driving Simulator Experiment

In this task, the research team utilized the Louisiana State University (LSU) driving simulation lab to design the required driving similar experiment for Task 4. The lab is equipped with a full-sized passenger car (Ford Focus), projectors, screens, and powerful desktop computers that can handle the development of multiple scenarios and a lot of data input and output. The lab was used to provide participants in the experiment (individuals who are 18 years or above with a valid driver license) with a realistic road network setting in a controlled and safe environment where participants can go through different lighting scenarios, such as no lighting, partial lighting, and full lighting as well as various intersection settings including roundabouts and two-way and four-way stop-controlled intersections. Projectors and screens were used to display the environment settings to participants while the cameras and sensors were used to capture driver experience while going through the experiment. It is worth mentioning that this study is the first one to examine the impact of intersections' lighting on drivers' behavior using a driving simulator experiment since this new feature (e.g., adding lighting poles to the roadway network) was provided to LSU in the trial version of the new simulator software. New updates of the simulator software have not yet released.

Task 5 – Conduct Cost – Benefit Analysis

Considering the results of Tasks 1, 2 and 3, a cost-benefit analysis was conducted to identify the costs and benefits of providing full lighting to roundabouts and stop-controlled intersections. The analysis explored the effectiveness of providing full lighting considering the costs associated with providing street lighting and the expected benefits of reducing number and/or severity of crashes occurred due to lack of street lighting.

Task 6 – Prepare Final Report

In this task, the research team consolidated the information and results obtained from all previous tasks (Tasks 1-5) and prepared a final report documenting the entire project findings along with conclusions and recommendations.

Analysis

The analysis has been divided into four sections as follows:

- Section 1: discusses the analysis of survey data.
- Section 2: presents the analysis of crash data,
- Section 3: discusses the analysis of driving simulation experiment, and
- Section 4: presents the cost-benefit analysis.

Section 1: Analysis of Survey Data

As indicated earlier, a national online survey (using Qualtrics survey tool) was designed and conducted among a sample of professionals who have relevant expertise in traffic safety and roadway lighting and are working at various state DOTs in the 50 US states. The main objectives of the survey were to:

- Investigate the current street lighting guidelines followed by other states,
- Identify the safety impacts of intersection lighting on road user,
- Investigate and assess the effectiveness of different lighting methods (e.g., minimum lighting requirement) adopted by different states at roundabout and stop intersections, and
- Identify cost-effective countermeasures adopted by US DOTs to improve traffic safety at roundabout and unsignalized intersections during nighttime.

The survey consisted of three main sections. Section one titled “Guidelines and Specifications” included 14 questions discussing the lighting guidelines and manuals adopted by state DOTs in addition to the factors that warrant street lighting at stop-controlled intersections and roundabouts. Furthermore, this section also explored the frequency of monitoring the performance of used lighting equipment as well as the method for maintenance methods used. Finally, this section concluded by asking participants to provide an approximate percentage of the lighting conditions at their state.

While section two titled “Safety” included 20 questions about the lighting requirements, primary reasons for nighttime crashes, and the main lighting approach used by their state DOT. In this section, participants were also asked to rate the impacts of the adopted lighting scheme and the overall traffic safety condition at their state and what action should be done regarding unlighted intersections. Finally, the third and last section of the survey titled “Cost-Benefit Analysis” discussed the benefits and costs associated with installing, operating, and maintaining different lighting schemes based on nine questions. Participants were also asked to provide approximate costs for providing partial lighting and full lighting to a typical stop-controlled intersection and roundabout in addition to their recommended low-cost countermeasure to improve nighttime traffic safety.

An invitation email was sent to DOT professionals working either in the traffic safety department or the street lighting departments at each DOT of the 50 US states. During the data collection period, the research team faced the challenge of low response rate. However, with the help of the PRC members and continuous reminders by the research team, the required number of responses were collected. After successfully collecting 43 responses from 32 different states (64% response rate), the research team proceeded to analyze the survey responses. While responding to the national survey, most states provided one consolidated answer for their state from the traffic safety and roadway lighting departments while several states provided two responses: one from the traffic safety department and the other from the roadway lighting department (where each department answered only their part). In this case, we have combined both these responses into one complete response that represents the corresponding state. All the survey results that will be discussed in this report are for the 32 states that participated in this study. The list of state DOTs that responded to this survey is shown in Table 1 below.

Table 1. List of state DOTs that responded to the survey

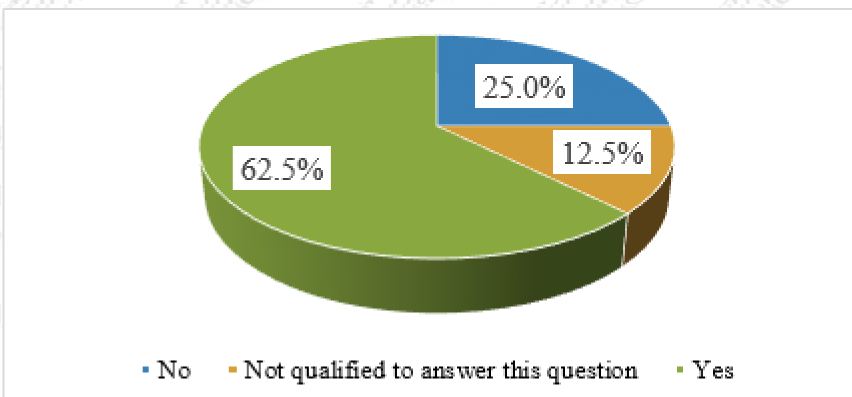
S.N.	State	S.N.	State	S.N.	State	S.N.	State
1	Alabama	9	Illinois	17	New Hampshire	25	South Carolina
2	Arkansas	10	Indiana	18	New Jersey	26	South Dakota
3	California	11	Kentucky	19	North Carolina	27	Tennessee
4	Delaware	12	Louisiana	20	Ohio	28	Texas
5	Florida	13	Maine	21	Oklahoma	29	Utah
6	Georgia	14	Michigan	22	Oregon	30	Vermont

S.N.	State	S.N.	State	S.N.	State	S.N.	State
7	Hawaii	15	Minnesota	23	Pennsylvania	31	Washington
8	Idaho	16	Montana	24	Rhode Island	32	Wisconsin

It is worth mentioning that the survey was reviewed and approved by the Institutional Research Board (IRB) at LSU. A copy of the survey questions can be found in Appendix A. The results of the survey are presented next.

Part 1: Guidelines and Specifications. Starting with the guidelines and specifications section, participants were asked to report whether they follow the same or different lighting guidelines and specification for stop-controlled intersections and roundabouts at their states. As shown in Figure 4, the results indicated that almost two-thirds (about 63%) of the states use the same lighting guidelines for both stop-controlled intersections and for roundabouts while one-fourth (25%) stated that they follow different lighting guidelines for each intersection type. Finally, almost 13% weren't qualified to answer this question (NA).

Figure 4. Lighting guidelines used for stop-controlled intersections and roundabouts



The second question was about whether it is mandatory to provide street lighting at stop-controlled intersections and at roundabouts at their states. As shown in Figure 5, it was found that none of the states have mandatory lighting requirement at stop-controlled intersections. In fact, around 72% mentioned that lighting is installed where is seems necessary based on the traffic safety status while about 28% indicated that street lighting isn't mandatory at their state. On the other hand, about two-thirds of the states (nearly 67%) mentioned that street lighting is mandatory at their roundabouts. However, about 21% indicated that lighting is installed based on the traffic safety status, and about 13% responded that street lighting is not mandatory at roundabouts.

In the third question, participants were asked to report the current manual used for illumination specification at their state. As presented in Figure 6, about 44% of the participants responded that they follow the *American Association of State Highway and Transportation Officials (AASTHO) Roadway Lighting Design Guide* for stop-controlled intersections compared to about 33% for roundabouts. Moreover, approximately 28% of the participants stated that AASHTO and other manuals are used for lighting specification at their stop-controlled intersections compared to about 38% for roundabouts. The reported percentage of states that use the Illuminating Engineering Society (IES) guideline was around 13% and 17% for stop-controlled intersections and roundabouts, respectively. Furthermore, almost 10% stated that they use other manuals for stop-controlled intersection compared to about 8% for roundabouts.

Figure 5. Mandatory of lighting at stop-controlled intersections and roundabouts

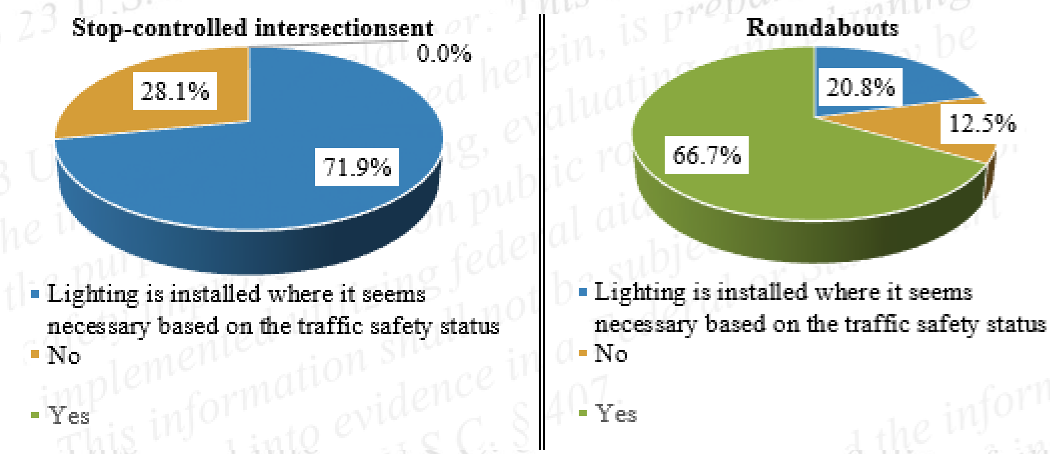
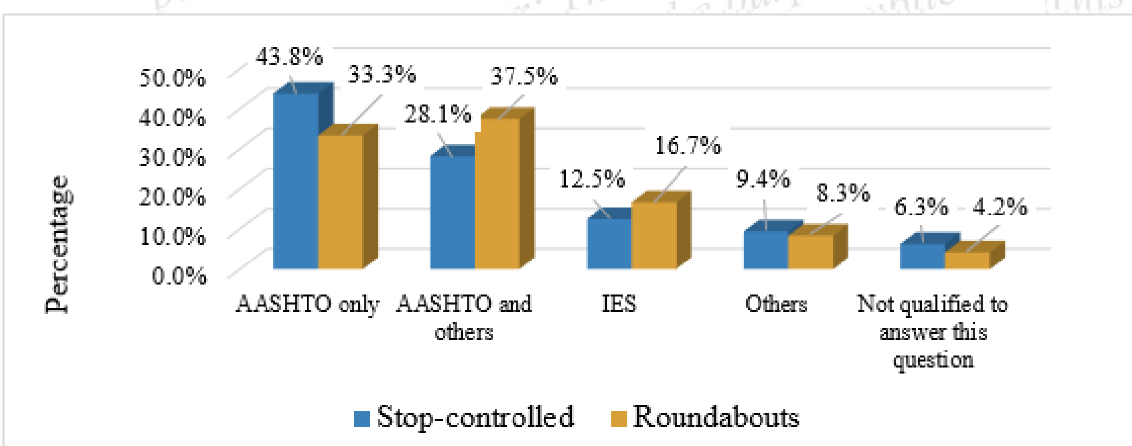
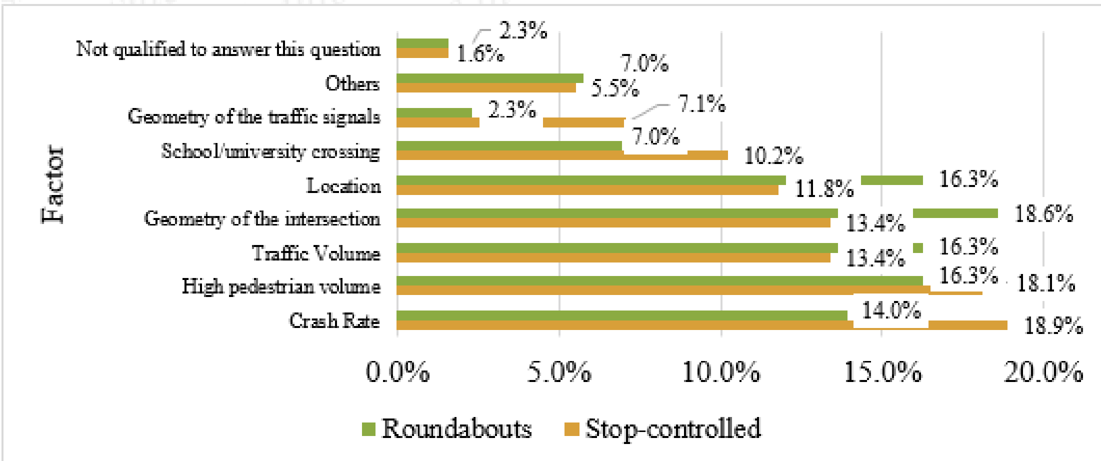


Figure 6. Manual for illumination specification used at unsignalized intersections



The fourth question was about the factors that their states consider for determining the necessity of street lighting at their unsignalized intersections. As presented in Figure 7, the most reported factor for stop-controlled intersection was crash rate (19%), high pedestrian volume (18%), and traffic volume and geometry of the intersection (13%) in addition to other factors. However, the most reported factor for roundabouts was geometry of the intersection at about 19% followed by high pedestrian volume, traffic volume, and location (16%) in addition to other factors.

Figure 7. Factors determining the necessity of street lighting



Participants were then asked to report the frequency of monitoring the lighting equipment performance at their states. Figure 8 shows that 53% of the states monitor the performance of lighting equipment at stop-controlled intersection only when required compared to 50% at roundabouts. In addition, only 6.2% of the participants monitor the performance of stop-controlled intersection lighting equipment annually compared to 4.2% for roundabouts. About one-fifth (22%) of the states monitor the performance at stop-controlled intersection during other times compared to 21% for roundabouts. Finally, about 19% of respondents for stop-controlled intersections indicated that they are not qualified to answer this question; whereas, the corresponding percentage in roundabouts was 25%.

The sixth question was about the method that state DOTs use to maintain the lighting equipment at their intersections. As presented in Figure 9, about 36% of stop-controlled intersection are partially maintained by state DOT and local district/municipality (compared to 33% for roundabouts). While almost 32% of the stop-controlled intersections are maintained by state DOTs compared to about 24% for roundabouts.

Only about 18% of the stop-controlled intersections are maintained by local district/municipality compared to about 29% for roundabouts. Finally, about 14% of stop-controlled intersections and roundabouts are maintained when required.

Figure 8. Frequency of monitoring lighting equipment performance at stop-controlled intersections and roundabouts

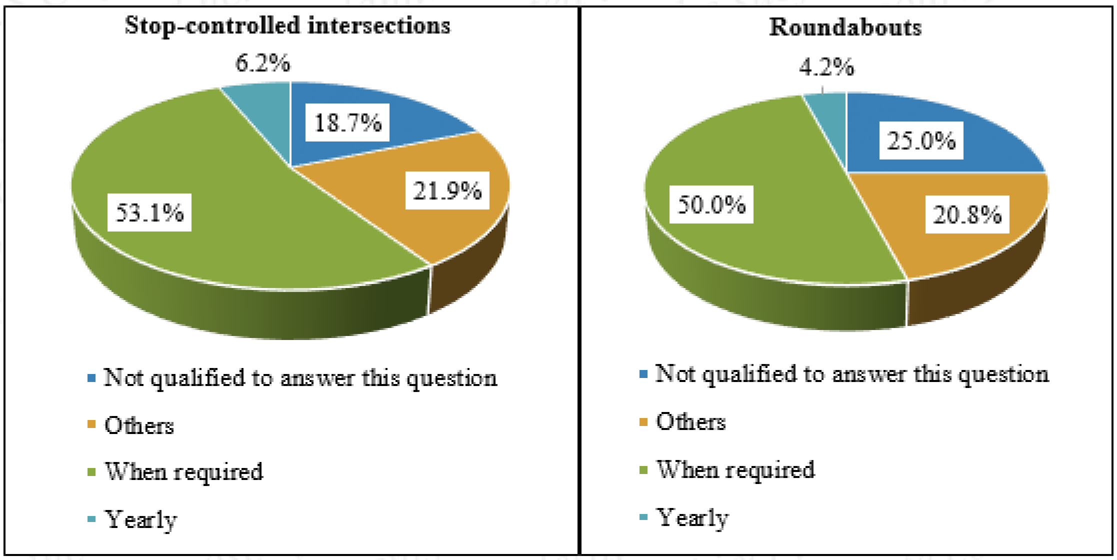
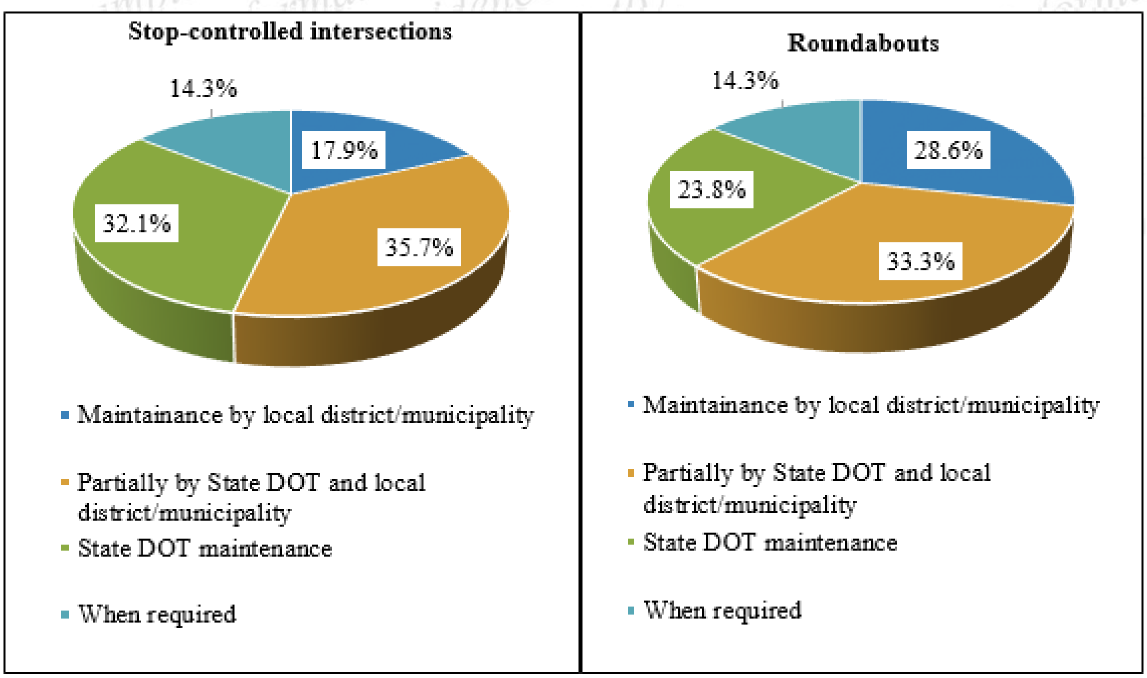
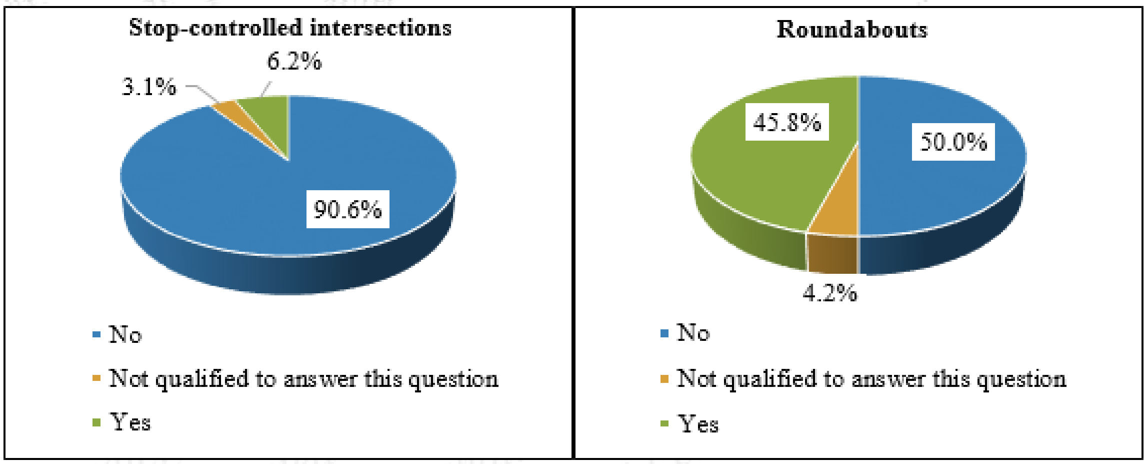


Figure 9. Maintenance of lighting equipment at stop-controlled intersections and roundabouts



Participants in the survey were then asked if they knew the current percentage of lighting conditions of unsignalized intersections at their state followed by another question to report these percentages if the information is known for them. Figure 10 shows that most survey respondents (91%) did not know the current lighting condition percentages of stop-controlled intersections compared to 50% for roundabouts. Only about 6% of the respondents reported that they know the lighting condition percentages of stop-controlled intersections compared to about 46% for roundabouts. Finally, only 3% of stop-controlled intersections and 4% of roundabouts weren't qualified to answer this question.

Figure 10. Current percentages of lighting conditions at stop-controlled intersections at roundabouts



In this regard, only three states (Florida, Georgia, and Kentucky) reported the percentages of the current lighting conditions at their stop-controlled intersections as presented in Table 2. On the other hand, 11 states reported the percentages of the current lighting conditions at their roundabouts as shown in Table 3. These states include: Alabama, Delaware, Florida, Georgia, Idaho, Indiana, Kentucky, Maine, Minnesota, Oregon, and South Dakota.

Table 2. Current percentages of lighting conditions for stop-controlled intersections

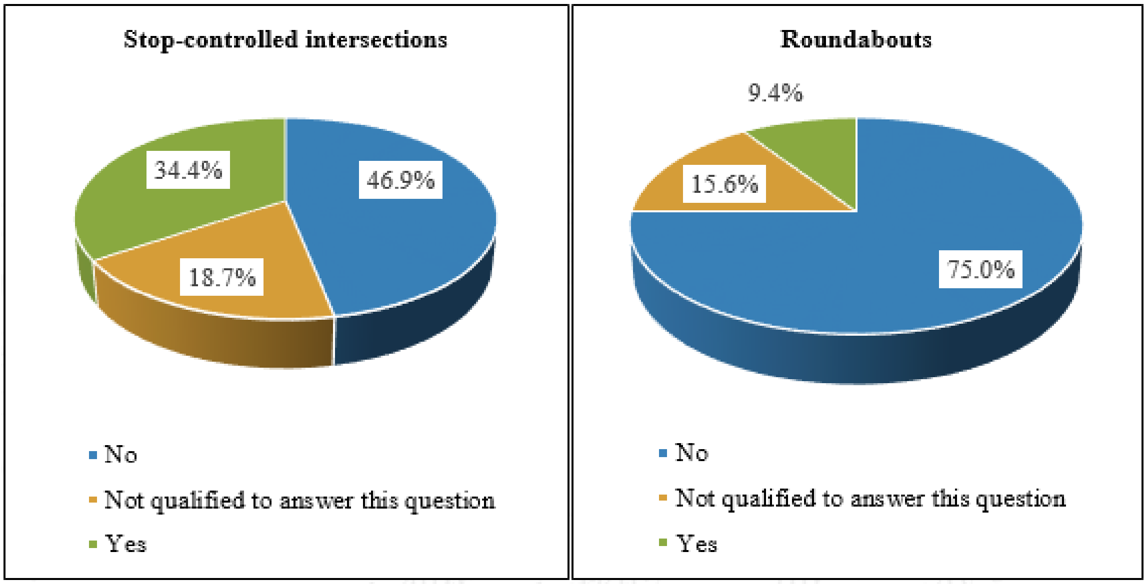
S.N.	State	Full Lighting	Partial Lighting	Other Lighting Schemes	No Illumination	Total
1	Florida	2%	50%	48%	0%	100%
2	Georgia	15%	30%	50%	5%	100%
3	Kentucky	0%	0%	0%	100%	100%

Table 3. Current percentages of lighting conditions for roundabouts

S.N.	State	Full Lighting	Partial Lighting	Other Lighting Schemes	No Illumination	Total
1	Alabama	50%	0%	0%	50%	100%
2	Delaware	100%	0%	0%	0%	100%
3	Florida	2%	50%	48%	0%	100%
4	Georgia	95%	4%	1%	0%	100%
5	Idaho	100%	0%	0%	0%	100%
6	Indiana	100%	0%	0%	0%	100%
7	Kentucky	80%	20%	0%	0%	100%
8	Maine	100%	0%	0%	0%	100%
9	Minnesota	100%	0%	0%	0%	100%
10	Oregon	100%	0%	0%	0%	100%
11	South Dakota	100%	0%	0%	0%	100%

Part 2: Safety. In the second section of the survey titled "Safety," respondents were asked to report whether there are any traffic safety problems due to lack of lighting at unsignalized intersection (stop-controlled intersections and roundabout) at their states. As presented in Figure 11, almost half of respondents (47%) indicated that there are not any traffic safety problems due to lack of lighting at their stop-controlled intersections compared to 75% who reported no traffic safety problems at roundabouts. However, almost 34% and 9% of the respondents mentioned that there are traffic safety problems due to lack of lighting at their stop-controlled intersections and roundabouts, respectively. Such problems included increased number of rear-end crashes, increased number of fatal crashes, increased percentage of drivers that don't notice the unsignalized intersections, and increased risk to pedestrians crossing the unsignalized intersections. Finally, about 19% and 16% of respondents indicated that they are not qualified to answer this question for stop-controlled intersection and roundabouts, respectively.

Figure 11. Traffic safety problems due to lack of lighting at stop-controlled intersections and roundabouts



The next question in this section requested survey's participants to state the primary reason(s) for traffic crashes at stop-controlled intersections and roundabouts during nighttime at their states. As presented in Figure 12, the main primary reasons of nighttime traffic crashes at stop-controlled intersections were driving under the influence of drugs or alcohol (19%) followed by distraction and speeding (18% each). Whereas the main primary reasons of nighttime traffic crashes at roundabouts were speeding (22%), driving under the influence of drugs or alcohol (21%), and distraction (18%).

The following question in this section of the survey requested the participants to report the main lighting approach applied at unsignalized intersections at their states. Figure 13 shows that the main lighting approaches for stop-controlled intersections were full lighting and other low-cost countermeasures (26% each) followed by partial lighting (24%). While, for roundabouts the main lighting approaches were full lighting (around 61%) followed by other low-cost countermeasures (about 18%) and then partial lighting (at 9%). These results are consistent with the fact that lighting is mandatory at roundabouts according to the guidelines of over two thirds of states participating in this study. Examples of low-cost countermeasures included using bigger signs, raised reflective pavement markers, reflective strips, blinker signs, and double signs among other solutions.

Figure 12. Primary reasons of nighttime traffic crashes at stop-controlled intersections and roundabouts

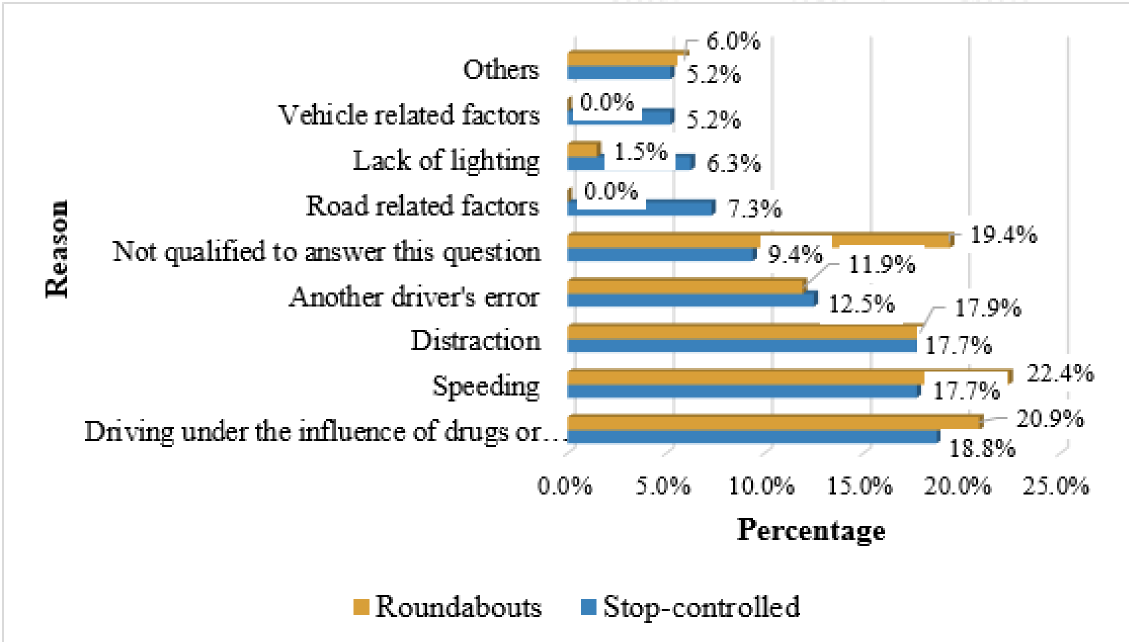
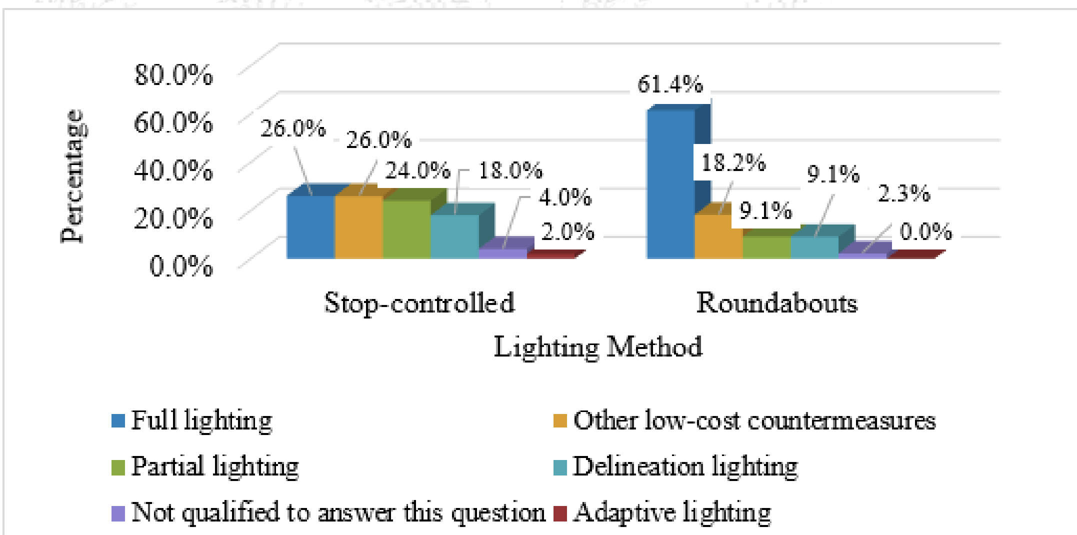


Figure 13. Main lighting approach applied at stop-controlled intersections and roundabouts



Two follow up questions were then asked to participants. The first question was asked if they selected partial lighting in the previous question while the other question was asked if they selected full lighting in the previous question. The two questions were designed to assess the effect of implementing partial/full lighting traffic safety at night.

The results for the partial lighting are shown in Table 4. It was found that more than half of participants (about 58%) claimed that stop-controlled intersections at their states did not have any evaluation after implementing the partial lighting followed by about one-third that indicated nighttime crash reduction. The remaining 8% mentioned that they are not qualified to answer this question. Whereas the results for the roundabouts are uniform as each of the four options received one-fourth of the responses.

Table 4. Observed results after partial lighting implementation

Observed results	Stop-controlled Intersections	Roundabouts
No evaluation was conducted	58.3%	25.0%
Nighttime crash reduction	33.3%	25.0%
Not qualified to answer this question	8.3%	25.0%
Daytime and nighttime crash reduction	0.0%	25.0%

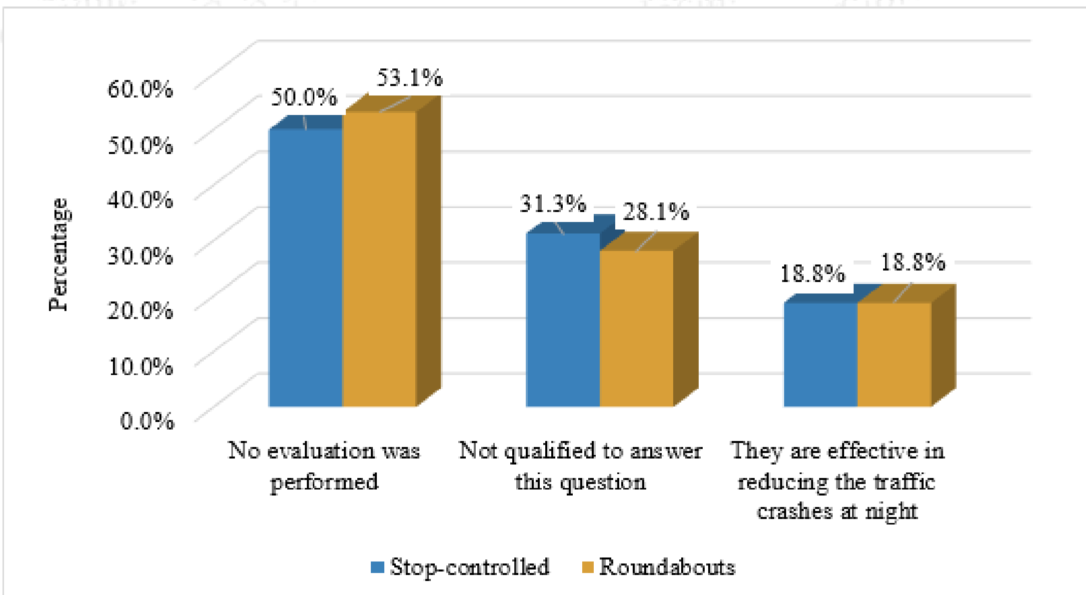
The results for the full lighting are shown in Table 5 where around 38% of respondents reported nighttime crash reduction at stop-controlled intersections at their states while another 38% indicated that no evaluation was conducted, and the remaining 25% was for participants that were not qualified to answer. However, regarding roundabouts, 50% of respondents stated that they did not have any evaluation conducted at roundabouts at their states, followed by one-fourth of the respondents who indicated that they were not qualified to answer. Additionally, about 14% mentioned that nighttime crashes were reduced after implementing full lighting at roundabouts while 7% indicated that the traffic safety status was not affected.

Table 5. Observed results after full lighting implementation

Observed results	Stop-controlled Intersections	Roundabouts
Nighttime crash reduction	37.4%	14.3%
No evaluation was conducted	37.5%	50.0%
Not qualified to answer this question	25.0%	25.0%
Daytime and nighttime crash reduction	0.0%	3.6%
Traffic safety status has not changed	0.0%	7.1%

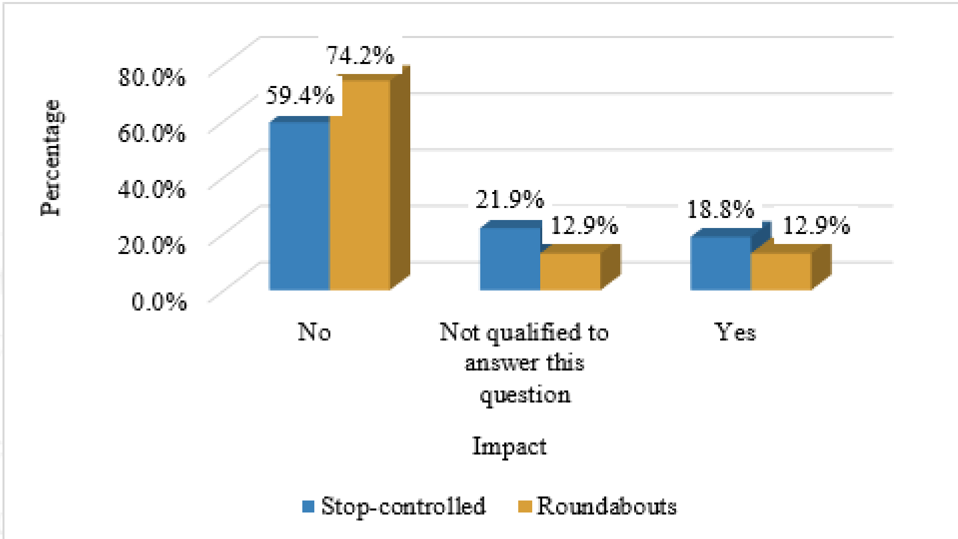
Participants were requested then to indicate the effectiveness of any low-cost countermeasures that have been used in their state. The responses between stop-controlled intersections and roundabouts were almost similar as shown in Figure 14 they were about 19% for both stop-controlled intersections, and for roundabouts, it was confirmed that low-cost countermeasures are effective in reducing the traffic crashes at nighttime. On the other hand, 50% of the responses for stop-controlled intersections and 53% for roundabouts indicated that no evaluation was performed. While 31% and 28% (for stop-controlled intersections and roundabouts, respectively) were for participants that weren't qualified to answer this question.

Figure 14. Effectiveness of low-cost countermeasures at stop-controlled intersections and roundabouts



Afterwards, survey participants were asked to report any negative impacts on traffic safety that were observed after installing lighting at unsignalized intersections at their states. As presented in Figure 15, only about 19% for stop-controlled intersections and 13% for roundabouts reported negative impacts due to installing lighting while the remaining percentages were either no negative impacts (59% for stop-controlled intersections and 74% for roundabouts) or participants weren't qualified to answer this question (22% and 13% for stop-controlled intersections and roundabouts, respectively). The reported negative impacts due to lighting installation included poorly designed lighting systems, increased glare, reduced visibility, and increased chance of crash occurrence by hitting the lighting pole foundation.

Figure 15. Negative impacts for installing lighting at stop-controlled intersections and roundabouts



Participants were then asked to suggest what should be done regarding unlighted intersections at their state. The responses of this question are presented in Figure 16. The main reported actions towards unlighted stop-controlled intersections were that they should be partially or fully lighted depending on the traffic safety status (almost 72%) while for roundabouts the action was that they should be fully lighted (about 41%). The remaining actions and their corresponding percentages are shown in the Figure 16.

Then, survey participants were asked to indicate how strongly they agree that partially lighted intersections should be converted to fully lighted on a 5-level Likert scale as shown in Figure 17. For stop-controlled intersections, the order of agreement from highest to lowest was as follows: neutral (44%), disagree (31%), strongly disagree and not qualified to answer (9%), agree (6%), and strongly agree (0%). While the responses for roundabouts were as follow: neutral (28%), strongly agree (19%), disagree and not qualified to answer (16%), agree (13%), and strongly disagree (9%). Overall, excluding neutral and NA responses, about 41% of responses do not agree that partially lighted stop-controlled intersections should be converted to fully lighted while 31% agree that partially lighted roundabouts should be converted to fully lighted.

Figure 16. Recommended action regarding unlighted intersections

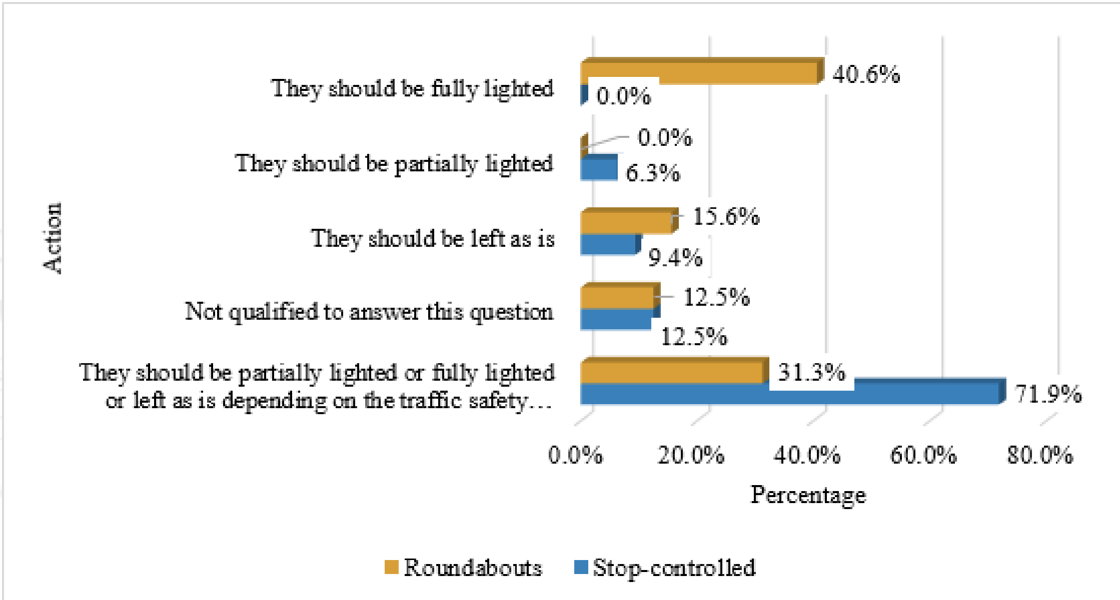
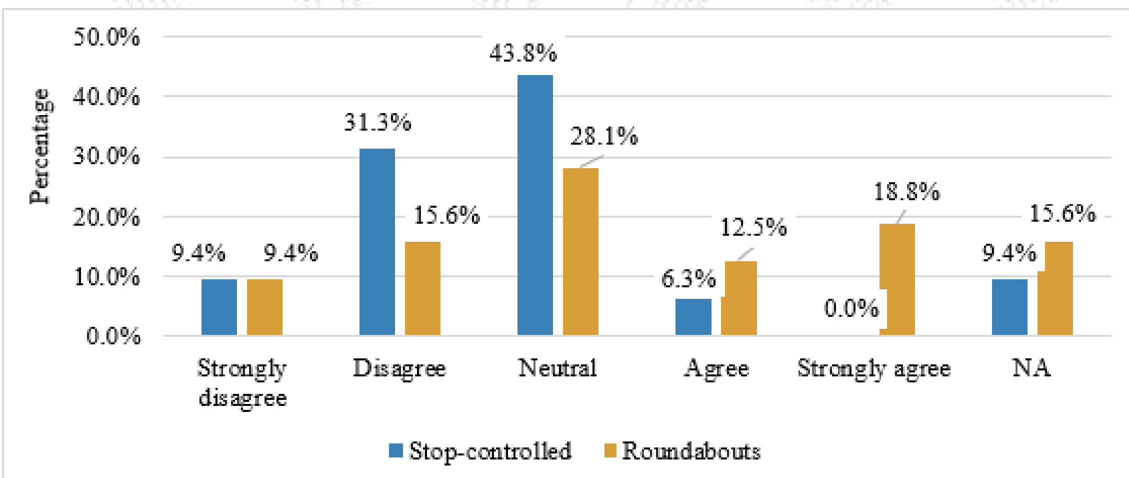
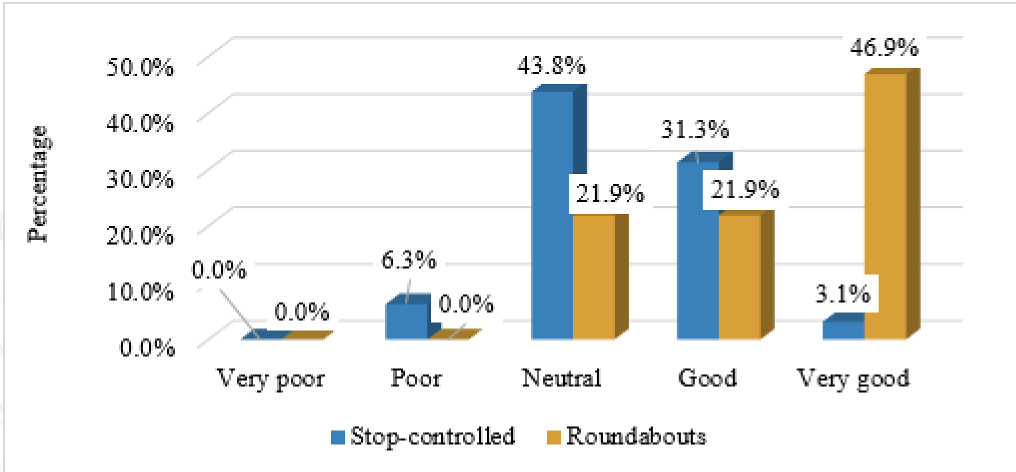


Figure 17. Level of agreement regarding converting partially lighted intersections to fully lighted



The last question in this section requested participants to rate the overall safety condition at their unsignalized intersections as shown in Figure 18. The overall safety condition at stop-controlled intersections ranked from highest to lowest was as follows: neutral (44%), good (31%), poor (6%), very good (3%), and very poor (0%), while the ratings for roundabouts were as follows: very good (47%), good and neutral (22%), and poor and very poor (0%). These results indicate that the overall safety condition was good for stop-controlled intersections (34.4%) and very good for roundabouts (68.8%).

Figure 18. Overall safety condition rating at stop-controlled intersections and roundabouts



Part 3: Cost-Benefit Analysis. The last section of the survey titled "Cost-Benefit Analysis," included questions related to cost and benefits of providing unsignalized intersections with street lighting. This section started by asking the participants to choose one of the statements that better represent the cost effectiveness of intersection lighting method used at their state. Table 6 presents the cost effectiveness of applied lighting schemes. Almost half of the participants (about 47%) indicated that they do not perform cost-benefit analysis, while about 28% indicated that their implemented lighting method is cost effective. Moreover, about one-fifth (nearly 19%) mentioned that they are looking for more cost-effective lighting methods, and finally about 6% stated that they are not qualified to answer this question.

Table 6. Cost effectiveness of applied lighting scheme

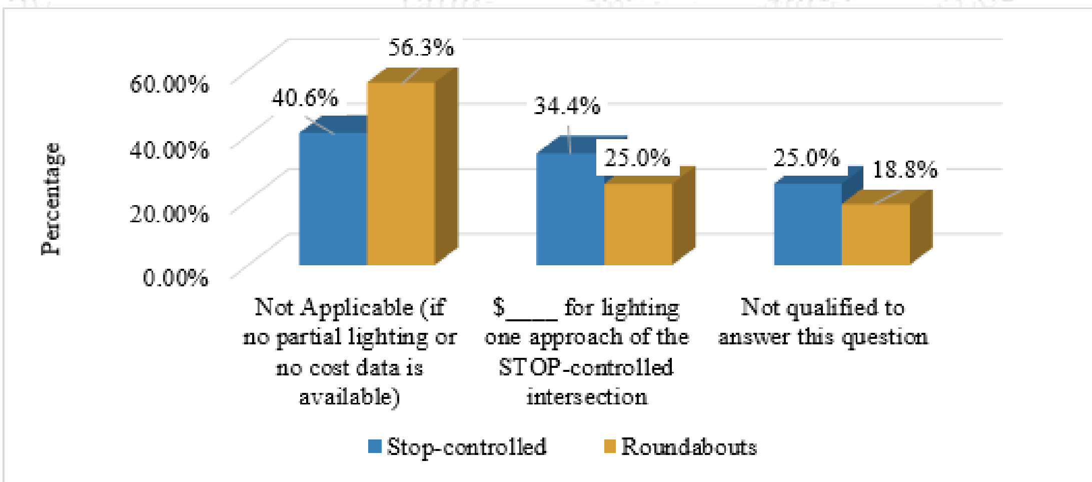
Cost Effectiveness of Applied Lighting Scheme in Your State	Percentage
We do not perform cost-benefit analysis for intersections illumination	46.9%
It is cost effective	28.1%
We are looking for more cost-effective lighting methods	18.8%
Not qualified to answer this question	6.3%

The next question was about the cost of installing full lighting scheme at a typical intersection. The results indicated that the installation cost varies from a state to another and the average cost for installing full lighting at a 4-leg stop-controlled intersection was approximately $110,000. While for a 4-leg roundabout, it was approximately $139,000.

Furthermore, DOT professionals were requested to report the cost of maintaining a typical fully lighted intersection. It was found that the average cost for maintaining a fully lighted 4-leg stop-controlled intersection was about $5,000; whereas, the cost for fully lighted 4-leg roundabout was nearly $6,000.

Then in the next question, participants were asked if they know the average initial costs of partial lighting for a typical 4-leg intersection. As shown in Figure 19, only about one-third (34%) of participants knew the initial cost of installing partial lighting for one approach of a 4-leg stop-controlled intersection, while the percentage of participants that knew the initial cost of installing partial lighting for one approach of a 4-leg roundabout was one-fourth (25%). The remaining percentages for stop-controlled intersections and roundabouts represent participants who aren't qualified to answer this question.

Figure 19. Availability of cost information for partial lighting



The following question was about reporting the cost for installing partial lighting at one approach of a typical unsignalized intersection. The average cost for installing partial lighting at one approach of a 4-leg stop-controlled intersection was approximately $27,000, while for a 4-leg roundabout, it was approximately $34,000.

The next question asked respondents to state how strongly they agree or disagree that the benefits of reduced crash rate outweigh the cost associated with the maintenance of intersections. As presented in Table 7, the overall level of agreement to the above statement for stop-controlled intersection was "agree" at about 41% followed by "neutral" with 25%. The overall level of agreement to the above statement for roundabouts was "agree" and "strongly agree," nearly 44% and 25%, respectively.

Table 7. Benefits of reduced crash rates compared to associated lighting costs

Does Benefits of Reduced Crash Rate Overweigh Lighting Costs	Stop-controlled Intersections	Roundabouts
Strongly disagree	6.3%	3.1%
Disagree	0.0%	3.1%
Neutral	25.0%	21.9%
Agree	40.6%	43.8%
Strongly agree	18.8%	25.0%
Not qualified to answer this question	9.4%	3.1%

The final question in this section and in the survey was about determining the best recommended countermeasure to improve nighttime traffic safety at unsignalized intersections. Table 8 shows the reported recommended countermeasure. The best recommended countermeasure for stop-controlled intersection was to "provide full or partial lighting based on traffic safety analysis," which accounted for about 44% of the responses; whereas, the best recommendation for roundabouts was to "providing full lighting to all intersections" that also accounted for nearly 44% of the responses.

Table 8. Recommended countermeasure to improve nighttime traffic safety

Recommended Countermeasure	Stop-controlled Intersections	Roundabouts
Providing full or partial lighting based on traffic safety analysis	43.8%	28.1%
Using other cost-effective countermeasures	25.0%	12.5%
Not qualified to answer this question	12.5%	9.4%
Providing partial lighting in addition to using other cost-effective countermeasures	12.5%	6.3%
Providing full lighting to all intersections	6.3%	43.8%

Section 2: Analysis of Crash Data

To achieve this task, the research team obtained the database of all crashes that occurred at roundabouts and stop-controlled intersections in Louisiana during the five-year period between 2016 – 2020. The data was obtained with the help of LTRC and PRC members. There were two datasets of crash data, one dataset corresponded to crashes that occurred at roundabouts, while the other one corresponded to crashes that occurred at stop-controlled intersections. Prior to proceeding with the analysis of crash data, a significant amount of time was required to collect some additional data that was missing in the crash data such as:

- Whether every intersection under investigation has street lighting or not,
- Whether every intersection has physical separation or not,
- Whether every intersection has right channelization or not, and
- The posted speed of both major and minor roads at an intersection.

Since this information was not available in the crash report or in any other sources, the research team had to perform manual investigation and verification (through Google Earth and Google Maps) to obtain this missing information for every intersection under investigation.

Traffic Crashes Collected at Roundabouts. Initially, there was a total of 863 traffic crashes that occurred at 27 intersections in the original dataset for roundabouts. However, 157 crashes and 7 intersections were excluded from further analysis due to the following reasons:

- 29 crashes that occurred at a single intersection were removed as the control type was traffic lights instead of a roundabout as shown in Figure 20.
- 78 crashes that occurred at 5 intersections were excluded as the control type at the time of crashes was a stop-controlled intersection instead of a roundabout. One example is presented in Figure 21.
- 50 crashes that occurred at 4 intersections were excluded as the control type at the times of crashes were unknown.
- 6 intersections were repeated under a slightly different name; however, the coordinates confirmed that they were the same intersection.
- 1 roundabout was removed for being in an urban area.

Therefore, the final number of crashes and roundabouts that were used for further analysis were: 705 crashes that occurred at 19 roundabouts.

Figure 20. Signalized interaction in roundabouts database

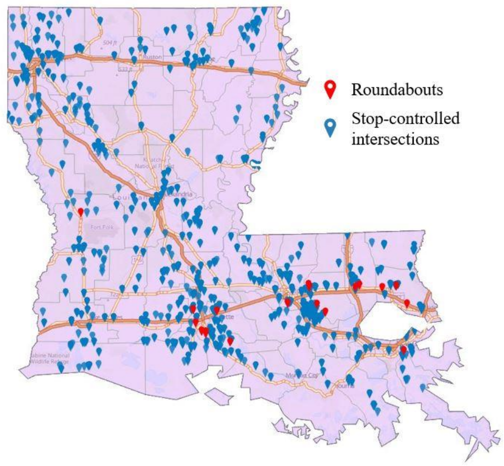
Figure 21. Intersection that was converted from stop-controlled to roundabout

Stop-controlled intersection in November 2017 | Roundabout in January 2019

Traffic Crashes Collected at Stop-controlled Intersections. Similarly, there was initially a total of 160,520 crashes that occurred at 24,327 stop-controlled intersections in the original dataset. However, and in line with the project's objective to investigate whether Louisiana has a traffic safety problem due to lack of lighting at its intersections, only crashes that occurred at intersections where at least one crash that occurred due to lack of lighting (as a primary or a secondary contributing factor) were considered for further analysis. Thus, 5,011 crashes that occurred at 613 intersections were analyzed. Furthermore, 741 crashes at 36 intersections were removed for being at urban areas, leaving 4,270 crashes at 577 stop-controlled intersections that were used for analysis.

The distribution of the crashes within the state of Louisiana is presented in Figure 22. As shown in the figure, roundabouts' crashes are mainly in the southern part of the state, while the stop-controlled intersections crashes are distributed throughout the state mainly at the big cities such as New Orleans, Baton Rouge, Lafayette, and Shreveport.

Figure 22. Distribution of crashes at roundabouts and stop-controlled intersections in Louisiana (2016 – 2020)



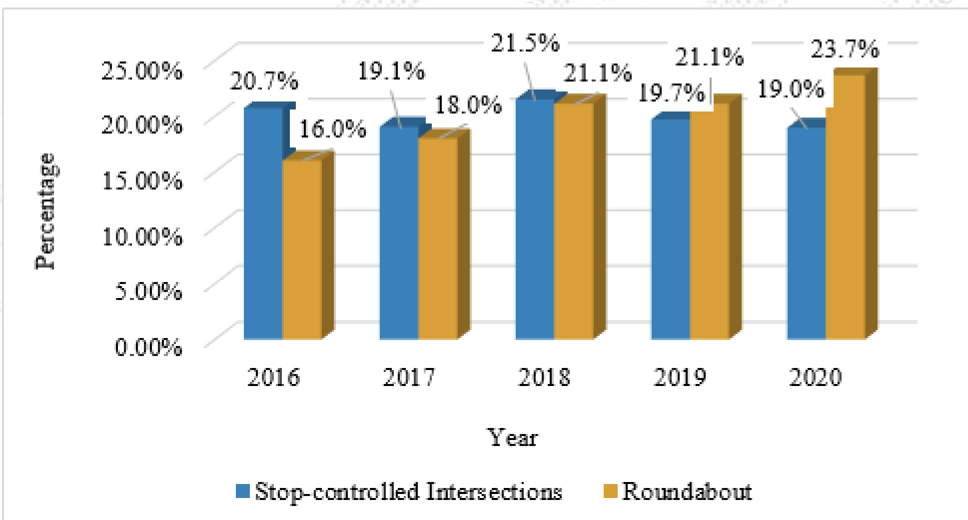
Methodology used in the Analysis of Crash Data. Several statistical techniques were employed in this task to analyze the crash data including:

- Descriptive summary statistics: it was used to provide an overall idea about the distribution of each variable in the crash dataset and the levels underneath it.
- Cross sectional analysis: it was used to compare the frequencies and ratios of crashes that occurred at lit intersections and compare them with statistics at unlit intersections (used by prior studies such as Sasidharan and Donnell, 2010 [12]).
- Multivariate Analysis (MVA): a statistical technique that analyzes data using more than one independent variable. In this study, two MVA techniques were employed as follows:
  - Poisson Regression: it was used to identify the contributing that affect the frequency of crash occurrence at both stop-controlled intersections and roundabouts (used by Sasidharan and Donnell, 2010 [12]).
  - Negative Binomial Regression: similarly, this method was used to model the variables that impacted the frequency of crash occurrence. It also accounts for data overdispersion which is one of the limitations of passion regression (used by Sasidharan and Donnell, 2010 [12] and Bhagavathula et al., 2017 [37]).

Descriptive Summary Statistics. A detailed summary statistic is provided for the main variables in the crash data for both roundabouts and stop-controlled intersections crashes.

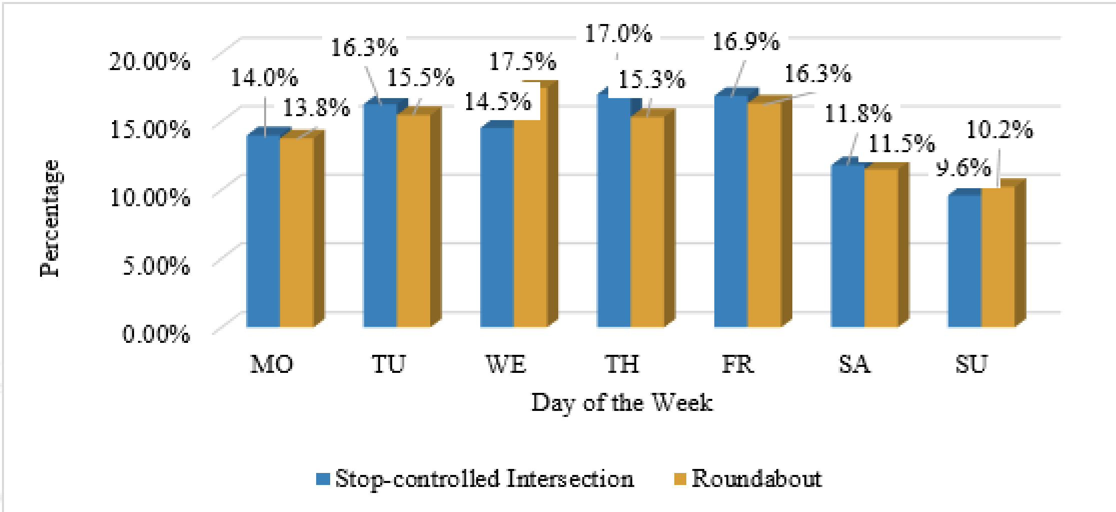
Figure 23 illustrates the distribution of the 705 crashes that occurred at roundabouts during the five years period between 2016 – 2020. As shown in the figure, the percentage of crashes continued to increase from one year to another except for 2018 – 2019 where it stayed the same. While the distribution of 4,270 crashes that occurred at stop-controlled intersection generally decreased except for 2017 – 2018 where it slightly increased by 2.4%. An interesting result is that the percentage of crashes at roundabouts has increased by 2.6% in 2020 compared to 2019, which indicates that crashes have increased during the first year of COVID-19 pandemic and is consistent with the findings of other recent studies.

Figure 23. Distribution of crashes by year



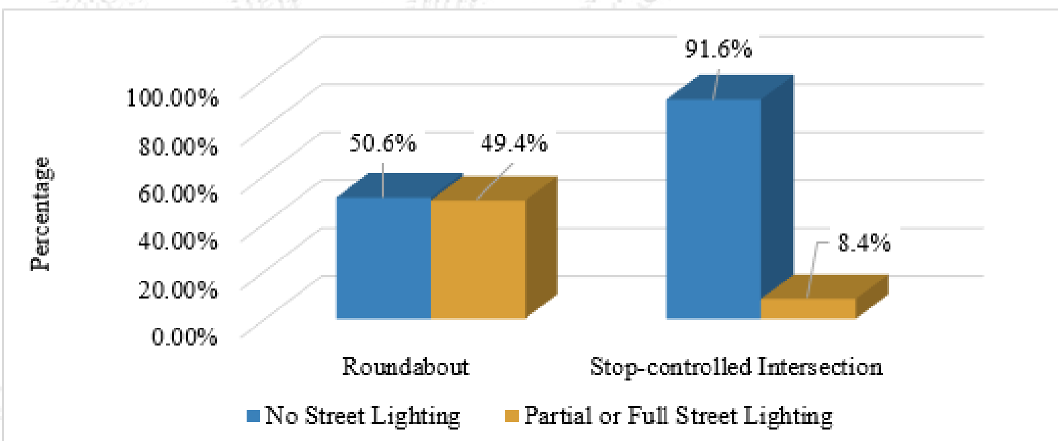
The distribution of the crashes among days of the week revealed that the highest percentage of roundabout crashes happened during Wednesdays (around 17.5%) while the lowest percentage of crashes occurred on Sundays (10%), as shown in the Figure 24. However, the highest percentage of stop-controlled intersection crashes occurred on Thursdays (about 17%) and the lowest percentage (9.6%) of crashes happened on Sundays as well similar to roundabouts.

Figure 24. Distribution of crashes by day of the week



The distribution of the crashes according to the lighting condition at the intersections showed that almost half of the roundabout crashes (50.6%) occurred at unlighted roundabouts, while more than 90% of the stop-controlled intersection crashes occurred at unlighted stop-controlled intersections as shown in Figure 25.

Figure 25. Distribution of crashes by street lighting condition at the intersection



In addition, the distribution of crashes by the primary contributing factor showed that violations and movement prior to crash were the two main primary contributing factors for crashes at roundabouts and at stop-controlled intersections as shown in Table 9. Lighting was not the primary factor for any of the roundabouts' crashes, while it was responsible for only 3.5% of stop-controlled intersections crashes.

Similarly, the distribution of crashes by the secondary contributing factor showed that movement prior to crash and violations are the two main secondary contributing factors for crashes at roundabouts and at stop-controlled intersections. Again, lighting was not a secondary factor for any of the roundabouts' crashes. However, it was the secondary contributing factor for about 12% of the stop-controlled intersection crashes. Table 10 presents the secondary contributing factor and their corresponding percentages for crashes occurring at both roundabouts and stop-controlled intersections.

Table 9. Distribution of crashes by primary contributing factor

Type of intersection	**Roundabouts**	**Stop-controlled Intersections**
Primary Contributing Factor	**Frequency (Percentage)**	**Frequency (Percentage)** *1
Violations	540 (76.6%)	2,898 (68.0%)
Movement Prior To Crash	122 (17.3%)	605 (14.2%)
Condition of Driver	27 (3.8%)	222 (5.2%)
Vehicle Conditions	9 (1.3%)	29 (0.7%)
Road Surface and Condition	3 (0.5%)	219 (5.1%)
Weather	2 (0.3%)	24 (0.6%)
Vision Obscurement	1 (0.1%)	36 (0.8%)
Kind of Location	1 (0.1%)	33 (0.8%)
Lighting	0 (0.0%)	149 (3.5%)
Pedestrian Action and Condition	0 (0.0%)	47 (1.1%)
Traffic Control	0 (0.0%)	3 (0.1%)

*1 There were 5 crashes at stop-controlled intersections with a missing primary contributing factor.

Table 10. Distribution of crashes by secondary contributing factor

Type of intersection	**Roundabouts**	**Stop-controlled Intersections**
Primary Contributing Factor	**Frequency (Percentage)** *1	**Frequency (Percentage)** *1
Movement Prior To Crash	502 (75.0%)	2,372 (64.0%)
Violations	128 (19.1%)	435 (11.7%)
Condition of Driver	20 (3.0%)	201 (5.4%)

Type of intersection	Roundabouts	Stop-controlled Intersections
Primary Contributing Factor	**Frequency (Percentage) *1**	**Frequency (Percentage) *1**
Kind of Location	6 (0.9%)	65 (1.8%)
Road Surface and Condition	6 (0.9%)	42 (1.1%)
Vehicle Conditions	3 (0.5%)	22 (0.6%)
Weather	2 (0.3%)	52 (1.4%)
Vision Obscurement	1 (0.2%)	53 (1.4%)
Traffic Control	1 (0.2%)	7 (0.2%)
Lighting	0 (0.0%)	451 (12.2%)
Pedestrian Action and Condition	0 (0.0%)	7 (0.2%)

*1 There were 36 crashes at roundabouts and 563 crashes at stop-controlled intersections with a missing secondary contributing factor.

The previous tables showed that violation was one of the major contributing factors for crashes at both types of intersections. After further investigation, Table 11 presents the most repeated violations by the at-fault drivers. At both roundabouts and stop-controlled intersections, failure to yield, careless operation and following too closely were the main three types of violations.

Table 11. Distribution of crashes by violation of responsible driver

Traffic Violations of Responsible Driver	Roundabouts	Stop-controlled Intersections
Failure to Yield	38.3%	25.6%
Careless Operation	28.9%	26.9%
Following Too Closely	12.1%	11.4%
Unknown	3.7%	4.9%
Other	3.7%	3.9%
Turned from Wrong Lane	3.7%	0.5%
No Violations	2.8%	14.5%
Other Improper Turning	2.7%	5.0%
Driver Condition	2.0%	3.2%

Traffic Violations of Responsible Driver	Roundabouts	Stop-controlled Intersections
Disregarded Traffic Control	1.7%	3.5%
Vehicle Condition	0.4%	0.7%

The responsible driver was inattentive in about two-thirds of the roundabout crashes (63.4%) and in around one-half of the stop-controlled intersection crashes (50.4%) as presented in Table 12, which shows the different conditions of the at-fault drivers.

Table 12. Distribution of crashes by the common condition of responsible driver

Conditions of the Responsible Driver	Roundabouts	Stop-controlled Intersections
Inattentive	63.4%	50.4%
Normal	18.6%	30.4%
Others or Unknown	10.2%	11.5%
Distracted	4.0%	4.4%
Drinking Alcohol or Drug Use	3.8%	3.4%

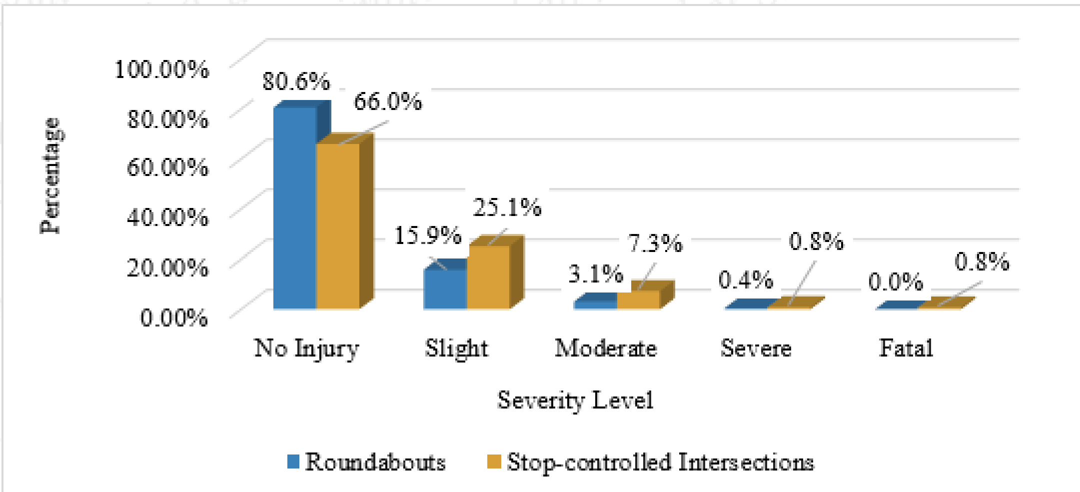
In addition, the distribution of crashes by weather condition at the time of crashes showed that almost three-quarters of the roundabouts and stop-controlled intersections crashes occurred under normal and clear weather conditions, 73.1% and 72.3%, respectively. The distribution of weather conditions at the time of crashes are presented in Table 13.

Table 13. Distribution of crashes by weather condition

Weather Conditions	Roundabouts	Stop-controlled Intersections
Clear	73.1%	72.3%
Cloudy	17.2%	15.4%
Rain	9.2%	10.8%
Fog/Smoke	0.3%	1.1%
Others or Unknown	0.1%	0.3%
Snow	0.1%	0.0%
Sleet/Hail	0.0%	0.1%

It was found also that most of the roundabouts' crashes (almost 81%) were property damage only (PDO) compared to about two-thirds of the stop-controlled intersections' crashes (about 66%). Figure 26 shows that no fatal crashes were observed at the roundabouts under investigation, while only 0.8% of fatal crashes occurred at the stop-controlled intersections.

Figure 26. Distribution of crashes by crash severity



Regarding injuries, the findings showed that most of the crashes that occurred at roundabouts (close to 81%) did not involve any injuries compared to about 67% of stop-controlled intersection, while approximately 15% of the roundabouts' crashes involved only one injury compared to about 20% of the stop-controlled intersections crashes as shown in Table 14.

Table 14. Distribution of crashes by number of total injuries

Number of Total Injuries	Roundabouts	Stop-controlled Intersections
0	80.6%	66.5%
1	14.6%	19.8%
2	3.4%	8.2%
3	0.6%	3.2%
4	0.6%	1.3%
5 or more	0.3%	0.9%

Most of the roundabout crashes (about 83%) and stop-controlled intersection crashes (around 71%) involved two vehicles as depicted in Table 15.

Table 15. Distribution of crashes by total number of involved vehicles

Number of Vehicles Involved	Roundabouts	Stop-controlled Intersections
1	13.9%	24.2%
2	83.1%	70.8%
3 or more	3.0%	5.0%

Regarding road surface condition, it was found that the majority of crashes at roundabouts (around 84%) and at stop-controlled intersections (around 83%) occurred on roads with dry surface condition. Whereas wet surface condition was responsible for close to 15% of roundabout crashes and approximately 16.5% of stop-controlled intersection crashes as presented in Table 16.

Table 16. Distribution of crashes by road surface condition

Road Surface Condition	Roundabouts	Stop-controlled Intersections
Dry	84.4%	83.1%
Wet	15.2%	16.5%
Snow	0.1%	0.1%
Ice	0.1%	0.1%
Contaminant (Sand, Mud, Oil, etc.)	0.1%	0.1%
Others	0.0%	0.2%

With respect type of collisions, it was found that rear-end crashes were the most frequent type of collision for roundabouts and stop-controlled intersection crashes at about 31% and about 26%, respectively. The distribution of crashes according to type of collision is presented in Table 17.

Table 17. Distribution of crashes by collision type

Type of Collision	Roundabouts	Stop-controlled Intersections
Rear-End	31.2%	26.3%
Sideswipe Same	14.0%	6.3%
Right Angle	13.8%	18.5%
Right Turn Same	13.3%	2.3%
Non-Collision with Motor Vehicle	12.2%	22.1%
Other	7.0%	8.3%
Left Turn Diagonal	4.1%	2.8%
Left Turn Same	1.8%	2.6%
Head On	0.9%	2.2%
Sideswipe Opposite	0.9%	2.1%
Left Turn Opposite	0.7%	5.6%
Right Turn Opposite	0.1%	0.8%

The distribution of crashes by road type showed that around 39% of roundabouts crashes and almost 76% of stop-controlled intersections crashes occurred at two-way roads without physical separation as presented in Table 18.

Table 18. Distribution of crashes by road type

Road Type	Roundabouts	Stop-controlled Intersections
Two-Way Road with No Physical Separation	39.2%	75.5%
One-Way Road	24.6%	3.9%
Two-Way Road with a Physical Separation	20.7%	18.4%
Others or Unknown	12.4%	0.5%
Two-Way Road with a Physical Barrier	3.1%	1.7%

Focusing on crashes that occurred at nighttime only, the distribution of crashes by primary contributing factor showed that lighting was the 5th primary contributing factor for crashes at stop-control intersections by 8%, while lighting was not among the contributing factors for roundabouts crashes as shown in Table 19.

Table 19. Distribution of night crashes by primary contributing factor

Type of Intersections	**Roundabouts**	**Stop-controlled Intersections**
Primary Contributing Factor	**Frequency (Percentage)**	**Frequency (Percentage)** *1
Violations	84 (70.0%)	323 (40.9%)
Movement Prior To Crash	17 (14.2%)	137 (17.4%)
Condition of Driver	16 (13.3%)	75 (9.5%)
Vehicle Conditions	2 (1.7%)	8 (1.0%)
Weather	1 (0.8%)	7 (0.9%)
Roadway Condition	0 (0.0%)	127 (16.1%)
Lighting	0 (0.0%)	63 (8.0%)
Pedestrian Action	0 (0.0%)	22 (2.8%)
Kind of Location	0 (0.0%)	18 (2.3%)
Vision Obscurement	0 (0.0%)	4 (0.5%)
Road Surface	0 (0.0%)	3 (0.4%)
Condition of Pedestrian	0 (0.0%)	2 (0.3%)

*1 There was 1 crash at a stop-controlled intersection with a missing primary contributing factor.

Furthermore, the distribution of crashes by secondary contributing factor showed that lighting was the 2nd contributing factor for crashes at stop-controlled intersections at 34.2% as shown in Table 20. However, lighting was not among the secondary contributing factors of roundabouts crashes.

Table 20. Distribution of night crashes by secondary contributing factor

Type of Intersections	**Roundabouts**	**Stop-controlled Intersections**
Secondary Contributing Factor	**Frequency (Percentage)** *1	**Frequency (Percentage)** *1
Movement Prior To Crash	86 (73.5%)	270 (38.5%)
Violations	27 (23.1%)	86 (12.3%)
Condition of Driver	4 (3.4%)	39 (5. 6%)

Type of Intersections	Roundabouts	Stop-controlled Intersections
Secondary Contributing Factor	**Frequency (Percentage) *1**	**Frequency (Percentage) *1**
Lighting	0 (0.0%)	240 (34.2%)
Kind of Location	0 (0.0%)	19 (2.7%)
Weather	0 (0.0%)	18 (2.6%)
Road Surface	0 (0.0%)	7 (1.0%)
Roadway Condition	0 (0.0%)	7 (1.0%)
Vehicle Conditions	0 (0.0%)	6 (0.9%)
Vision Obscurement	0 (0.0%)	5 (0.7%)
Pedestrian Actions	0 (0.0%)	3 (0.4%)
Condition of Pedestrian	0 (0.0%)	1 (0.1%)

*1 There were 3 crashes at roundabouts and 89 crashes at stop-controlled intersections with a missing secondary contributing factor.

Cross Sectional Analysis. A cross sectional analysis was performed to compare the frequencies of crashes occurring at lit intersection to unlit intersections. Also, to compare the ratios of night-to-day and night-to-total crashes. It was found that there were 11 lighted roundabouts (either partially or fully) while 8 roundabouts were unlit. In total, 348 crashes occurred at lighted roundabouts while 357 occurred at unlighted roundabouts. Table 21 provides a detailed comparison between the lighted and unlighted roundabouts. The rates of day crashes per intersection and night crashes per intersection were higher at unlighted roundabouts compared to lighting ones, meaning that there were more crashes at unlighted roundabouts (37.63 and 7.00, respectively) compared to lighted roundabouts (25.82 and 5.82, respectively). However, the rates of night-to-day crashes and night-to-total crashes were higher for lighted roundabouts (0.23 and 0.18, respectively) compared to unlighted ones (0.19 and 0.16, respectively). One of the reasons that might explain why lighted roundabouts ratios were higher than unlighted roundabouts is that lighting may have been used as a countermeasure to improve nighttime traffic safety at those intersections. Therefore, one limitation of the cross-sectional analysis is the lack of information about when lighting was installed at the intersections under investigation.

Table 21. Cross sectional analysis between lit and unlit roundabouts

Type	Number of intersections	Total Crashes	Day Crashes	Night Crashes	Day Crashes/ Intersection	Night Crashes/ Intersection	Night-to-Day Crash Ratio	Night-to-Total Crash Ratio
Lighted	11	348	284	64	25.82	5.82	0.23	0.18
Unlighted	8	357	301	56	37.63	7.00	0.19	0.16
Total	19	705	585	120	–	–	–	–

Similarly, for the stop-controlled intersections, there were 43 lit intersections (either partially or fully) compared to 534 that were unlit. In total, 357 crashes occurred at lit intersections, while 3,897 occurred at unlit intersections. The remaining 16 crashes were not analyzed as the time of crash was unknown. Table 22 provides a detailed comparison between the lit and unlit stop-controlled intersections. The results of the cross-sectional analysis for stop-controlled intersections show higher ratios of day crashes/intersection and night crashes/intersection at lighted intersections compared to unlit ones. For example, the day crashes/intersection and night crashes/intersection ratios were 6.86 and 1.44, respectively, at lighted intersections compared to 5.93 and 1.36, respectively for unlighted intersections. The same explanation and limitation that was mentioned for the roundabout is applicable to the stop-controlled intersections. However, the night-to-day and night-to-total crash ratios at lighted intersections were lower compared to unlighted stop-control intersections. For instance, the night-to-day crash ratio and night-to-total crash ratio at lighted intersections were 0.21 and 0.17, respectively, compared to 0.23 and 0.19, respectively for unlighted intersections.

Table 22. Cross sectional analysis between lit and unlit stop-controlled intersections

Type	Number of intersections	Total Crashes	Day Crashes	Night Crashes	Day Crashes/ Intersection	Night Crashes/ Intersection	Night-to-Day Crash Ratio	Night-to-Total Crash Ratio
Lighted	43	357	295	62	6.86	1.44	0.21	0.17
Unlighted	534	3,897	3,169	728	5.93	1.36	0.23	0.19
Total	577	4,254	3,464	790	–	–	–	–

Note: 16 crashes excluded from the cross-sectional analysis as the time of crash was unknown.

Multivariate Analysis (MVA) – Poisson Regression. Poisson regression model is a statistical analysis technique used by many prior studies [7] [12] [14] [15] [17] [40] to study the factors that affected occurrence of crashes. The form of the Poisson regression model is shown below:

$$y \sim Poisson\ (\mu) \quad (1)$$

$$log(\mu) = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n$$

$$\mu = e^{\alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n}$$

Where,

μ is the response/predictor variable,
$\alpha_0, \alpha_1, \alpha_2, \ldots, \alpha_n$ are the parameter estimates of the model, and
$X_1, X_2, \ldots, X_n$ are the explanatory variables.

To develop the Poisson regression model, crash frequency was used as the dependent (response) variable while the following explanatory variables were used as independent variable: street lighting condition, number of street lights, availability of physical separation (median), number of legs with physical separation, number of legs of the intersection, posted speed, surface type, availability of right turn channelization, number of legs with right turn channelization, and the log of average daily traffic (ADT). Table 23 provides more information about the variables used to develop the Poisson regression model and their levels.

Table 23. Response and explanatory variables used in multivariate analysis models

Variable	**Definition**	**Parameter**	**Notes**
Response Variable	Frequency of crashes	μ	Continuous
Explanatory Variable 1	Street lighting condition	L	0 – No lighting 1 – Lighting available
Explanatory Variable 2	Number of street lights	NL	Continuous
Explanatory Variable 3	Availability of physical separation (median)	P	0 – Not available 1 – Available
Explanatory Variable 4	Number of legs with physical separation	NP	Continuous
Explanatory Variable 5	Number of legs of the intersection	N	Continuous
Explanatory Variable 6	Posted speed – Major Road	MS	Continuous
Explanatory Variable 7	Variation in posted speed	VarS	Continuous
Explanatory Variable 8	Surface type	S	0 – Asphalt 1 – Others

Variable	Definition	Parameter	Notes
Explanatory Variable 9	Availability of right turn channelization	R	0 – Not available 1 – Available
Explanatory Variable 10	Number of legs with right turn channelization	NR	Continuous
Explanatory Variable 11	Log of average daily traffic	ADT	Continuous

Two models were developed using the same explanatory variables; however, the response variable was different in each model where:

- Model 1 - All crashes model: response variable was the number of crashes that occurred at the intersection (during the night as well as during the day), and
- Model 2 - Nighttime crashes model: response variable was the number of crashes that occurred at night only.

Both models were then developed twice: one time for roundabouts crashes and one time for stop-control intersections. The results of these four Poisson regression models are presented in Table 24.

Table 24. Results of the Poisson regression models

Model	Intersection Type	Constant Term	L	P	N	S	R	ADT	Goodness of Fit
All crashes	Roundabout	-11.22	-0.18	–	1.29	1.33	–	2.16	14.27
Night crashes	Roundabout	-14.71	–	-0.98	1.53	2.93	–	2.08	2.87
All crashes	Stop-controlled	-0.63	–	0.28	0.62	-0.19	0.51	0.17	16.00
Night crashes	Stop-controlled	-0.02	–	–	–	–	0.55	0.18	1.66

Note: Significance at $P<0.05$

However, the goodness of fit for all these models except the night crashes at stop-controlled intersections were not acceptable (value of scaled Pearson X2/DF were above 2.0). Therefore, the results of the Poisson cannot be used, and negative binomial regression was used instead. While the goodness of fit for the night crashes model at stop-controlled intersections was acceptable, the model showed that lighting is not a significant factor that affected crash occurrence.

Multivariate Analysis (MVA) – Negative Binomial Regression. Similar to Poisson regression model, negative binomial regression is another statistical analysis technique used by many prior studies [5] [7] [10] [12] [37] [40] to model the factors that affected occurrence of crashes; the form of the negative binomial regression model is presented below:

$$\ln \lambda_i = \beta X_i + \varepsilon \quad (2)$$

Where,

λ_i is the expected number of crashes at intersection i,
β is the parameter estimates of the model,
X_i is the explanatory variables, and
ε is the error term.

The same variables and number of models were used to develop the negative binomial regression models. The results of the models are presented in Table 25.

Table 25. Results of the negative binomial models

Model	**Intersection Type**	**Constant Term**	**L**	**P**	**N**	**S**	**R**	**ADT**	**Goodness of Fit**
All crashes	Roundabout	-14.73	–	–	1.21	1.33	–	3.07	0.90
Night crashes	Roundabout	-14.92	–	-0.90	1.45	2.88	–	2.21	1.19
All crashes	Stop-controlled	-0.19	–	–	0.68	–	0.62	–	1.86
Night crashes	Stop-controlled	-0.005	–	–	–	–	0.54	0.17	1.28

Note: Significance at $P<0.05$

The goodness of fit for the negative binomial regressions were acceptable as the value of scaled Pearson X2/DF was below 2.0. Table 25 shows that for all crashes at roundabout model, the higher the number of legs (N) and higher ADT, the higher chance of crash occurring at the roundabout. Also, roundabouts with asphalt surface (S) have more chances for crashes compared to other surface types. While the night crash model for roundabouts showed that in addition to the above factors, roundabouts with physical separation (P) have lower chance of crash occurrence.

The stop-controlled intersections model indicated that the higher the number of legs, the higher the chance of crash occurrence. Also, availability of right turn channelization (R) also increased crash occurrence as they introduce more conflict points compared to intersections without right channelization; Figure 27 presents an example of stop-controlled intersection with right turn channelization. The night crashes model of stop-controlled intersection indicated that the availability of R and higher number of ADT have a positive relationship with increased chance of crash occurrence.

Figure 27. Google Earth screenshot of a stop-controlled intersection with right turn channelization

Section 3: Analysis of Driving Simulation Experiment

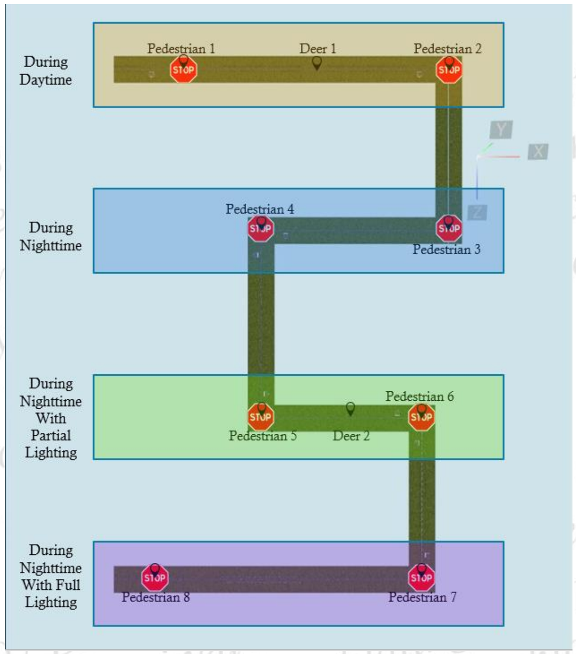
In addition to analyzing the crash data as presented in the previous section, the research team designed a driving simulator experiment to investigate the impact of street lighting on drivers' behavior and their ability to drive safely at nighttime.

Two scenarios were developed to achieve the objectives of this task. The first scenario included road environments consisting of eight stop-controlled intersections as follows:

- Two stop-controlled intersections during daytime,
- Two stop-controlled intersections during nighttime (without street lighting),
- Two stop-controlled intersections during nighttime (with partial lighting), and
- Two stop-controlled intersections during nighttime (with full lighting).

The surrounding environment setting for the experiment was rural area and the speed limit was 40 mph. A plan view of the stop-controlled intersection experiment is presented in Figure 28.

Figure 28. Plan view of the stop-controlled intersection scenario



A screenshot of the intersections with different lighting conditions is also shown in [Figure 29(a) to 29(d)].

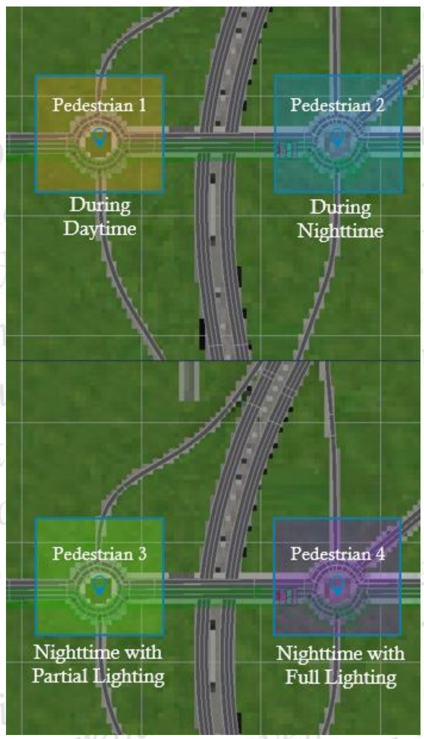
Figure 29. A screenshot of the driving simulator scenarios of the stop-controlled intersections

In addition, the second scenario consisted of four roundabouts as follows:

- One roundabout during daytime,
- One roundabout during nighttime (without street lighting),
- One roundabout during nighttime (with partial lighting), and
- One roundabout during nighttime (with full lighting).

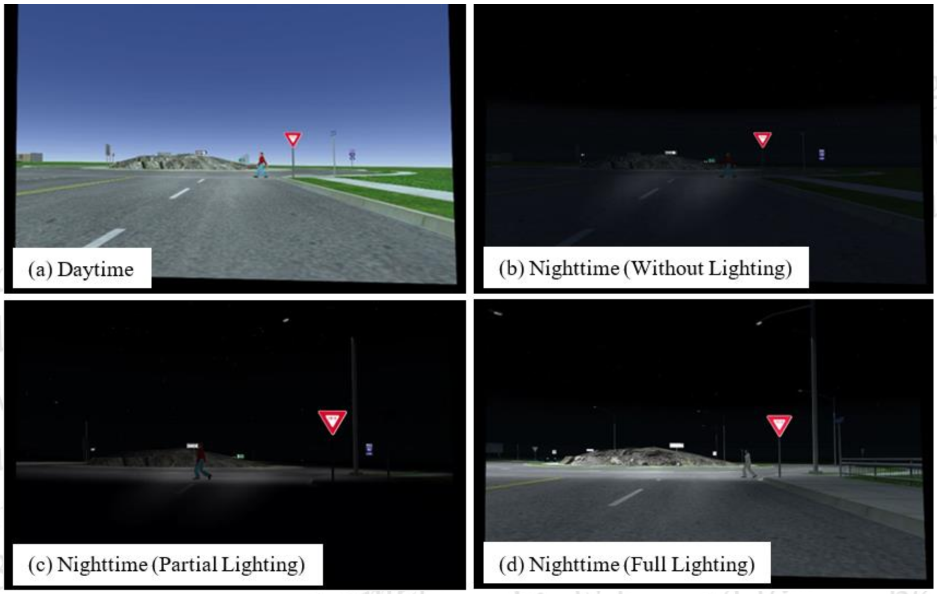
The surrounding environment setting for the experiment was also rural area and the speed limit was also 40 mph. A plan view of the roundabout experiment is presented in Figure 30.

Figure 30. Plan view of the roundabout scenario



A screenshot of the intersections with different lighting conditions is shown in [Figure 31(a) to 31(d)].

Figure 31. A screenshot of the driving simulator scenarios of roundabouts



Participants with a valid driver's license who are 18 years or older were invited to participate in the experiment, which took on average between 15 – 20 minutes to be completed. A total of 30 participants were able to complete the driving simulator experiment. While only one participant could not complete the experiment due to the motion sickness from the simulator and hence their responses were disregarded from further analysis.

To evaluate the impact of lighting on drivers' behavior several measures were recorded during the experiment including acceleration, deceleration, speed and time to collision (TTC). The concept of TTC was introduced in 1979 as a surrogate safety measure (SSM) that can be used to assess traffic safety. It is defined as "the time that remains until a collision between two vehicles (or two objects such as a vehicle and a pedestrian) would have occurred if the collision course and speed difference are maintained." Numerous prior studies used TTC as a SSM including Johnsson et al. (2018), Li et al. (2016), Jin et al. (2011), Vogal (2003), and Minderhoud et al. (2001) [41] [42] [43] [44] [45]. In this study, TTC was calculated between the participants' vehicle and pedestrians crossing the road at each intersection. The research team spent significant time during the design of the driving simulation experiment to code this SSM in the driving simulation software as it was not a built-in feature. Moreover, the coding of adding street lighting at night was also an obstacle that faced the research team as the lighting didn't work for some intersections in the beginning. However, the research team were able to overcome these issues during the experiment.

Figure 32 shows the results of the stop-controlled intersection scenario, while Figure 33 shows the results of the roundabout scenario. The red values correspond to the TTC, the blue values correspond to average speed, and the green values correspond to average acceleration/deceleration. For both stop-controlled intersections and roundabouts scenarios, participants drove at the intersections under different street lighting conditions. In the first scenario, participants drove through a total of eight stop-controlled intersections as follow: two intersections during daytime, two intersections during nighttime (without street lighting), two intersections during nighttime with partial lighting and two intersections during nighttime with full lighting. Several weather conditions (such as rain and fog) were added at some straight road segments between the intersections. Moreover, two deer were also added at two mid-blocks straight road segments between the intersections (one during daytime and the other one during nighttime). In the second scenario, participants drove through four roundabouts as follow: one roundabout during daytime, one roundabout during nighttime (without street lighting), one roundabout during nighttime with partial lighting and one roundabout during nighttime with full lighting. It is worth mentioning that drivers' behaviors were collected about 230 ft. before reaching the pedestrians (who were simulated to cross the roads at several locations throughout the experiment). In some cases, TTC was not applicable (represented by N/A) due to some possible reasons such as:

- The vehicle stopped too early before reaching the pedestrian, or
- There was a queue of vehicles ahead that caused the vehicle to reduce speed before reaching the intersection.

The results of the first scenario (stop-controlled intersections) show that introducing street lighting (partial and full) increased overall traffic safety compared to nighttime without street lighting. For example, as shown in Figure 32, TTC at partial lighting (pedestrian 6) was higher at 5.4s compared to intersection at night without street lighting (pedestrian 4) which is 5.1s. Furthermore, TTC for intersections with full lighting (pedestrians 7 and 8) weren't calculated as the visibility from the full lighting allowed participants to notice the intersection way in advance allowing them to reduce their speed gradually before reaching the intersections. However, TTC for the first intersection during night without street lighting (pedestrian 3) wasn't calculated because there was a queue of vehicles (ambient traffic) that caused participants to reduce their speed before reaching the intersection. In general, the average speed was similar during the night under different street lighting condition (approximately 15-16 mph) except for the first fully lighted stop-controlled intersection (pedestrian 7), which was 17 mph. Whereas, the acceleration/deceleration rates showed that comparing the average acceleration/deceleration for intersections without lighting to intersections with partial or full lighting revealed that during nighttime without street lighting (pedestrian 4) participants made sudden and quick deceleration as they noticed the intersection later compared to intersections with partial lighting and full lighting (pedestrians 5-8). Furthermore, the mid-block crossings (deer 1 and 2) results showed that the TTC was lower during the night (2.2s) compared to daytime (9.5s); whereas, the average speed and deceleration were higher during the night compared to daytime indicating that participants didn’t notice the deer at night until the last few seconds due to lack of lighting. While in the second scenario as shown in Figure 33, the TTC was not collected at any of the roundabouts due to the low design speed of the road (15 mph). The average speed is similar during the different lighting conditions (15-16 mph), while the average deceleration is higher during nighttime without street lighting compared to other lighting conditions.

Figure 32. Results of the driving simulator study for stop-controlled intersections

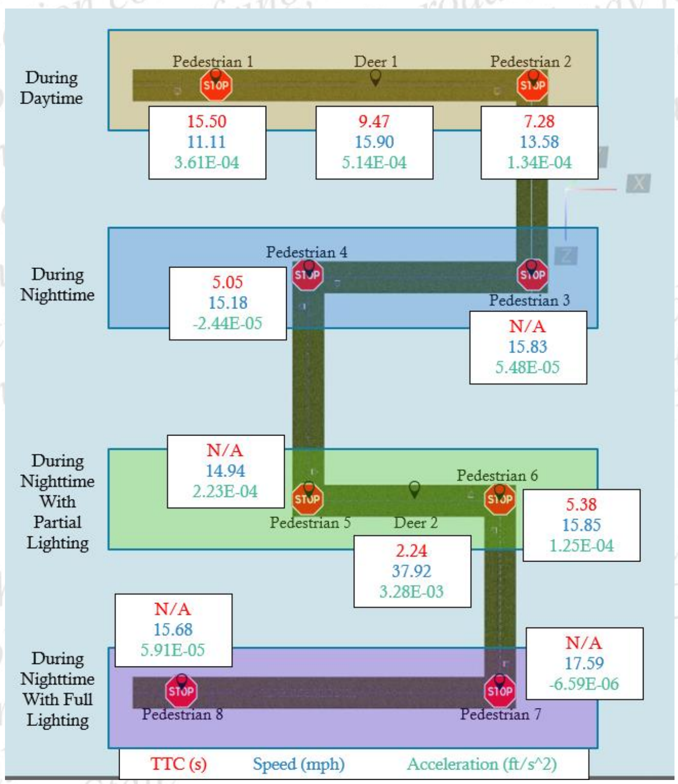


Figure 33. Results of the driving simulator study for roundabouts

Section 4: Cost-benefit Analysis

In this task, a cost-benefit analysis was conducted to compare the cost associated with providing street lighting with the expected benefits of preventing crashes that occurred due to lack of lighting. The main purpose is to evaluate the feasibility of providing full street lighting as a countermeasure to intersections where crashes occurred due to lack of lighting.

Cost of Providing Full Street Lighting. The cost of providing full street lighting to a typical four-leg stop-controlled intersection or a typical four-leg roundabout varies from one state to another. There are many factors that affect the cost of providing street lighting at an intersection such as location, type of intersection, complexity of the surrounding road network, the lighting condition of the intersecting roads, whether power supply is available near the intersection, or the lighting scheme required among other factors.

Street lighting costs in Louisiana were not available online. The research team attempted to obtain the cost of street lighting for roundabouts and stop-controlled intersections of Louisiana. However, since the data was not available, the research team used the average of the street lighting costs reported by other states during the national survey (Task 2) to come up with a reasonable estimation of the street lighting cost in Louisiana. In addition, a value of $300,000 reported by one of the PRC members was also included in the calculation of the average lighting cost at a typical roundabout. The reported cost for providing full street lighting to a typical unsignalized intersection and the estimated average lighting cost are provided in Table 26. The estimated average cost for providing full street lighting to a typical four-leg roundabout and a typical four-leg stop-controlled intersection are $162,143 and $109,583, respectively.

Table 26. Calculating the average cost of providing street lighting to a typical four-leg unsignalized intersection (Source: National Survey and DOTD)

State	Typical four-leg Roundabout	Typical four-leg Stop-controlled Intersection
Louisiana	$300,000	NA
Kentucky	$240,000	$160,000
Alabama	$180,000	$120,000
Indiana	$120,000	$112,500
Utah	$105,000	$70,000
South Dakota	$100,000	$80,000
North Carolina	$90,000	$115,000
Average cost of providing street lighting	$162,143	$109,583

Benefit of Avoiding a Crash. After obtaining the cost of providing street lighting, the next step is to calculate the estimated benefit from providing the countermeasure [which is providing street lighting in this case). Therefore, the expected benefits would be the cost of crashes saved by avoiding these crashes [which occurred due to the lack of the countermeasure (street lighting)]. According to the National Safety Council (NSC), there are two cost components associated with any crash that occurs, the economic cost and the quality-adjusted life years (QALY). The economic cost of a crash includes the direct and indirect monetary impact due to a crash. Therefore, the economic cost consists of: medical cost, lost wages, damaged goods, damaged properties, legal cost, and congestion impact on lost man hours and fuel. Whereas QALY is the quantified estimated value people put on their lives. It is estimated from revealed preferences based on how much people are willing to pay to avoid a risk of death or injury. The crash unit cost (CUC) for the year 2020 was obtained from NSC's website. The values are presented in Table 27 below [46]:

Table 27. Crash unit cost per crash severity (Source: [46])

Year	Type	K-fatal	A-severe injury	B-minor injury	C-possible injury	O-property damage only
2020	Economic	$1,750,000	$101,000	$29,200	$23,900	$12,800
2020	QALY	$11,449,000	$1,252,000	$345,000	$160,000	$52,700
2020	Total	$13,199,000	$1,353,000	$374,200	$183,900	$65,500

Then, the fraction of nighttime crashes that occurred during the total 5 years due to lack of lighting based on severity was determined. There were no crashes due to lack of lighting at roundabouts while there were 303 crashes that occurred in which lack of lighting was either the primary or the secondary contributing factor as presented in Table 28.

Table 28. Proportions of nighttime intersection crashes due to lack of lighting by severity for stop-controlled intersections

Severity	Count	Percentage among Total	Percentage among KABC
K – Fatal Injury	9	3.0%	14.5%
A – Severe Injury	4	1.3%	6.5%
B – Minor Injury	14	4.6%	22.6%
C – Possible Injury	35	11.6%	56.5%
KABC – Fatal and injury crashes	62	20.5%	100.0%
O – Property Damage Only	241	79.5%	-
Total (KABC+O) – All crashes	303	100.0%	-

Next, the overall CUC regardless of severity was determined by the following formula:

$$CUC_{all} = CUC_k * P_k + CUC_A * P_A + CUC_B * P_B + CUC_C * P_C + CUC_0 * P_O \quad (3)$$

Where,

CUC_{all} = Overall crash unit cost regardless of severity
CUC_i = Crash unit cost for severity
P_i = Proportion of crashes of severity in the overall crash population

Since none of the roundabout crashes that occurred at night were due to lack of lighting, the overall CUC_{all} and CUC_{KABC} for fatal and injury crashes were $0.0/crash for both.

Whereas, the overall CUC for a crash regardless of severity at a stop-controlled intersection would be:

$$CUC_{all} = \$13{,}199{,}000 \times 3.0\% + \$1{,}353{,}000 \times 1.3\% + \$374{,}200 \times 4.6\% + \$183{,}900 \times 11.6\% + \$65{,}500 \times 79.5\% \quad (4)$$

$$CUC_{all} = \$504{,}177.1/\text{crash}$$

Similarly, the overall CUC for fatal and injury crashes at stop-controlled intersections would be:

$$CUC_{KABC} = \$13{,}199{,}000 \times 14.5\% + \$1{,}353{,}000 \times 6.5\% + \$374{,}200 \times 22.6\% + \$183{,}900 \times 56.5\% \quad (5)$$

$$CUC_{KABC} = \$2{,}190{,}272.7/\text{crash}$$

Benefit to Cost Ratios. The benefit to cost ratio can be obtained by using the following formula:

$$Benefit\ to\ Cost\ Ratio = \frac{Total\ Benefit}{Total\ Cost} \quad (6)$$

Since none of the nighttime crashes at roundabouts were due to lack of lighting, providing street lighting at rural and suburban roundabouts does not seem feasible as there are no expected benefits (in crash reduction) from providing this countermeasure based on the cost benefit analysis as shown in Table 29 below. On the other hand, the benefit to cost ratios for stop-controlled intersection crashes showed that providing street lighting to rural and suburban stop-controlled intersections is feasible as the benefit to cost ratios (BCR) was 4.6 (greater than 1) as shown in the Table 29.

Table 29. BCR for roundabouts and stop-controlled intersections

Intersection Type	Benefit	Cost	BCR = (Benefit/Cost)
Roundabouts	$0.0	$162,143	0.0
Stop-controlled Intersections	$504,177	$109,583	4.6

It should be noted that the methodology adopted in this study for calculating the expected benefits (savings in reducing crash costs) from installing lighting at roundabouts and stop-controlled intersections is based on a previous relevant study (Lee et al., 2020). This methodology is based on the fact that the number and severity type of crashes to be prevented by a countermeasure (e.g., street lighting) cannot be predicted. In this regard, when implementing a countermeasure (i.e., intersection's lighting in our case), the worst-case scenario is that this countermeasure will only prevent one crash. That is why the BCR value was calculated based on this assumption. So, if implementing the countermeasure is feasible in the worst-case scenario (when preventing only one crash) then if more crashes were prevented, the value of BCR will increase, which indicates that the countermeasure is even more feasible. For example, if three crashes were to be prevented at stop-controlled intersections, then the BCR would be 13.8 (4.6*3).

Once more accurate lighting costs used in Louisiana become available, then the BCR can be estimated by dividing the expected benefit (shown in Table 29 above) by the actual cost of providing street lighting.

Discussion of Results

This section discusses the analysis outcomes of the four tasks implemented in this study.

National Survey Results

It was found that the AASHTO Roadway Lighting Guide was the most frequently used guideline by the participating states (reported by 72% and 71% for stop-controlled intersections and roundabouts, respectively). About 72% of the respondents indicated that lighting at stop-controlled intersections is not mandatory at their states. However, it is mandatory at their roundabouts as reported by about 67% of the participating states. When states were asked to provide current percentages of lighting conditions at intersections in their states, none of the states is providing full lighting to its stop-controlled intersections while more than two-thirds (72%) of the states are providing full street lighting to roundabouts.

This result is consistent with the literature review conducted in this study about specifications and guidelines used in many states [4] [18] [19] [20] [22] [21] [23] [24] [25] [26] [27] [28] [29] [30] [31]. Similarly, DOT professionals were requested to report the main lighting approach used at their state. It was found that full lighting at roundabouts counted for about two-thirds (61%) of the responses. While for stop-controlled intersections, the main lighting approaches were using other low-cost countermeasures (26%) and full lighting (26%) followed by partial lighting (24%).

When DOT professionals were asked about the traffic safety problems due to lack of lighting, some of the received responses mentioned:

- Increased crash frequency: due to increased rear-end crashes and many drivers do not notice the intersections, especially for stop-controlled.
- Increased crash severity: especially fatal crashes and increased risk to pedestrian hit.

According to the survey results, a very small percentage of respondents attributed traffic crash occurrence at nighttime at their states to the lack of lighting (1.5% for roundabouts and 6.3% for stop-controlled intersections). The top three reasons reported by survey participants for nighttime crash occurrence at their states were:

- For roundabouts: speeding (22.4%), followed by driving under the influence (20.9%) and distraction (17.9%).
- For stop-controlled intersections: driving under the influence (18.8%), followed by speeding and distraction (both were responsible for 17.7% each).

Furthermore, about half of the participants (53% for stop-controlled intersections and 50% for roundabouts) indicated that street lighting performance is only monitored when required. Similarly, about 50% of the respondents do not perform cost-benefit analysis for intersection illumination.

When the respondents were asked about the recommended countermeasures to improve nighttime traffic safety, they responded as follows:

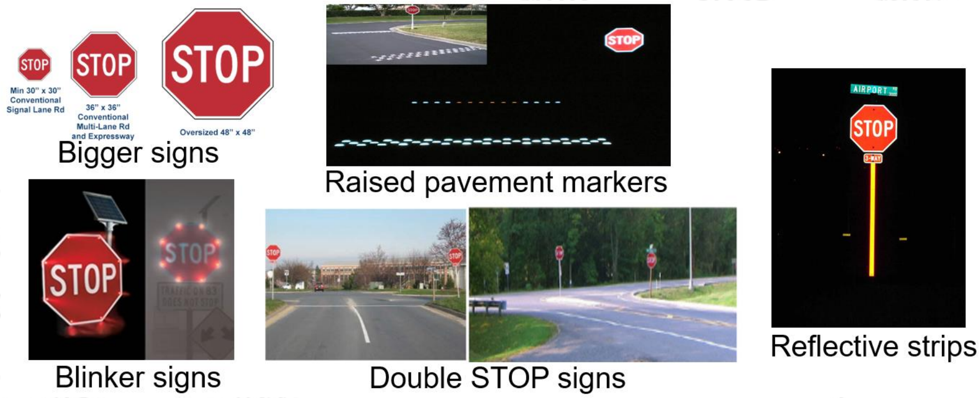
- 72% recommended to provide partial/full lighting to stop-controlled intersections based on traffic safety analysis, and
- 41% suggested to provide full lighting to all roundabouts.

A follow-up question asked DOT professionals to list examples of low-cost countermeasures they use in their states. The reported low-cost countermeasures were:

- Reflective pavement markings,
- Reflectorized raised pavement markers,
- Reflectorized signs and stripes,
- Wider stripes,
- Doubling signs,
- Larger signs,
- Blinker signs,
- Advanced warning signs, and
- Delineators.

Figure 34 provide an example of these low-cost countermeasures [47] [48] [49] [50] [51].

Figure 34. Examples of low-cost countermeasures used by other states (Source [47] [48] [49] [50] [51])



Crash Data Results

There were 4,254 crashes that occurred at 577 stop-controlled intersection and 705 crashes that occurred at 19 roundabouts used in the crash data analysis. All of these crashes occurred between 2016 – 2020 at rural and suburban unsignalized intersections within Louisiana. The results of the crash data indicate that a lack of lighting is not among the primary or the secondary factors for any of the roundabouts’ crashes. However, lack of lighting was responsible for only 3.5% of crashes at stop-controlled intersections as a primary contributing factor and for almost 12.2% of crashes as a secondary contributing factor. The distribution of crashes by primary contributing factor showed that the main primary contributing factors for crash occurrence were violations and movement prior to crash at roundabouts (76.6% and 17.3%, respectively) and at stop-controlled intersections (68.0% and 14.2%, respectively). These statistics are the first indication that there is no evidence that Louisiana has a traffic safety problem due to lack of lighting at its stop-controlled intersections and roundabouts. While the main secondary contributing factors were movement prior to crash at roundabout and violations (75.0% and 19.1%, respectively) and at stop-controlled intersection (64.0% and 11.7%, respectively). This is another indication that Louisiana does not have a traffic safety problem due to lack of lighting at its stop-controlled intersections and roundabouts. The main violations at roundabouts were failure to yield and careless operation (38.3% and 28.9%, respectively) and for stop-controlled (25.6% and 26.9%, respectively).

However, when considering only nighttime crashes, lack of lighting was a primary and secondary contributing factor for about 8.0% and 34.2% of the stop-controlled intersections crashes, respectively.

The results of the cross-sectional analysis showed that night-to-day crash ratio and night-to-total crash ratio of lighted roundabouts were generally higher (0.23 and 0.18, respectively) compared to unlighted roundabouts (0.19 and 0.16, respectively). This could be due to lighting being installed as a countermeasure to improve night traffic safety at a high-risk crash location. However, date of lighting installation will be required to conduct further investigation using a before-and-after analysis. Whereas the night-to-day crash ratio and night-to-total crash ratio of unlighted stop-controlled intersections (0.23 and 0.19, respectively) were generally higher compared to lighted stop-controlled intersections (0.21 and 0.17, respectively).

The results of the Poisson regression were not utilized as the goodness of fit for the model was not acceptable (value of scaled Pearson X^2/DF were above 2.0). Therefore, negative binomial regression was used, and the results indicated that lighting condition doesn't affect the occurrence of crashes as it wasn't a significant factor in any of the models (all crashes and night crashes only) for stop-controlled intersections and roundabouts. The goodness of fit for the negative binomial regression was acceptable (value of scaled Pearson X^2/DF were below 2.0).

Driving Simulator Results

The results of the driving simulator showed that in the stop-controlled intersections scenario TTC during the day is higher than during the night. When comparing TTC for pedestrian 5 [which was at night without street lighting (5.1s)] with pedestrian 7 [which was at night with partial lighting (5.4s)], TTC for the partial lighting is slightly higher compared to no lighting, indicating that participants were able to notice the intersection in advance due to the availability of street lighting and thus reduce their speed earlier (the average deceleration is higher at pedestrian 5 compared to pedestrian 7). In the case of full lighting, TTC wasn't recorded because all the participants stopped too early. The lack of TTC at full lighting location is a sign that participants were able to notice the intersection way in advance and gradually reduce their speed before reaching the intersection due to the availability of street lighting. The acceleration/deceleration rates comparison shows that intersections without street lighting had the highest deceleration rate as participants pressed the brake very hard late due to lack of visibility compared to intersections with partial or full street lighting where participants gradually reduced their speed as they were able to notice the intersection in earlier. For the mid-block crossing of Deer 1 (during daytime) and Deer 2 (during nighttime without lighting), the average TTC showed that participants didn't notice the deer at night until the last few seconds (2.2s) compared to the TTC during the daytime (9.5s). Similarly, the average speed and deceleration rates concluded the same results as they were higher at nighttime compared to daytime.

In the scenario of roundabouts, TTC wasn't collected for any of the intersections which could be due to the average low driving speed of participants (15 mph). However, the acceleration/deceleration rates indicate that partial and full lighting aided participants to notice the pedestrians at the intersection early thus, allowing them to reduce their speed in advance.

Cost-Benefit Results

The results of the cost-benefit analysis showed that there would be no expected benefit to providing street lighting to roundabouts in rural and suburban areas in Louisiana as none of the nighttime crashes that occurred at these roundabouts were due to lack of lighting as shown in Table 29. Accordingly, the BCR of installing lighting at roundabouts was zero.

On the other hand, there were 303 crashes that occurred due to lack of lighting at rural and suburban stop-controlled intersections in Louisiana between 2016 and 2020. The BCR for installing street lighting at stop-controlled interactions was 4.6 as presented in Table 29. Therefore, the analysis showed that it would be feasible to providing street lightning at stop-controlled intersections in rural and suburban areas in Louisiana as the BCR was greater than one.

The expected benefit was calculated based on the assumption of preventing at least one crash that occurred due to lack of lighting regardless of its severity. Therefore, if more than one crash was to be prevented by providing street lighting then the benefit to cost ratio would increase even higher.

Study Limitations

One of the limitations of this study is the lack of lighting installation dates, which prevented the research team from conducing before/after analysis to assess the impact of providing street lighting at intersections. Furthermore, the actual cost for providing street lighting at roundabouts and stop-controlled intersections in Louisiana was not available to the research team at the time of conducting this research. Therefore, an average cost was estimated based on street lighting installation cost reported by other states that participated in the national survey (Task 2).

Conclusions

The main objective of this study was to investigate whether Louisiana has a traffic safety issue due to lack of street lighting at its intersection, particularly at stop-controlled intersections and roundabouts in rural and suburban area. Underlying this objective, this study aimed to (1) document lessons learned from other states who have adopted partial or full lighting policies or other potentially low-cost countermeasures at their intersections, (2) investigate if an intersection's lighting has a significant impact on drivers' behavior and safety, (3) assess the feasibility of installing lighting at stop-controlled intersections and roundabouts in Louisiana through the estimation of the benefit to cost ratios.

To achieve these goals, the research team first conducted a comprehensive literature review of the most related studies to the scope of the project and guidelines used by different transportation authorities related to unsignalized intersections (stop-controlled intersections and roundabouts). Many prior studies showed that street lighting has a positive impact on the overall nighttime traffic safety. Furthermore, based on the guidelines of many US states that were reviewed, it was found that signalized intersections should be fully lighted, while unsignalized intersections such as stop-controlled intersections or roundabouts are assessed using warrant analysis. While some state DOTs such as DOTD's guidelines mention that lighting is not mandatory at their intersections. Many other state DOTs such as the DelDOT's guidelines dictate that warrant analysis is not required for roundabouts and that all roundabouts shall be illuminated. Many prior studies reported that providing street lighting to roundabouts is important even if traffic safety analysis is not warranted due to three main reasons:

- Due to the changing road geometry while approaching roundabouts and the limitations of fixed headlights of vehicles [23] [35].
- To enhance the visual perception of drivers during nighttime [31].
- To allow drivers to safely and efficiently navigate through the roundabout [32] [34].

Additionally, the research team conducted an online national survey that targeted state DOT engineers working in traffic safety and roadway lighting departments to obtain their valuable input on the subject and to document lessons learned from other states who have adopted partial or full lighting policies or other potentially low-cost countermeasures at their intersections. A total of 43 responses were received from 32 different states (64% response rate).

The main findings from the survey were:

- The AASHTO Roadway Lighting Guide is the most frequently used lighting manual by the states that participated in this study (72% for stop-controlled intersections and 71% for roundabouts).
- Lighting at stop-controlled intersections is not mandatory for almost 72% of the responding states. However, lighting is mandatory for roundabouts according to two-thirds of the states (67%).
- About half of the survey participants (53% for stop-controlled intersections and 50% for roundabouts) indicated that street lighting performance is only monitored when required.
- Speeding was the primary reason of crashes at nighttime for roundabouts (reported by 22.4% of participants) while driving under the influence (reported by 18.8% of participants) was the main cause of crashes at stop-controlled intersections.
- Some states use low-cost countermeasures, such as using reflective pavement markings, reflective pavement markers, larger traffic signs, double signs, and blinker signs and advanced warning to improve nighttime traffic safety.
- The recommended countermeasures to improve nighttime traffic safety according to 40% of the states:
  — Provide full or partial lighting based on traffic safety analysis for stop-controlled intersections, followed by using low-cost countermeasures.
  — Provide full lighting to all roundabouts.

Then, a crash data analysis was performed using data of traffic crashes that occurred in Louisiana during the five-year period between 2016 to 2020. There were 577 stop-controlled intersections and 19 roundabouts in rural and suburban areas within Louisiana. The total number of crashes analyzed was 4,270 crashes at stop-controlled intersections and 705 crashes at roundabouts. Several statistical analysis techniques were employed on the crash data. Summary statistics and cross-sectional analysis were conducted to compare traffic safety indicators between lighted and unlighted intersections in terms of crash frequencies and ratios. Multivariate regression models (Poisson and negative binomial models) were developed to identify the contributing factors that affect crash frequency at these intersections. In this regard, two models were created for each intersection type (stop-controlled intersections and roundabouts). The first model included all crashes (daytime and nighttime) to investigate the factors that caused crashes regardless of the time of day. While the second model included only nighttime crashes, which was developed to focus only on the factors that caused nighttime crashes and examine whether lack of street lighting was one of the significant variables.

The results of the crash data analysis indicated that Louisiana doesn't seem to have a traffic safety issue due to lack of street lighting at its roundabouts and stop-controlled intersections in rural and suburban areas. The summary statistics and the cross-sectional analysis showed that lighting was not the primary or the secondary contributing factor to crashes at roundabout/stop-controlled intersections. In addition, the results of the negative binomial regression analysis showed that street lighting was not a significant factor that affected crash occurrence in any of the models for both stop controlled intersections and roundabouts.

Furthermore, a driving simulator experiment was conducted to investigate the impact of street lighting on drivers' behavior and safety. The study consisted of two scenarios for stop-controlled intersections and roundabouts. In each scenario, different lighting conditions were used, and drivers' behavior was collected and analyzed. The four lighting conditions used in this experiment included: daytime, nighttime without street lighting, nighttime with partial lighting, and nighttime with full lighting. The collected data included TTC, speed, and acceleration/deceleration rates.

The results of the driving simulator experiment (especially for stop-controlled intersections) indicated that providing street lighting (partial or full) improves the overall traffic safety by increasing the TTC parameter, and decreasing the deceleration rates at these intersections. TTC at stop-controlled intersections during daytime (15.5s) and nighttime with partial lighting (5.38s) were higher compared to nighttime without lighting (5.1s). Also, the deceleration rate at night (without lightening) was the highest compared to intersections with partial lighting and full lighting, meaning that participants broke suddenly and quickly due to lack of lighting at the intersections. However, no significant difference for TTC at different lighting conditions was noticed at the roundabouts.

Furthermore, cost-benefit analysis was also conducted to evaluate the feasibility of providing street lighting to stop-controlled intersections and roundabouts in Louisiana. The cost-benefit analysis was completed considering the following:

- Cost: obtained from different state DOTs that participated in the national survey, and
- Benefit: potential savings of reducing one crash due to lack of lighting per year.

The results of cost-benefit analysis showed that providing full street lighting to rural and suburban roundabouts is not feasible as there were no crashes that occurred due to lack of lighting at roundabouts in Louisiana between 2016 and 2020. Therefore, the benefit to cost ratio of providing street lighting at roundabouts was zero. However, the cost-benefit analysis of stop-controlled intersections showed that the expected benefit outweighs the associated cost of providing street lighting, which was feasible as the BCR was 4.6.

Finally, it is recommended to use DOTD's Agile Assets System to track work orders and progress of lighting installation/maintenance at roundabouts and stop-controlled intersections in Louisiana. This system would make the operation and maintenance of the street lighting faster and more efficient. The system would enable DOTD to record valuable information such as date of lighting installation, lighting performance at intersections, maintenance schedules, etc.

Recommendations

Based on the findings of all project's tasks, the research team recommends the following:

- Monitor traffic safety performance at intersections where lighting is installed (e.g., evaluate frequencies of crashes before and after lighting installation);
- Provide lighting at stop-controlled intersections and roundabouts in rural and suburban areas in Louisiana should not be mandatory based on the project's results. However, it may be warranted based on traffic safety analysis (e.g., where the intersection has on average at least one nighttime fatal or injury crash per year over a three-year period);
- If lighting is warranted but lighting installation is not feasible due to lack of funding or site constrains, it is recommended then to install other low-cost countermeasures such as reflective pavement markings, reflective pavement markers, larger traffic signs, double signs, blinker signs and advanced warning; and
- Deliver awareness campaign to drivers to obey traffic rules as the primary cause of nighttime crashes was traffic violations (speeding and driving under the influence).

Future studies are recommended to continue evaluating the impact of lack of street lighting at unsignalized intersections in Louisiana on traffic safety once missing information become available (e.g., availability of lighting at each intersection in Louisiana, date of lighting installation, etc.) to further validate the results of this research.

Acronyms, Abbreviations, and Symbols

Term	Description
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ALDOT	Alabama Department of Transportation
ARIES	Automated Reporting Information Exchange System
ATE	Average Treatment Effect
BCR	Benefits to Cost Ratio
CEI	Construction Engineering Inspection
CIE	Commission Internationale de l’Eclairage
CMF	Crash Modification Factor
CODOT	Colorado Department of Transportation
CRASH	Collision Report Analysis for Safer Highways
CRF	Crash Reduction Factor
CUC	Crash Unit Cost
DelDOT	Delaware Department of Transportation
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
FARS	Fatality Analysis Reporting System
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
ft.	foot (feet)
GDOT	Georgia Department of Transportation
GES	General Estimates System
GIS	Geographic Information System
GPS	Global Positioning System
HPS	High-pressured Sodium
IES	Illuminating Engineering Society
IRB	Institutional Research Board

Term	Description
KDOT	Kansas Department of Transportation
LED	Light-emitting Diode
LSU	Louisiana State University
LTRC	Louisiana Transportation Research Center
MMS	Maintenance Management System
MnDOT	Minnesota Department of Transportation
MPH	Miles per Hour
MVA	Multivariate Analysis
NA	Not Applicable or Not qualified to answer this question
NCHRP	National Cooperative Highway Research Program
NDDOT	North Dakota Department of Transportation
NHDOT	New Hampshire Department of Transportation
NHTSA	National Highway Traffic Safety Administration
NJDOT	New Jersey Department of Transportation
NSC	National Safety Council
ODOT	Oregon Department of Transportation
PDO	Property Damage Only
QALY	Quality-Adjusted Life Years
RLMMS	Roadway Lighting Mobile Measurement System
RVP	Relative Visual Performance
s	Second (s)
SCDOT	South Carolina Department of Transportation
SSM	Surrogate Safety Measure (SSM)
TAC	Transportation Association of Canada
TDOT	Tennessee Department of Transportation
TTC	Time to Collision
US	United States
VDOT	Virginia Department of Transportation
VMT	Vehicle Miles Traveled
VPH	Vehicles Per Hour

Term	Description
VTRANS	Vermont Agency of Transportation
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation

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Appendix A

Survey on Illumination of Roundabouts and Unsignalized Intersections: Minimum Requirements and Impacts on Traffic Safety

You are invited to participate in a survey on “Illumination of Roundabouts and Unsignalized Intersections: Minimum Requirements and Impacts on Traffic Safety.” This survey has been developed by the researchers at Louisiana State University, USA and is part of a Louisiana Transportation Research Center (LTRC) research project (LTRC project 20-3SA) funded by Louisiana Department of Transportation and Development (DOTD). The primary objectives of this survey are to:

- Investigate the safety impacts of intersection lighting on all road user types including drivers, pedestrians, and motorcyclists, specially at roundabouts and stop-controlled intersections in rural and suburban areas.
- Identify and assess the effectiveness of different lighting methods (e.g., minimum lighting requirement) adopted by different states at such intersections.
- Identify cost-effective countermeasures adopted by US DOTs to improve traffic safety at roundabout and unsignalized intersections during nighttime.

It is expected that the results of this research will provide useful insights regarding the challenges and needs of improving the traffic safety at roundabouts and stop-controlled intersections in rural and suburban areas when it comes to intersection lighting. In addition, the survey results will help in assessing the effectiveness of different lighting methods such as partial, full, or other lighting schemes used by different states to reduce the number and severity of traffic crashes during nighttime. These findings will provide transportation and traffic safety authorities with actionable measures/countermeasures that can help in improving the safety of all road user types at roundabouts and stop-controlled intersections in rural and suburban areas specially during nighttime.

The survey is intended for DOT professionals who have relevant expertise with this area of research. The survey should take approximately 15-20 minutes of your time; however, for some it could take longer. We hope that you find the experience to be informative and engaging.

Inclusion Criteria

To participate in this study, you MUST meet the following two requirements:

- Currently working at a department of transportation in the US or other US transportation authorities such as NHTSA or FHWA.
- Have at least 3 years of experience in the field of transportation engineering or Intelligent transportation systems and familiar with your state's lighting and safety policies.

Potential Benefits

An immediate benefit for participating in this study is to gain more insights regarding the countermeasures that US states are implementing to reduce crash rates due to the lack of lighting at stop-controlled intersections and roundabouts in rural and suburban areas. In addition, this research will assist transportation agencies such as DOTD to determine the required strategies, policies, and action plans to better improve the safety of road users during nighttime at roundabouts and stop-controlled intersections.

Confidentiality

All collected responses will be treated with the utmost confidentiality and stored securely in facilities that belong to Louisiana State University. In our work, no effort will be made to identify respondents to the survey including linking with other data sets that could help in this regard.

Participation and Withdrawal:

Your participation in this study is voluntary. It is your choice to be part of this study or not. If you decide to be part of the study, you can still stop (withdraw) from the survey for whatever reason, even after signing the consent form. Your data will be permanently removed from the database. However, it should be noted that once survey results are submitted, withdrawal is not possible because your data are anonymous.

Questions about the Study

If you have questions or need more information about the study itself, the following members of research team from Louisiana State University can be contacted.

Name	Role	Faculty	Department	Email address
Dr. Hany Hassan	Principal Investigator	Engineering	Civil and Environmental Engineering	hassan1@lsu.edu
Hisham Abdu Kunnah	Graduate Student (Master)	Engineering	Civil and Environmental Engineering	habduk1@lsu.edu
Taniya Sultana	Graduate Student (PhD)	Engineering	Civil and Environmental Engineering	tsulta2@lsu.edu

Having read the aforementioned information, I understand that by clicking the "yes" button below, I agree to take part in this study under the aforementioned terms and conditions.

Select One:

Screening Questions:

❑ Yes, I meet the inclusion criteria listed above and agree to participate in this survey

❑ No, I do not meet the inclusion criteria listed above or do not agree to participate in this survey

What is the name of the transportation authority/agency you are working at?

____

Which department within the authority/agency you are working at?

____

Which state department you are working at?

____

Section 1: Guidelines and Specifications

Do you follow different lightning guidelines for stop-controlled intersections and roundabouts in urban and suburban areas?

- Yes, we have different guidelines for both types of intersections
- No, we follow the same guideline for both types of intersections
- Not qualified to answer this question

If **"No" was selected** for the above question, participants will only see one section from sections **1.1** and **1.2**

1.1: Stop-controlled intersections

Is lighting mandatory at stop-controlled intersections in rural and suburban areas in your state?

- ○ Yes
- ○ No
- ○ Lighting is installed where it seems necessary based on the traffic safety status
- ○ Not qualified to answer this question

Which manual is currently being used for illumination specifications at stop-controlled intersections in rural and suburban areas in your state?

- ☐ AASHTO Roadway Lighting Design Guide
- ☐ The Illuminating Engineering Society (IES)
- ☐ The International Commission on Illumination (CIE)
- ☐ Others, please specify: ____________________
- ☐ Not qualified to answer this question

What factors does your state consider for determining the necessity of lighting at stop-controlled intersections (select all that apply)?

- ☐ Crash rate
- ☐ Traffic volume
- ☐ Geometry of the intersection
- ☐ Presence of the traffic signals
- ☐ School/university crossing
- ☐ Location
- ☐ High pedestrian volume
- ☐ Others, please specify: ____________________
- ☐ Not qualified to answer this question

What is the frequency of monitoring the performance of lighting equipment at stop-controlled intersections in rural and suburban areas in your state?

- ○ Monthly
- ○ Quarterly
- ○ Biannually
- ○ Yearly
- ○ When required
- ○ Others, please specify: ____________________
- ○ Not qualified to answer this question

How does your state maintain the lighting equipment at stop-controlled intersections in rural and suburban areas?

- ○ ………
- ○ Not qualified to answer this question

Do you know the current percentages of lighting conditions at stop-controlled intersections in rural and suburban areas in your state?

Lighting Conditions	Percentage
Fully lighting (all approaches of intersection are provided with lighting)	%
Partial lighting (lighting is provided to one or two approaches of intersection)	%
Other lighting scheme (e.g., pavement reflectors, adaptive lighting)	%
No illumination	%

- Yes
- No
- Not qualified to answer this question

If you selected Yes, approximately, what are the current percentages of lighting conditions of stop-controlled intersections in rural and suburban areas in your state?

- Fully lighting (all approaches of intersection are provided with lighting): _________%
- Partial lighting (lighting is provided to one or two approaches of intersection): _______%
- Other lighting scheme (e.g., pavement reflectors, adaptive lighting): ______%
- No illumination: _________%

1.2: Roundabouts

Is lighting mandatory in roundabouts in rural and suburban areas in your state?

- Yes
- No
- Lighting is installed where it seems necessary based on the traffic safety status
- Not qualified to answer this question

Which manual is currently being used for illumination specifications in roundabout in rural and suburban areas in your state?

- ☐ AASHTO Roadway Lighting Design Guide
- ☐ The Illuminating Engineering Society (IES)
- ☐ The International Commission on Illumination (CIE)
- ☐ Others, please specify: ___________________
- ☐ Not qualified to answer this question

What factors does your state consider for determining the necessity of lighting in a roundabout (select all that apply)?

- ☐ Crash rate
- ☐ Traffic volume
- ☐ Geometry of the intersection
- ☐ Presence of the traffic signals
- ☐ School/university crossing
- ☐ Location

☐ High pedestrian volume
☐ Others, please specify: ____________________
☐ Not qualified to answer this question

What is the frequency of monitoring the performance of lighting equipment in roundabouts in rural and suburban areas in your state?

- Monthly
- Quarterly
- Biannually
- Yearly
- When required
- Others, please specify: ____________________
- Not qualified to answer this question

How does your state maintain the lighting equipment at roundabouts in rural and suburban areas?

- ………………………………………………………………………………………… …………………………………………………………………………………………
- Not qualified to answer this question

Do you know the current percentages of lighting conditions in roundabouts in rural and suburban areas in your state?

Lighting Conditions	Percentage
Fully lighting (all approaches of intersection are provided with lighting)	%
Partial lighting (lighting is provided to one or two approaches of intersection)	%
Other lighting scheme (e.g., pavement reflectors, adaptive lighting)	%
No illumination	%

- Yes
- No
- Not qualified to answer this question

If you selected Yes, approximately, what are the current percentages of lighting conditions of roundabouts in rural and suburban areas in your state?

- Fully lighting (all approaches of intersection are provided with lighting): ________%
- Partial lighting (lighting is provided to one or two approaches of intersection): _______%
- Other lighting scheme (e.g., pavement reflectors, adaptive lighting): _______%
- No illumination: ________%

Section 2: Safety

2.1: Stop-controlled intersections

Are there traffic safety problems due to lack of lighting at stop-controlled intersections in rural and suburban areas in your state?

- Yes, please mention the safety problems………………………………………
- No
- Not qualified to answer this question

What are the primary reasons of traffic crashes at stop-controlled intersections during nighttime in rural and suburban areas in your state (Select all that apply)?

- ☐ Lack of lighting
- ☐ Speeding
- ☐ Distraction
- ☐ Driving under the influence of drugs or alcohol
- ☐ Another driver errors
- ☐ Road related factors
- ☐ Vehicle related factors
- ☐ Others, please specify: ________________
- ☐ I do not know
- ☐ Not qualified to answer this question

What is the main lighting approach applied in your state for stop-controlled intersections? select all that apply.

- ☐ **Partial lighting**: When lighting only covers the portion of the intersection which are potentially hazardous and important to maneuver safely.
- ☐ **Full lighting**: When lighting uniformly covers all traveled approaches of an intersection.
- ☐ **Delineation lighting**: Lighting, which illuminates the vehicle, marks the intersection for the maneuvers of approaching vehicle.
- ☐ **Adaptive lighting**: Changing the level of lighting depending on environmental or traffic condition.
- ☐ **Other low-cost countermeasures** (e.g., striping in the influence area, reflective strips on signing, doubled up signing) to light the intersection, please specify: ________
- ☐ Not qualified to answer this question

If you selected partial lighting, which of the following scenarios did you observe after the implementation?

- Daytime crash reduction
- Daytime crash increase
- Nighttime crash reduction
- Nighttime crash increase

- Both increased
- Both decreased
- Traffic safety status has not changed
- No evaluation was conducted
- Not qualified to answer this question

If you selected full lighting, which of the following scenarios did you observe after the implementation?

- Daytime crash reduction
- Daytime crash increase
- Nighttime crash reduction
- Nighttime crash increase
- Both increased
- Both decreased
- Traffic safety status has not changed
- No evaluation was conducted
- Not qualified to answer this question

If your state is using any low-cost countermeasures (e.g., striping in the influence area, reflective strips on signing, doubled up signing) for the stop-controlled intersections in your state, how effective they are?

- They are effective in reducing the traffic crashes at night
- They are ineffective in reducing the traffic crashes at night
- No evaluation was performed
- Not qualified to answer this question

Are there any negative impacts on traffic safety after installing lighting at intersections in your state?

- Yes, (e.g., daytime crashes increase), please specify: ___________________
- No
- Not qualified to answer this question

What should be done regarding the unlighted stop-controlled intersections in your state?

- They should be partially lighted
- They should be fully lighted
- They should be partially lighted or fully lighted or left as is depending on the traffic safety status (e.g., no. of observed crashes at night)
- They should be left as is
- Not qualified to answer this question

How strongly do you agree that partially lighted stop-controlled intersections in your state should be converted to fully lighted?

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree
- Not qualified to answer this question

How would you rate the overall safety conditions at stop-controlled intersections in rural and suburban areas in your state?

- Very poor
- Poor
- Neutral
- Good
- Very Good
- Not qualified to answer this question

2.2: Roundabouts

Are there any traffic safety problems due to lack of lighting in roundabouts in rural and suburban areas in your state?

- Yes, please mention the safety problems………………………………………
- No
- Not qualified to answer this question

What are the main reasons of traffic crashes at roundabouts during nighttime in rural and suburban areas in your state (Select all that apply)?

- ☐ Lack of lighting
- ☐ Speeding
- ☐ Distraction
- ☐ Driving under the influence of drugs or alcohol
- ☐ Another driver errors
- ☐ Road related factors
- ☐ Vehicle related factors
- ☐ Others, please specify: ____________________
- ☐ I do not know
- ☐ Not qualified to answer this question

What is the main lighting approach applied in your state for roundabouts? Click all that apply.

- ☐ **Partial lighting**: When lighting only covers the portion of the intersection which are potentially hazardous and important to maneuver safely.
- ☐ **Full lighting**: When lighting uniformly covers all traveled approaches of an intersection.
- ☐ **Delineation lighting**: Lighting which illuminates the vehicle, marks the intersection for the maneuvers of approaching vehicle.
- ☐ **Adaptive lighting**: Changing the level of lighting depending on environmental or traffic condition.
- o **Other low-cost countermeasures** (e.g., striping in the influence area, reflective strips on signing, doubled up signing) to light the intersection, please specify: __________
- o Not qualified to answer this question

If you selected partial lighting, which of the following scenarios did you observe after the implementation?

- o Daytime crash reduction
- o Daytime crash increase
- o Nighttime crash reduction
- o Nighttime crash increase
- o Both increased
- o Both decreased
- o Traffic safety status has not changed
- o No evaluation was conducted
- o Not qualified to answer this question

If you selected full lighting, which of the following scenarios did you observe after the implementation?

- o Daytime crash reduction
- o Daytime crash increase
- o Nighttime crash reduction
- o Nighttime crash increase
- o Both increased
- o Both decreased
- o Traffic safety status has not changed
- o No evaluation was conducted
- o Not qualified to answer this question

If your state is using any low-cost countermeasures (e.g., striping in the influence area, reflective strips on signing, doubled up signing) for the roundabouts in your state, how effective they are?

- o They are effective in reducing the traffic crashes at night
- o They are ineffective in reducing the traffic crashes at night

- No evaluation was performed
- Not qualified to answer this question

Are there any negative impacts on traffic safety after installing lighting at roundabouts in your state?

- Yes, (e.g., daytime crashes increase), please specify: ____________________
- No
- Not qualified to answer this question

What should be done regarding the unlighted roundabouts in rural and suburban areas in your state?

- They should be partially lighted
- They should be fully lighted
- They should be partially lighted, fully lighted or left as is depending on the traffic safety status (e.g., no. of observed crashes at night)
- They should be left as is
- Not qualified to answer this question

How strongly do you agree that partially lighted roundabouts in your state should be converted to fully lighted?

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree
- Not qualified to answer this question

How would you rate the overall safety conditions in roundabouts in rural and suburban areas in your state?

- Very poor
- Poor
- Neutral
- Good
- Very Good
- Not qualified to answer this question

Section 3: Cost-Benefit Analysis

Which of the following is true regarding the cost effectiveness of the intersections' lighting method used in your state?

- It is cost effective
- We are looking for more cost-effective lighting methods
- We do not perform cost-benefit analysis for intersections illumination
- Not qualified to answer this question

Approximately, how much does your state spend for installing full lighting intersections?

- $_____________ for a four-leg stop-controlled intersection
- $_____________ for a four-leg roundabout
- Not Applicable (if no full lighting or no cost data is available)
- Not qualified to answer this question

Approximately, how much does your state spend for the maintenance of full lighting intersections annually?

- $_____________ for a four-leg stop-controlled intersection
- $_____________ for a four-leg roundabout
- Not Applicable (if no full lighting or no cost data is available)
- Not qualified to answer this question

3.1: Stop-controlled intersections

What are the average initial costs for partial lighting in a four leg stop-controlled intersection?

- $_____________ for lighting one approach of the stop-controlled intersection
- Not Applicable (if no partial lighting or no cost data is available)
- Not qualified to answer this question

How strongly do you agree that the benefits of reduced crash rate outweigh the cost associated with the maintenance of stop-controlled intersections lighting in your state?

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree
- Not qualified to answer this question

Overall, what is the recommended countermeasure in your state to improve traffic safety at stop-controlled intersections at night?

- Providing full lighting to all intersections
- Providing full or partial lighting based on traffic safety analysis
- Providing partial lighting in addition to using other cost-effective countermeasures, please specify: ______________________
- Using other cost-effective countermeasures, please specify: ______________________
- Not qualified to answer this question

3.2: Roundabouts

What are the average initial costs for partial lighting in a roundabout?

- $____________ for lighting one approach of the roundabout
- Not Applicable (if no partial lighting or no cost data is available)
- Not qualified to answer this question

How strongly do you agree that the benefits of reduced crash rate outweigh the cost associated with the maintenance of roundabout lighting in your state?

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree
- Not qualified to answer this question

Overall, what is the recommended countermeasure in your state to improve traffic safety at roundabouts?

- Providing full lighting to all roundabouts
- Providing partial lighting to the roundabouts based on traffic safety analysis
- Providing partial lighting in addition to using other cost-effective countermeasures, please specify: ____________________
- Using other cost-effective countermeasures, please specify: ____________________
- Not qualified to answer this question

End of Survey

The research team would like to thank you for your time spent taking this survey.