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Lighting Levels for Isolated Intersections: Leading to Safety Improvements

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Research Project
Final Report 2015-05

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Roadway lighting provides a benefit in reducing nighttime crashes that lead to injuries and fatalities. A number of studies have linked the benefits of roadway lighting to a reduction in crash rates at night for a variety of roadway types including rural intersections. Assessing the effectiveness of intersection lighting has primarily relied upon crash database modeling comparing lighted intersections to unlighted intersections. The current research effort is intended to gather similar metrics for comparison but also to measure the quantity and quality of roadway lighting levels at isolated rural intersections to assess how these metrics impact nighttime crash rates. Sixty-three intersection locations were chosen for intersection lighting measurement from six different counties within Minnesota. Both lighted and unlighted intersections were measured for quantity of lighting using an illuminance meter data collection system mounted on the roof of a passenger vehicle. The data collection system utilized five separate illuminance meters and captured horizontal illuminance while driving through all 63 intersection locations. Following data collection, a series of negative binomial regression models were used to assess the horizontal lighting level in conjunction with the nighttime crash ratio, intersection configuration type, and proximity of an intersection to a curve in the roadway. The results showed that overall, average horizontal illuminance reduced nighttime crash rates by 9%, but for lighted intersections alone, the crash reduction factor was 20%. Furthermore, for unlighted intersections, average illuminance levels reduced nighttime crash ratios by 94%. Intersection configuration and proximity to curves also affected the nighttime crash ratios. The results of this effort are discussed in terms the impact of horizontal illuminance on crash rates. Additional items discussed include thresholds for minimum and maximum lighting levels and future research investigating and validating these efforts.

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Executive Summary

In 2012 the Fatality Analysis Reporting System (FARS) showed that rural intersection collisions accounted for 16% of all fatalities nationwide, with almost 30% of those fatalities occurring at night. The crash rate in Minnesota is slightly lower but still shows a 10% fatality rate for intersection crashes at night for those intersections without roadway lighting. Intersection lighting has been identified as an effective mitigation strategy for reducing nighttime collisions. Intersection lighting illuminates the rural intersection areas providing drivers with additional visual information prior to making a turn decision. The roadway lighting also provides drivers access to otherwise low contrast information when approaching a rural intersection. While rural intersection lighting has been connected to a reduction in rural intersection nighttime crashes to some extent, limited information is available about how the quality or quantity of that roadway lighting effects nighttime crashes.

Lighting warrants and lighting level recommendations are provided by the American National Standard Institute and the Illuminating Engineering Society (e.g., ANSI/IES, RP-8-14) and a number of other national and statewide reports. These recommendations suggest a minimum amount of horizontal illuminance required at intersection locations (and for other roadway lighting applications) that allows drivers sufficient illumination for object visibility. The horizontal illuminance was utilized as a method to provide sufficient and appropriate lighting levels at intersection locations. A number of other parameters are included when calculating an appropriate lighting design for an intersection including, pavement classification, glare, luminaire type, headlights, and foliage. These recommendations provide an excellent foundation for establishing new lighting at intersections, yet little is understood about the benefits of any amount of roadway lighting at intersection locations.

The objective of this study was to identify isolated rural intersections of interest, build a lighting data collection system, take lighting measurements at these intersections, and then analyze that data with respect to the factors within the crash data. Finally, the recommendations from the analysis would provide some insight into lighting levels for rural intersections and future research directions given the data analyzed. A number of steps were implemented to achieve these efforts:

1) Surveying county engineers about intersection lighting
2) Identifying intersections where data collection could be completed
3) Identifying and building a data collection system
4) Collecting horizontal illuminance data at those intersections
5) Comparing nighttime crash ratios using illuminance data
6) Providing results and conclusions

A county engineering intersection lighting survey was created and then administered to all county engineers within the Minnesota. Of the 87 counties, a total of 45 county engineers responded by completing the survey. The survey asked the country engineers (or designates) if they maintained any intersection lighting, what type of lighting they maintained, estimate of the cost of installing and maintaining the intersection lighting, questions about any recent lighting projects, and whether they had any specific intersections that would be appropriate for horizontal illuminance measurement. Of the total counties that responded, 27% of them concluded they did not currently maintain any rural intersection lighting. The remaining respondents identified approximate totals of lighting, installation, maintenance, and additional costs associated with rural intersection lighting. The respondents also provided the researcher with a number of locations where intersection lighting measurements could be taken. These suggestions were accumulated and then compared with the crash database information to identify appropriate intersections of interest.

During the intersection identification process, a crash database was used to examine the number of crashes at the intersection location, the status of the intersection lighting (e.g., lighted or unlighted), intersection geometry (e.g., near a curve), and intersection configuration (e.g., 'T' or crossroad). A final list of intersections was generated prior to building the data collection equipment. Upon review of the intersections a number were removed to streamline the data collection process. In addition, a number of intersections were added around the greater metro area in an effort to reduce data collection time and expedite the project. A final list of intersections from a total of six different counties identified 63 intersections of interest to be measured by the data collection system.

To collect the required horizontal illuminance measurements in a reasonable amount of time using an effective method, the researcher identified an effective measurement apparatus as previously created by the Center for Infrastructure Based Safety Systems at the Virginia Tech Transportation Institute. The data collection device utilizes a number of Minolta illuminance meters that are positioned on the roof of a vehicle in such a manner as to collect horizontal illuminance data while the vehicle is in motion. The data collection technique allows a researcher to collect data at multiple intersections without having to stop the vehicle and take measurements using a hand held device. The technique also allowed the researcher to take horizontal illuminance measurements from all approaches for each of the rural intersection locations in order to collect as much data as possible. The device utilized a Trimble R7 Global Positioning System attached to the vehicle to map the data to the actual location of the intersection. After data collection was complete, the researcher cleaned and checked the data for errors before combing the information into an overall data file.

The data was then analyzed using a number of negative binomial regression models that reviewed all the data, just those intersections that contained roadway lighting, and just those intersections that had no lighting installed. The results showed a significant benefit of horizontal illuminance for all of the analyses but was particularly pronounced for the lighted and unlighted intersection locations. The overall model showed a 9% reduction in the nighttime crash ratio for the overall analysis, but this number increased to 20% for lighted intersections and was 94% for unlighted intersections. Contrary to other research, 'T' intersections were identified as providing reductions in the nighttime crash ratio (e.g., 200%) compared to crossroad intersections. Also, those intersection locations that were near a curve were found to have reduced nighttime crash ratios (e.g., 178%) compared to those that were not located near a curve. A number of interactions also occurred between the predictor variables that influenced the impact of intersection type and also the average horizontal illuminance.

The research concluded and re-confirmed the beneficial nature of roadway lighting at isolated rural intersections. Furthermore, the research recommends investigating minimum horizontal illuminance levels around or greater than 5-lux as a baseline for testing nighttime visual performance and for comparisons with crash rates. Future research is suggested where additional data is collected from more intersections in an effort to validate both minimum and maximum horizontal illuminance, vertical illuminance, and luminance levels at rural intersection locations. The researcher recommends investigating the impact of newer roadway lighting technologies (e.g., Light Emitting Diode) as a method to reduce lighting levels but still maximize driver visual performance. Newer technologies can also provide cost savings at the reduced levels in addition to maintenance and longevity benefits, which may in turn counteract any high upfront costs.

Chapter 1
Introduction

Nighttime crashes at rural intersection locations are reduced when roadway visibility is improved by installing lighting at that location. Specifically, nighttime-to-daytime crash ratios have been significantly lower at those intersection locations containing roadway lighting [1, 2, 3, 4, 5]. While roadway lighting at intersections provides an appropriate mitigation technique for reducing nighttime crashes little is known about how the quality and quantity of lighting impacts visual performance of drivers and in turn, nighttime crash statistics [6, 7].

According to the 2012 Fatality Analysis Reporting System (FARS; 8), rural intersection collisions accounted for 16.1% of all fatalities across the nation, 29.7% of which occurred during dark conditions (excluding dusk and dawn conditions). The same year, the reported number of traffic fatalities in Minnesota was 395 [9]. Of those fatalities, 36 occurred at rural intersection at night (e.g. dark conditions without lighting). For the reported statistics, *intersection* was confined to four-way intersections, T-intersections, Y-intersections, and five+ point intersections. *Rural*, was defined as Rural-Principal Arterial-Interstate, Rural-Principal Arterial-Other, Rural-Minor Arterial, Rural-Major Collector, Rural-Minor Collector, Rural-Local Road or Street, and Rural-Unknown.

The human visual system is optimal in high levels of illumination [10, 11]. In the case of night-time driving, vehicle headlamps provide some illumination of the forward roadway; however, depending on the quality of pavement markings and roadway geometry drivers may be more likely to 'overdrive' the environment illuminated by the headlamp beam [12]. Driving too fast for the visible conditions and failure to identify objects in a timely manner are just some causes of vehicle crashes at night. The application of roadway lighting at various highways or rural intersection locations provides visual benefits for drivers, beyond headlamps, as they navigate critical visual information in the dark.

The safety benefit of roadway lighting at isolated rural intersections has received some attention over the years. For example, Wortman, Lipinski, Fricke, Grimwade & Kyle (1972) completed a project to develop warrants for at-grade rural intersection lighting. They also set out to identify the types and levels of illumination to be used. At that time, Wortman et al. (1972) concluded that intersections chosen for lighting were often locations with high percentages of nighttime accidents or locations with raised channelization. However, there were no specific rural intersection warrants; just the American Standards Association's "Warrants" which recommended lighting levels when a location had been identified as having a high number of crashes. Wortman et al. (1972) focused on identifying a relationship between the nighttime accident rate and the lighting level while controlling for other factors (e.g., traffic volumes). The methodology included comparing daytime and nighttime accident rates at intersection locations, such that the intersection was its own control and presumably, only the visibility changed. The results showed that nighttime illumination had a significant and beneficial effect with the average nighttime accident rate reduced by 30%. In a later report [14], the researchers concluded that lighting reduced the nighttime accident rate by 45%.

Walker and Roberts (1976) performed an analysis using a before (lighting)/after (lighting) approach with respect to crash data. The researchers found significant reductions in nighttime crashes for intersections with Average Daily Traffic (ADT) rates of more than 3,500 vehicles when lighting was used. The researchers found that nighttime crash rates were significantly reduced from 1.89 to 0.91 (before/after the installation of lighting – per million entering vehicle miles). They also found that channelized intersections showed significant reductions in nighttime crash rates when lighting was used, but found no significant differences for the non-channelized intersections [14].

Preston & Schoenecker (1999) administered surveys to city and county engineers in rural Minnesota, generating 91 total responses, and compared previous crash records to the lighting installation efforts. The researchers accessed MnDOT records from 1995, 1996, and 1997, looking at day versus night crash rates based on intersections without street lighting (3,236) and intersections with street lighting (259). They found that 78% of counties and 66% of cities reported no illumination at rural intersections while remaining within the warrant standards. The intersection analysis found that of the 2,153 intersection crashes, 1,926 of them occurred at intersections with no lighting. It was discovered that the correlation of nighttime crash rate at intersections with no lighting was significantly higher (0.63) than nighttime crash rate at rural intersections with lighting (0.47). The results of this study indicate that stricter warrants may be necessary, which eventually prompted changes to Minnesota's rural intersection lighting warrants. Prior to the 1999 study, the requirement in Minnesota required that lighting be installed at rural intersections where 3 or more crashes occurred over a 1 year time frame. After the study was completed, the guidelines lowered to required lighting installation where three nighttime crashes over three years occurred [5].

For the same study, Preston & Schnoecker (1999) conducted a 3-year pre-lighting vs. 3-year post-lighting analyses of 12 sample intersections to identify the efficacy of lighting installation efforts. Before/after comparisons were made, using a Poisson distribution, for crash severity, crash type, and crash rate. Results showed that there was a decrease in all three before-and-after variables (crash severity, crash type, and crash rate). Significant decreases were observed in overall nighttime crash rate, with a 40% decrease after lighting was installed (95% CI). A 20% decrease in fatal and personal injury crashes was observed after lighting was installed (90% CI). A cost-benefit analysis suggests that installing lighting is economically beneficial (approximately a 15:1 ratio) when weighing the costs of installation, maintenance, and operation with the benefits of saving money from property damage, personal injury, and fatal crashes.

Using the state crash database, researchers at University of Kentucky isolated nine rural intersections with a high frequency of critical nighttime crashes [15]. The cutoff for critical crashes was two or more at each given intersection over a three year period. Lighting was installed at nine T and 4-way intersections based on design criteria from American Association of State Highway and Transportation Official (AASHTO) and American National standard Practice for Roadway Lighting (ANSI/IESNA RP 8-00; 16, 17). Researchers used a Minolta T-10 Illuminance Meter to take measurements of average illuminance and uniformity of illuminance within the boundaries of each intersection to ensure it met the standards. Pre-lighting and post-lighting crash data were compared. Although the cutoff limits and sample size were small, it was found that lighting reduced crashes by 45% on average.

A follow up to the Preston & Schoenecker (1999) study was conducted in 2006 to expand the rural intersection sample [1]. Isebrands et al., surveyed all counties in Minnesota for representative intersections that had a recorded date of lighting installation with no other intersection safety modifications. A 3 year pre-installation, 3 year post-installation study was conducted covering 33 rural intersections. Rural intersections were defined as "located at least 1 mile from areas with significant development or 1 mile from a signalized intersection on the same roadway." Records from MnDOT were accessed to investigate crashes that occurred within 300 feet of each intersection. Traffic volume was accounted for, similar to previous studies; however, the current study considered dawn and dusk in their time-of-day analysis. Full highway lighting was used on 4 intersections and a single-light (installed on an existing utility pole) was used on 29 intersections. Crash rate was compared for day/night and before/after installation. A general linear model for Poisson distribution found that 63% fewer crashes occurred during the day at the intersections selected and there was a 37% reduction in nighttime crash rate after the installation period. Lastly, they found that a substantial portion (e.g., 75%) of the luminaires at the sampled locations were mounted on existing utility poles which were deemed to be "destination" lighting. Destination lighting is considered to act more like a visible landmark than illuminate an intersection to a recommended specification. Hence, some level of lighting is beneficial [1, 4].

The results of these studies demonstrate that the benefit of lighting is not in question however, the amount of light required by drivers requires further understanding. Current rural intersection lighting systems appear to serve two purposes. The first is it provides a point of reference for drivers in a rural area about an important area ahead. The second is that it provides valuable visible information about the geometric structure of the intersection, intersection signage, general conditions, and may prompt drivers to increase awareness at these critical locations.

Recommended Practices

The intent of warrants is to aid in the identification of situations where lighting may be appropriate in the reduction of crashes and fatalities. Warrants and recommended practices/standards [e.g., 16, 17, 18] provide a set of criteria or threshold that must be met in order to for lighting to be considered. The installation of lighting, however, is up to the discretion of the State or other agencies. The decision to install lighting can be influenced by a number of other factors. For example, the Minnesota Department of Transportation's methods for installing street lighting at rural intersections are documented in Chapter 10, Section 3.01 of the Traffic Engineering Manual [19].

The following standards were identified from the newly released 2014 Approved American National Standard and Illuminating Engineering Society [18] for roadway lighting. According to ANSI/IES, the three methods for evaluating lighting design are luminance, illuminance, and Small Target Visibility (STV). These methods are often combined when determining standards for lighting and are also dependent on the roadway type in question. Horizontal illuminance was the selected design method set out by ANSI/IES for determining intersection lighting. Determining the horizontal illuminance level requires calculating the pavement luminance first. The average luminance standard for "Major" roadways that generate low pedestrian traffic is 0.6 (cd/m^2). "Major" routes, defined as 'routes [that] connect areas of principal traffic generation and important rural roadways entering and leaving the city', are the closest match to the rural roadways used in the current study. Finally, to get the horizontal illuminance, a ratio of $1cd/m^2 \cong 10 – 15$ (depending on the pavement classification) is the standard for Major roadways with low pedestrian traffic at intersections.

Another suggested method for standardizing rural intersection lighting applies to intersecting roads that are no larger than two lanes. The ANSI/IES recommends average illumination of

15.0/1.5 (Lux/fc) for zones designated "Major/Collector" and 13.0/1.3 (Lux/fc) for "Major/Local". These zones closely resemble the rural intersections of interest in the current study with respect to volume and average speed. Major/Collector refers to intersections with 1,500 – 3,500 average daily traffic (ADT) where Major/Local are intersections having 100 to 1,500 ADT [18; pp 15].

There are also a number of general considerations that apply to intersection lighting design which are also outlined in the ANSI/IES document, which include:

- *Pavement Classification* – Classes are determined based on pavement "lightness" and mode of reflectance. Common surfaces are R1 (cement concrete) and R3 (asphalt with dark aggregates).
- *Glare* – By installing lighting with a limited veil luminance ratio the effects of disability glare will be reduced. Trespass glow and night glow were also considered. These can be reduced by limiting the amount of uplight (light that is directed toward the sky).
- *Luminaire Classification System* – The updated LCS has changed from the previous system which used light intensity as the main basis for target luminance. The new system is still being evaluated; however, it proposes the use a rating system where the basis for target luminance uses percentage of luminaire lumens within a given area to determine the LCS.
- *Headlights* – Since low beam headlights are standard for traveling speeds of 30mph with no pedestrians, it is suggested that headlights alone are not sufficient for providing illumination for detecting objects at higher speeds.
- *Trees* – Presence of leaves and maturity of trees should be accounted for when designing lighting, especially in areas like Minnesota. Exact standards are not set, but it is estimated that 10-20% of light is lost due to trees, and this should be factored into the design.

Mn/DOT Roadway Lighting Design Manual

In addition to the ANSI/IES suggestions there are additional factors to be considered as outlined in the Mn/DOT Roadway Lighting Design Manual [19]. These factors include those identified by the Engineering manual in addition to suggestions by AASHTO for rural highways where drivers may drive through complex intersections with raised channelization or unusual geometry. The manual aligns with the ANSI/IES standards for intersection lighting, but also lays out a 14 step process for the design and installation of roadway lighting in Minnesota [19].

Lastly, counties within the State have either established their own warranting guidelines or utilize the research completed thus far as a basis for warranting rural intersection lighting. Usually the counties rely on the guidelines provided by AASHTO and also information as referenced in the Local Road Research Board Report No. MN/RC-1999-17. However, there are counties that do not have specific polices or guidelines for rural intersection lighting. In these instances, investigating the impact of lighting level and the utility of providing, at minimum, destination lighting may be beneficial to these communities. In an effort to identify and gather additional information, a survey was created and sent to all county engineers within the State of Minnesota to update rural intersection information.

Objectives

The objective of this study was to identify isolated rural intersections of interest, build a lighting data collection system, take lighting measurements at these intersections, and then analyze that data with respect to the factors within the crash data. Finally, the recommendations from the analysis would provide some insight into lighting levels for rural intersections and future research directions given the data analyzed. A number of steps were implemented to achieve these efforts which included:

1) Surveying county engineers about intersection lighting
2) Identifying intersections where data collection could be completed
3) Identifying and building a data collection system
4) Collecting horizontal illuminance data at those intersections
5) Comparing nighttime crash ratios using illuminance data
6) Providing results and conclusions

A roadway lighting system is only useful if it reduces nighttime crashes and fatalities. As a comparison, the current data collected and analyzed for the intersections of interest were assessed against newly published guideline and practices provided by ANSI/IES RP-8-14 national standards. Identifying illuminance levels at isolated rural intersection locations and the corresponding potential safety improvements, even if lighting levels are not at suggested standards, can provide MnDOT and county engineers with information on potential proactive safety requirements at isolated rural intersections.

Chapter 2
State of Minnesota County Lighting Survey

In November 2012, the researcher emailed an isolated rural intersection lighting survey to 87 counties in the State of Minnesota. The surveys were created using the University of Minnesota Survey (UM Survey), an online academic survey creation package that is managed by the Office of Technology at the University of Minnesota. The researcher chose UM Survey, as opposed to other online survey tools, as the data had integrity and security assurances in use by the University. Furthermore, the site is advertisement free, which in turn maintains a professional appearance for distribution outside of the University – a goal of the current research. The online survey followed a similar format to the previous questionnaires that were previously used [1, 4, 5, 20], where counties in Minnesota and Iowa were surveyed regarding rural intersection lighting practices. The format of the questionnaire was adapted to internet web browser access standards and questions were modified and added to gather additional information. A copy of the questionnaire distributed to the counties is presented in Appendix A.

Survey Responses

The survey link and reminder was emailed to all 87 county engineers 45 responses were gathered from the 87 counties that received the survey. The responses varied in the number of questions completed and the amount of information available to the research team. The response locations are shown in Figure 1 below:

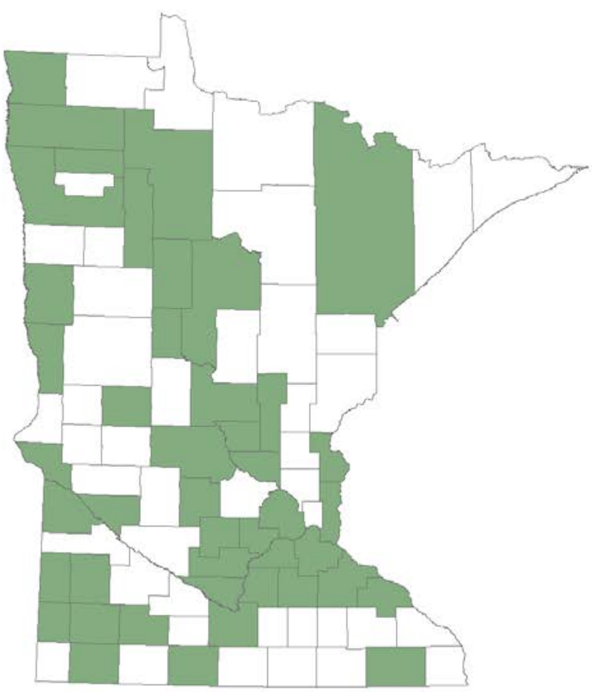

Figure 1. Rural Intersection Lighting Survey County Responses (green indicates county responded)

Summary of Responses

The response type and information acquired through the responses varied greatly between each of the counties surveyed. Of the respondents (45), 12 out of 45 (27%) counties concluded they did not have or maintain any isolated rural intersection lighting within their jurisdiction. The remaining counties varied on the amount of rural intersection lighting within their county. Table 1 provides an overview of the amount of rural intersection lighting within counties and the associated costs with installing and maintaining the lighting.

Table 1. Number of installations and installation costs

Survey question	Response range	Averaged Response
How many rural intersections does your county currently maintain?	0-1000*	125
Estimate of installation costs (total)	$1500-$15000	$4200
Estimate of maintenance costs (per light/month)	$0-$100	$32
Estimate of additional costs (per light/month)**	$20-$75	$50

*At least 4 counties responded "Cannot be determined/Too many to count"
** Additional costs include motor vehicle damage, 'gopher locates' etc.

In addition to the amount of lighting and the associated costs, participants were also asked about how the lighting installation was funded, installation guidelines (e.g., warrants/policies), the type of lighting typically installed, and any limitations to the installation process. Twenty-four (53%) counties had funding from County State Aid Highway (CSAH), County Highway Safety Plan (CHSP), Highway Safety Improvement Program (HSIP), MnDOT, or a mix of state and county funding. Five counties (11%) had funding through city/township funds and/or property tax. The remainder did not have funding (e.g., no lighting installed) or did not recall/know the exact funding source for the lighting installations (36%).

The responses also varied for the installation guidelines followed for rural intersection lighting. Twenty-one counties (47%) responded they used roadway classification, traffic volume, and crash history as factors for warranting the installation of lighting. Four counties (8%) did not know the policy/warrant that was applied. Nine counties (27%) responded they don't have lighting (or applicable warrants), and of the remaining that answered, two counties had no direct policy, one installed with traffic signals, and three used engineering judgment.

One survey question aimed at addressing the total number of lights installed at intersections was answered by 12 county engineers. Engineers in 8 out of 12 counties (66%) responded that at two-way stop sign controlled intersections 8 of 12 counties (66% of those that responded) used 1-point lighting, where one luminaire was at the location. The remainder (4 of 12) used two-point lighting, one for each stop area are the intersection. In terms of four-way stops, half of the counties that responded states that the intersections contained one light and half stated that there were two lights. The remainder did not have any applicable response.

Another survey question looked at the type of lighting installed by counties at rural intersections. Of the 33 respondents, 16 reported using 250 W High Pressure Sodium (HPS) lighting, three reported using Mercury Vapor, and one county using a mix of HPS, Mercury Vapor, and Light Emitting Diode (LED). Of the remainder (i.e., 13 counties), nine counties did not know the type of lighting, two responded 'likely LED', and two responded that the information was not available.

When respondents were queried about any potential issues or road blocks they encountered when funding or installing lighting, 13 of 31 responded "no" and 18 had various issues arise. Of the remaining responses, six counties reported issues with cost or ongoing maintenance, five had issues with county/district policies, four reported issues of power companies/power location/justification of effort, two had issues with residents, and one had very specific requirements to meet.

Lastly, respondents were asked to report any upcoming lighting projects, of which 12 responded "yes". In order to increase future intersection samples, the survey requested feedback for specific rural intersections that would be good candidates for lighting measurement. Seven communities responded with intersections of interest, one community reported that measurements were recently taken at their rural intersections, and the remaining did not respond or responded with "no". A list of eligible candidates for sampling intersections was compiled and the updated survey results were recorded. Some of those intersections identified by the county engineers were examined in the remaining research effort while the remainder remain on file for future work. The next portion of the research required measuring the lighting levels at the intersection of interest.

Chapter 3
Minnesota Rural Intersection Lighting Data

Minnesota Intersection Crash Database

The intersections selected for measurement were obtained through the Mn/DOT crash database and had previously been refined and assigned a risk rating via another project and safety plan reviews [21, 22]. The data was extracted from the database and save in Microsoft Excel format. The data contained a number of different categorizations and attributes that were selectable. The data file and the various associated variables are outlined in Table 2 below:

Table 2. Rural intersection variables from the Mn/DOT crash database.

County	County Number	Intersection Number	System (CSAH/CNTY)
Intersection Description	Type	Configuration ('X' or 'T')	Config 2 (Divided or Undivided)
Skew ('Yes/No')	On/near curve ('Yes/No')	Development ('Yes/No')	RR Xing ('Yes/No')
Crashes	ADT	Traffic control device	Streetlights ('Yes/No')
Location 'Rural'	Years of Data	VMT	Actual Crashes
Expected Crashes	Critical Rate	Total Crashes	Number of Severe Crashes
Severe %	Severe Right Angle	Severity (K, A, B, C, PDO)	Diagram (Severe only)
Light Conditions (Severe only)	Road Condition	Crash Cost	County Ranking
Latitude	Longitude	Risk Rating	

The associated variables shown in Table 2 were used to review and identify intersections of interest. To begin, intersections were selected based on risk ratings of 3 or higher. The risk ratings were part of the refined dataset obtained by the researchers, but were rated based on a number of factors. These factors included number of previous crashes, severe crashes, approach (e.g., skew), intersection lighting present ('yes/no'), proximity to a railroad crossing, average annual daily traffic, etc. After an initial review of the data, a total of 244 intersection locations were preliminarily identified for additional review. These intersections included both lit and unlit locations in various counties within the State of Minnesota. After additional review, discussions, and further refinement, the total number of intersections selected were 63 and were located in areas around the greater metro area. The locations were chosen based on proximity to the research teams equipment and also ease of access, safety of the data collection effort, and infrastructure influences (e.g., construction). A final list of 63 intersection locations are presented in Appendix B.

Initially 65 intersections were measured, however due to a failure in the data collection software, two intersection locations had to be removed from the overall assessment. Intersection locations were chosen based on their geometric features (i.e., Crossroads or ‘T” intersection). Figure 2 provides a diagram of the intersection types chosen. Alternative intersection types were not chosen for measurement or analysis due to the prevalence of intersections available. All intersection locations had a maximum speed limit of 55 miles per hour.

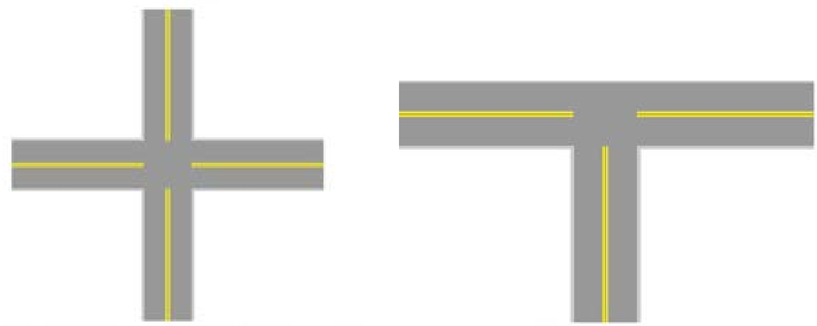

Figure 2. Diagram of a Cross-Intersection and ‘T’-Intersection types.

Table 3 provides a summary of the chosen intersection locations and the corresponding attributes for those locations. All intersection locations measured were controlled and labeled as Thru-Stop and consisted of rural two-lane roadways.

Table 3. Rural Intersection Features

County Locations	Number of Intersections	Number of Cross-roads	Number of T-intersections	Intersections with Lighting	Intersections without Lighting
Carver	7	5	2	7	0
Dakota	6	1	5	3	3
Scott	13	8	5	9	4
Sherburne	8	3	5	1	7
Washington	15	6	9	10	5
Wright	14	10	4	10	4
Totals	**63**	**33**	**30**	**40***	**23***

* As per the original database - these totals were modified as discussed in the data review.

Equipment

The lighting illuminance data was collected using a set of illuminance meters that was positioned on the rooftop of a large passenger vehicle (e.g.,sedan). The set-up of the illuminance meters was similar in concept to that of a system developed by the Lighting Infrastructure Technology group at the Virginia Tech Transportation Institute [see e.g., 23]. However, unlike the VTTI data collection set up, the current illuminance meter array was positioned differently on a sedan and the system did not collect vertical illuminance or luminance data. The main elements of the data collection set up were: Global Positioning System, illuminance meters, and portable in-vehicle data collection system.

A total of 5 Konica-Minolta waterproof mini receptor heads were placed on a 2009 Chevrolet Impala. The heads were positioned and secured horizontally onto the roof rack and the rear trunk of the vehicle. The sensors were placed in such a manner that the left and right outboard sensors were positioned over the left and right wheel paths of the vehicle. The remaining three sensors were positioned down the center line of the vehicle. The illuminance sensors were plugged into a series of Konica-Minolta receptor heads that were connected to a Konica-Minolta T10 main body. The T-10 main body was also connected to a power supply and a portable data collection laptop that collected the data through a Universal Serial Bus (USB) cable. In addition to the waterproof illuminance meter heads, there was also a Trimble R7 GPS unit mounted on the roof of the vehicle that provided GPS coordinate positions for the vehicle (see e.g., Figure 1). The positions of the sensors were calibrated to the center of the Trimple R7 to allow for precise measurement locations between the GPS and the respective illuminance meters on the left, right, and center line of the vehicle.

Figure 3. Illuminance measurement system with four visible heads (one positioned on the trunk) and the Trimble R7 GPS unit (white).

The illuminance data network was connected to the data collection laptop that resided in the vehicle. The illuminance meters were synchronized to the GPS unit through the data collection laptop. The data collection software initiated the GPS and synchronized the data input from the GPS and the illuminance meters through a common timestamp (see e.g., Figure 3).

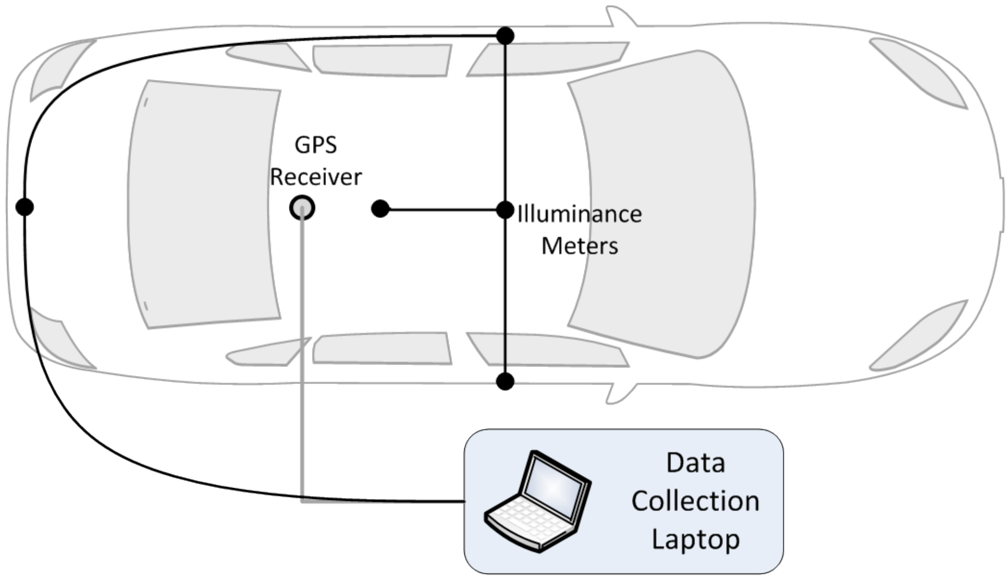

Figure 4. Diagram of the illuminance data collection system.

The illuminance meters were controlled by a software script developed in Python and run in Ubuntu; a Linux distribution. Illuminance data was collected at a rate of 2 Hz and was not collected by all the sensors at once. A small time delay occurred while data was being read by the Python script for each sensor head. The GPS receiver provided position fixes at a rate of 10Hz. With information from the MnDOT operated CORS/VRS, the approximate accuracy of each fix was within a few centimeters. The data collected by the illuminance meters was then combined with the GPS data with post-processing software that determined the position of each sensor at the time of the reading and then corrected the data for the location of the sensor on the vehicle (e.g., left, right, front, and trunk of the vehicle). This data was added to the data collected from the illuminance meters and then combined into a text output file.

Data Collection Procedures

As previously described a representative sample of isolated rural intersections was used from a variety of different Minnesota counties that included: Carver, Dakota, Scott, Sherburne, Washington, and Wright. A total of 63 intersection locations were chosen based on ease of access and ease of measurement.

Data collection occurred during similar evening/early morning hours over the course of 10 non-consecutive days. Data collection occurred at least 1 hour after sunset to allow any ambient lighting to diminish (e.g., dusk). The ambient lighting during this time was during the last moon phase (e.g., ¼ to ½ moon visible) and most evenings (8 of the 10) had medium to heavy cloud cover. The remaining evenings had scattered cloud cover.

In order to navigate to the locations effectively, data collection sessions were broken up by counties. Each rural intersection location was then mapped using Google Maps and entered into an in-vehicle GPS device. The GPS device then provided the route to each of the locations, minimizing driving time and maximizing data collection effort. For each intersection, data was collected from all possible approaches. The following Figure shows the data collection points and general data collection pattern for each of the approaches to a crossroad and 'T' intersection location (Figure 5).

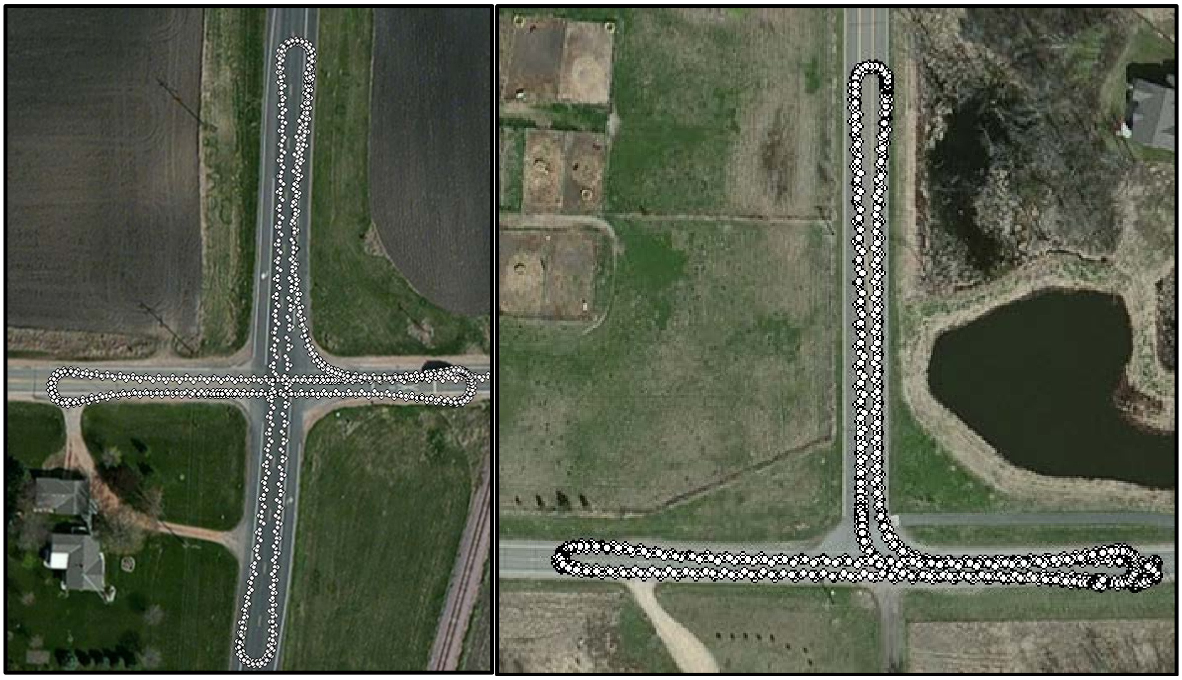

Figure 5. Data Collection Paths at the Intersections of Interest

Upon arrival at the data collection site, the researcher pulled onto a shoulder lane or nearby driveway within approximately ~300-400 feet of the measurement intersection. Prior to measurement, the GPS software receiver was checked and then the data collection program was activated. Upon verification that no oncoming cars were approaching and no other traffic was sighted the data collection proceeded. Data collection then proceeded throughout the intersection in the patterns presented in Figure 5. When all approaches had been collected the researcher then pulled the vehicle into the shoulder lane and discontinued the data collection software. During data collection the primary lighting type encountered was High Pressure Sodium (see Figure 6).

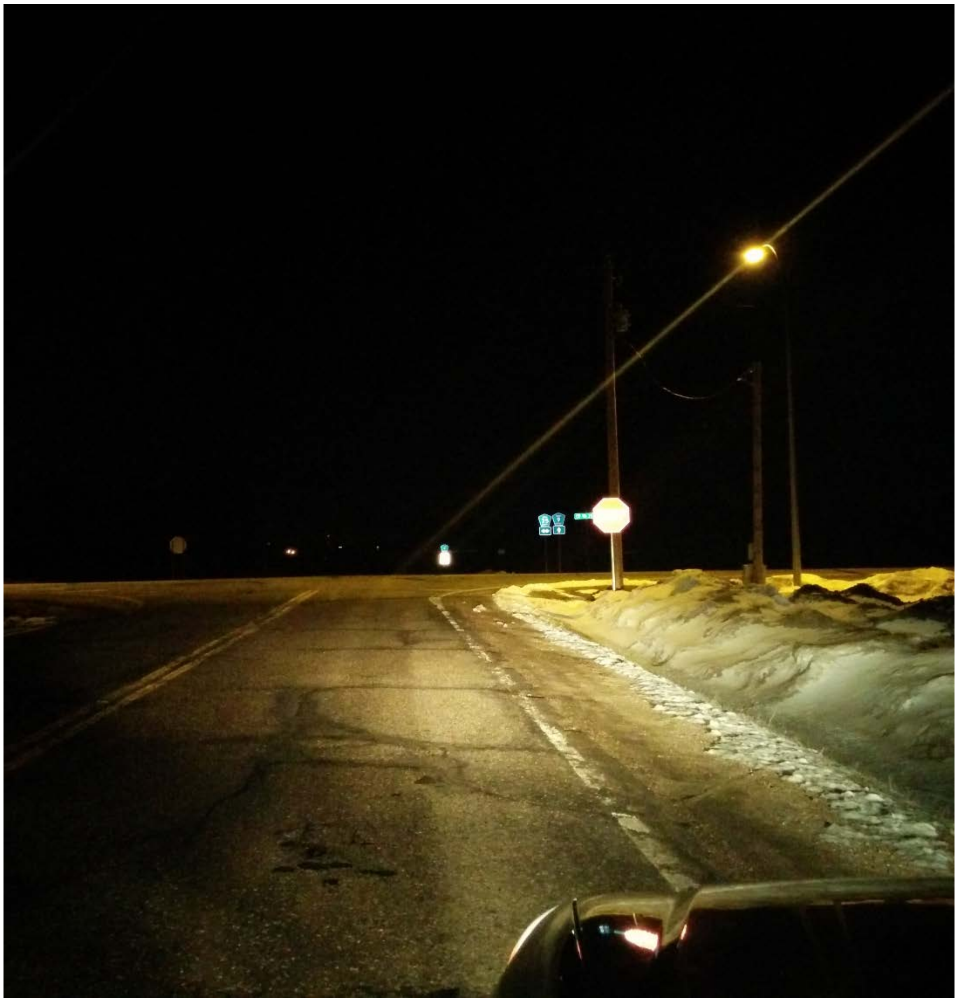

Figure 6. Rural through-stop intersection with High Pressure Sodium Lightings (HPS)

While the primary roadway lighting source encountered during the data collection effort was HPS, it should be noted that alternative lighting was also measured (e.g., see Figure 7), however fewer numbers of these lighting types were observed compared to intersections intersections containing HPS.

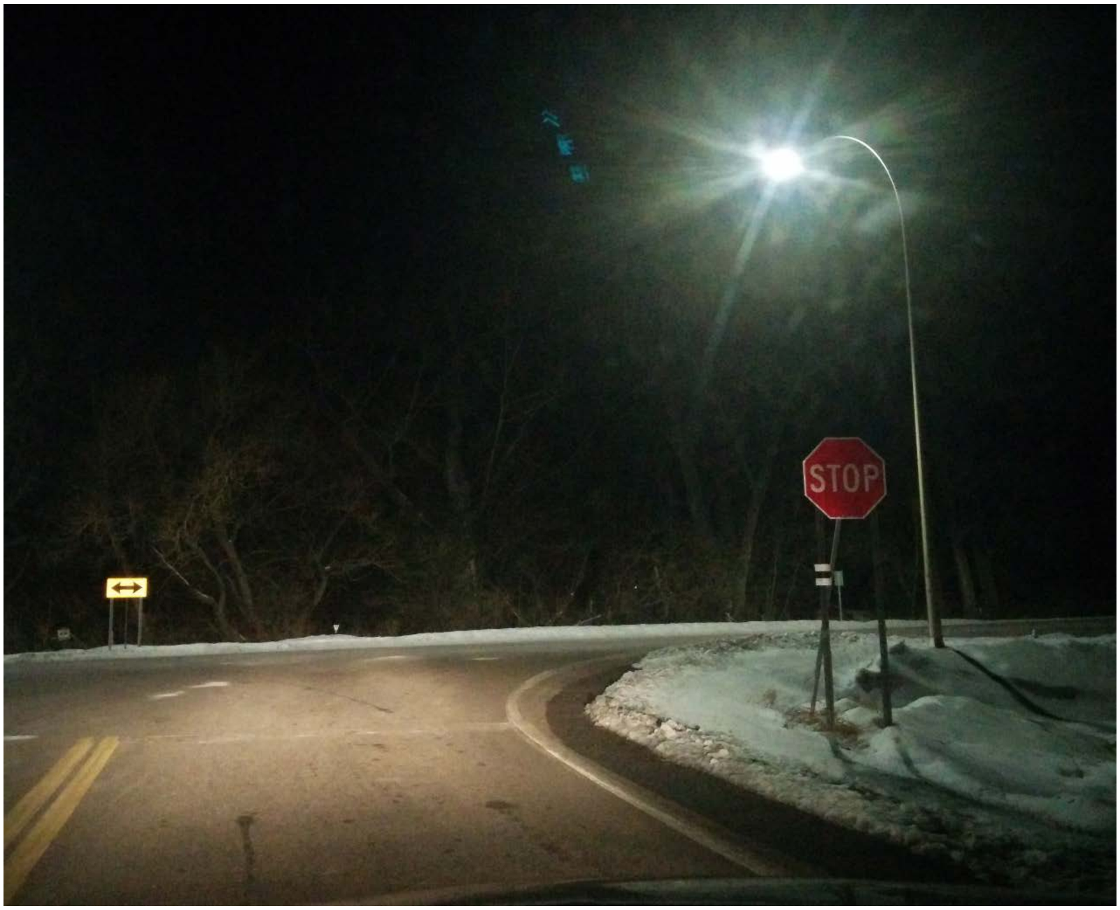

Figure 7. Rural through-stop intersection with Light Emitting Diode (LED)

Data Screening

When all 63 intersections were completed, each of the output files was merged together into a single file format. Each data collection point contained a timestamp, data from each of the illuminance heads, and a latitude and longitude set of coordinates. Prior to uploading the data into ArcMap and checking each of the position locations, the data was screened for errors in illuminance, GPS, and timestamp values. Errors did occur for some of the GPS data, where coordinates were not available for some of the data collection points. Upon further examination, the researchers concluded these points occurred when initiating the data collection software and resulted in the loss of data for 2 intersection locations.

After the GPS data was reviewed the illuminance data was then scanned for outlier information. Outliers and errors were found for 3% of the data collected at the intersections of interest. Errors usually occurred when a negative or overinflated number (from one of the illuminance heads) appeared in the data stream. These outliers were removed from the overall data set prior to any additional analysis of the data. Average illuminance was then calculated based on a specific protocol described in the next section.

Illuminance Data

In order to calculate the illuminance level of a rural intersection of interest, each data collection point was mapped using the coordinates from the GPS and uploaded to ArcMap for further processing. When all points had been successfully uploaded, the researcher then created a 164-ft radius (50m) around the center point of every intersection. The center point was defined as either the very center of the crossroad or the center of the 'T' intersection location. A 164-ft (50m) radius was chosen based on IESNA RP-8 recommendations that suggests measurements at isolated intersections include the area between the stop bars. The radius also ignores the turn-around areas during data collection and thus removes any additional influence or data collection points when the vehicle is moving slower. When the all the radii had been defined for each intersection, only that data with each of the circles at each of the intersections was used to calculate average illuminance (Figure 8). That data was exported to a separate file to be further analyzed.

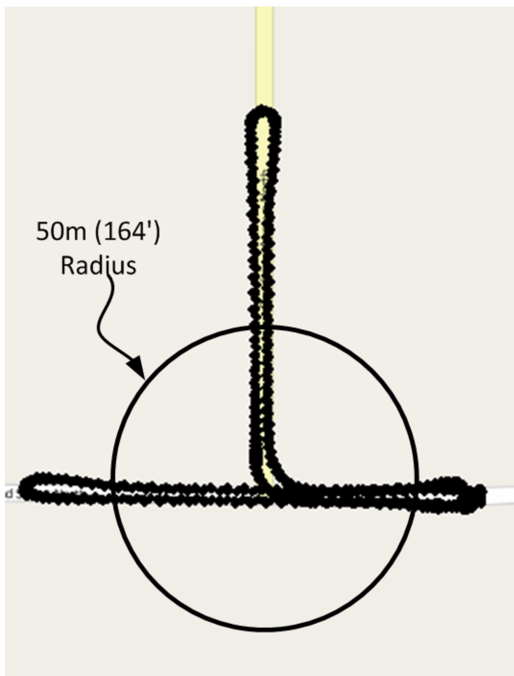

Figure 8. 'T' intersection with GPS data coordinates plotted. Data was trimmed based on the 100-ft radius of circle applied from the center of the intersection in ArcMap.

Chapter 4
Rural Intersection Data Review

The data was a refined set of the original crash database provided [21,22]. The data analyzed spanned a 5-year period from 2007-2011 and contained both daytime and nighttime crashes for lighted and unlighted rural intersections. The next sections of this chapter provide some summary statistics of the lighting data prior to the crash analysis using a specified count data model. The summary data will provide number of crashes, crash ratios, and other elements across those intersections of interest. As a final component to this chapter, the average illuminance levels will also be examined across intersection types for both lighted and unlit intersections.

Number of Crashes

As with the components of the intersection location, each intersection also had a different number of daytime and nighttime crashes. Of particular interest for this study were those collisions occurring at night, however day and night crash ratios were also calculated to identify any particularly problematic intersection locations. To begin, Table 4 shows the crash counts for lighted and unlighted intersections and also the ratio rates per year. Overall, from the frequency and corresponding ratio data, lighted intersections had lower nighttime crash ratios compared to unlit intersections. In addition, these intersections also had a lower dusk/dawn ratio rate, but did have higher daytime crash ratios (Figure 9). While these counts provide some estimate of crashes occurring at intersections, the frequency of crashes is better examined through day to night crash ratios.

Table 4. Crash Counts at the Intersections of Interest

2007–2011	Lighted	Unlighted	Total	Lighted/Int/Year	Unlighted/Int/Year
Daytime	173	60	233	0.86	0.52
Nighttime	25	19	44	0.12	0.19
Dusk/Dawn	11	10	21	0.06	0.10
Other Crashes	3	1	4	0.02	0.01
Total Crashes	212	90	302	0.99	0.90

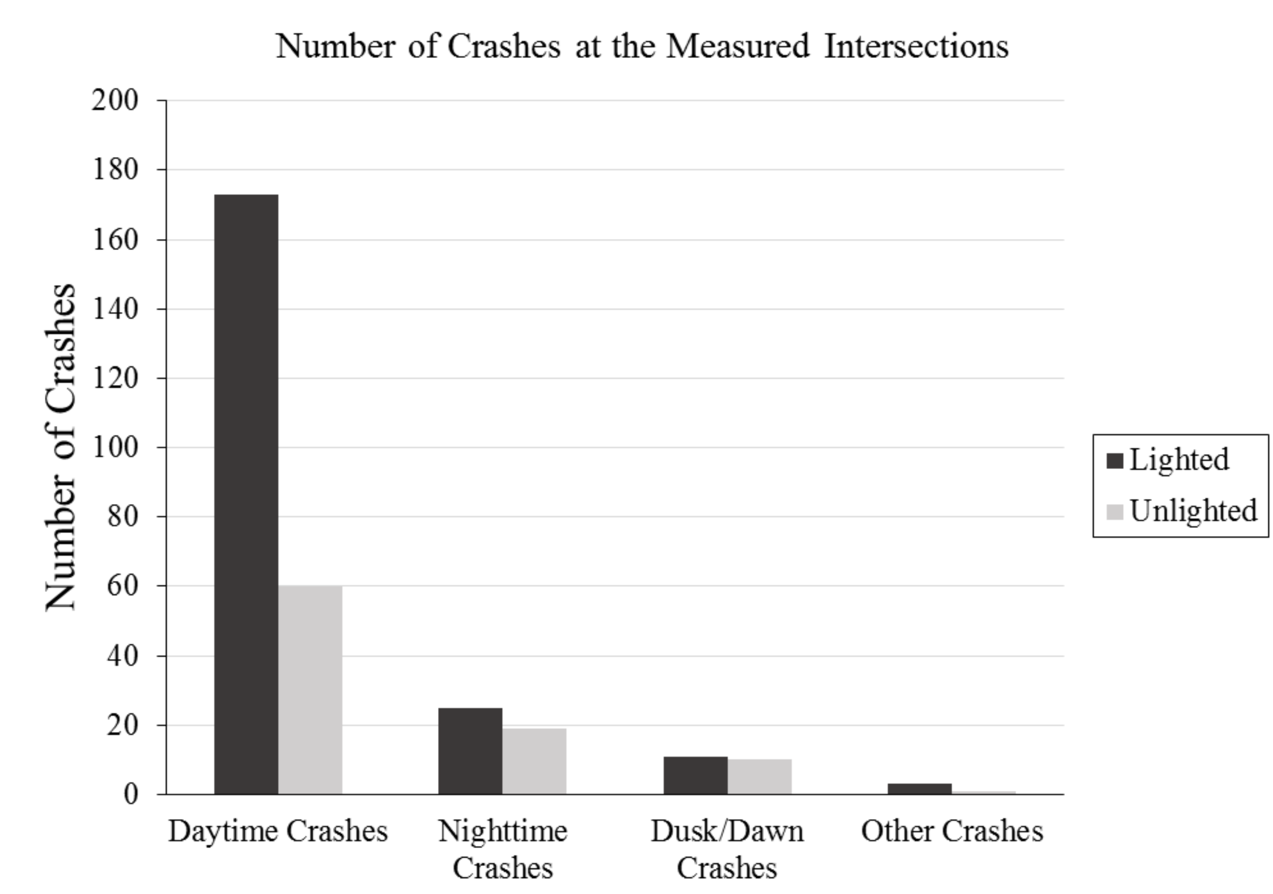

Figure 9. Number of crashes by time of day at lighted or unlighted intersections of interest.

Crash Ratios

In addition to the frequencies of crashes, the night-to-day crash ratio and night-to-total crash ratio was also calculated for the lighted and unlighted intersections. The data is presented in Table 5. Lighted intersections had substantially lower night-to-day crash ratios and night-to-total crash ratios. Again, these values provide insight into the crash ratio rate comparisons between night and daytime conditions, but to evaluate these intersections further there is a need to examine traffic rate (e.g., ADT) to establish a true vehicle volume rate and corresponding crash rate.

Table 5. Rural intersection crash ratios for combined 5 years of data

	Lighted	**Unlighted**
Night-to-day	0.14	0.32
Night-to-total	0.12	0.21

Intersection Crash Rate

For intersection locations, crash rate is most often derived as a rate of per million vehicle miles traveled. ADT was available for each intersection locations, thus crash rate was calculated for lit and unlit intersection locations. The crash rate per Million Entering Vehicles (MEV) is calculated by:

$$Intersection\ Crash\ Rate = \frac{\text{C x 1,000,000}}{\text{365 x N x V}} \quad (1)$$

Where:

C = Total number of crashes in that period
N = Data collection time period
V = Intersection Average Daily Traffic

The intersection crash rate, using ADT information, was calculated for all of the lighted and unlighted intersections and is denoted in Table 6. The intersection crash rate, in this instance, is a general measurement of the rates at lighted and unlighted intersections and does not reflect a specific intersection location. Integrating the ADT information shows that lighted intersections generally have a higher intersection crash rate compared to unlighted intersections. For additional information, the specific intersection crash rates, lighting status, daytime, and nighttime crash rates are presented in Appendix C.

Table 6. Accumulated intersection crash rate across intersection types

	Lighted	**Unlighted**
Average intersection crash rate (per MEV)	0.56	0.43

Average Horizontal Illuminance

The data collection effort for this study utilized horizontal illuminance as a measure of the lighting levels at the intersections of interest. When the data file processing was complete (e.g., as described earlier), a mathematical mean or average illuminance level was calculated. The average was derived as the average illuminance incident on the roadway lanes and captured within the 50 meter or 164-foot radius from the center of the intersection location (e.g., see Figure 8). The lighted intersections had illuminance measure ranges between 0.12 to18.42 lux, with an average of 6.41 lux. The unlighted intersections had substantially lower ranges (as expected) from 0.05 – 0.91 lux. The average illuminance for all unlighted intersections was 0.20 lux. The data for each of the intersections is presented in Table 7.

Table 7 Average, Max, and Minimum Illuminance at Lighted and Unlighted Rural Intersections

	Lighted			Unlighted		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Average Horizontal Illuminance (lux)	6.41	0.12	18.42	0.20	0.05	0.91

The distribution of the illuminance levels across both lighted an unlighted intersection locations is presented in Figure 10.

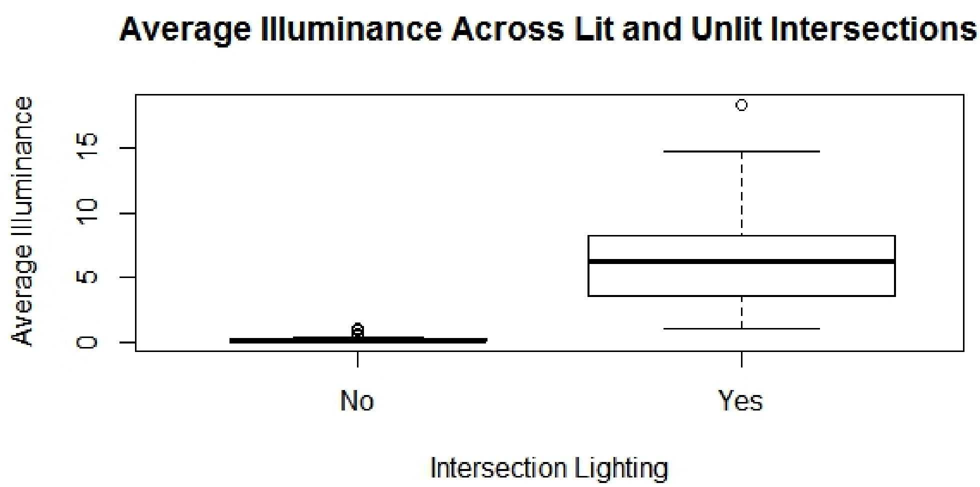

Figure 10. Boxplotof Illuminance Levels across Lighted and Unlighted Intersections

Chapter 5
Rural Intersection Data Analysis

Vehicle Crash Prediction Modeling

A number of analysis techniques have been utilized in the rural intersection lighting domain in an attempt to identify a set of mitigation strategies that would reduce crashes at intersections. Given the different types of analysis in prior research, the effort is to identify an appropriate approach for the data collection at Minnesota intersections (Karlatis & Golias, 2002). The current project utilized similar data to the previous examples (e.g., Isebrands et al., 2010), but focused on Minnesota data that included a subset of intersections where the lighting level had been measured. The measurement of the lighting level is expected to provide additional insight into the prediction model for crashes at rural intersections.

To begin, a number of models will need to be reviewed prior to processing the data in the associated data set. A brief review of the Poisson distribution and Poisson Regression is provided followed by the intersection analysis.

The Binomial and Poisson Distribution

The Binomial distribution focuses on events occurring a certain amount of time given the number of times specified. For example, you can ask how many heads will be identified when a coin is flipped a certain number of times. Conversely, the Poisson distribution still uses a discrete random variable, but one that is infinite. Poisson changes the type of question that's asked, such that an event may occur at any point in time, or it may not [24, 25]. For example, a vehicle crash may occur at any point in time at a specific intersection location. However, there is no "opportunity" when a vehicle may crash or it may not, unlike when a coin is flipped, there is an opportunity for a head or not [26]. In essence, the Poisson distribution is a subset of the Binomial distribution in that it's a limiting case when *n* gets large and *p* gets small. For example, if we let $\lambda = np$ (lambda; equal the average number of successes), and then substitute into equation 1 (inserting equation 2 into *n* chooses k) from above and get:

$$P(X=k) = \frac{n!}{k!\,(n-k)!} p^k (1-p)^{n-k} \tag{2}$$

$$\lim_{n\to\infty,\ p\to 0} P(X=k) = \lim_{n\to\infty,\ \lambda/n\to 0} \left[\frac{n!}{k!\,(n-k)!} \left(\frac{\lambda}{n}\right)^k \left(1-\frac{\lambda}{n}\right)^{n-k} \right]$$

$$= \lim_{n\to\infty,\ \lambda/n\to 0} \left[\frac{n(n-1)(n-2)\ldots(n-k+1)}{k!} \left(\frac{\lambda^k}{n^k}\right) \left(1-\frac{\lambda}{n}\right)^{n-k} \right]$$

$$= \lim_{n\to\infty,\ \lambda/n\to 0} \frac{n^k}{k!} \left(\frac{\lambda^k}{n^k}\right) \lim_{n\to\infty,\ \lambda/n\to 0} \left(1-\frac{\lambda}{n}\right)^{n-k}$$

$$= \frac{\lambda^k}{k!} \lim_{n\to\infty,\ \lambda/n\to 0} \left(1 - \frac{1}{n}\right)^{\lambda(n-k)} = \frac{\lambda^k}{k!} \left[\lim_{n\to\infty} \left(1 - \frac{1}{n}\right)^{n}\right]^{\lambda} = \frac{\lambda^k}{k!} \left(\frac{1}{e}\right)^{\lambda}$$

$$= \frac{\lambda^k e^{-\lambda}}{k!} \tag{3}$$

The equation steps show the limiting case of the Binomial distribution that result in the Poisson distribution when the value of *n* gets large and the *p* or probability of success moves towards zero. An important note of the Poisson distribution is that if X is a Poisson random variable, that the E(X) or the $\mu = \lambda$, $\sigma^2 = \lambda$, and $\sigma = \sqrt{\lambda}$.

The Poisson distribution can be extended into the General Linear Model Family by adding the log link (or Canonical link; 27), and be utilized in R (e.g., glm function), where the natural logarithm is applied to the linear regression equation (5).

$$= \log\big(\lambda\ (X_1, X_2, \ldots X_k)\big) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \tag{4}$$

The reciprocal to this function is to take the exponent of the log and to produce the following equation that results in the mean (e.g, equation 6).

$$\lambda = \mu = e^{\alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots . \beta_k X_k} \tag{5}$$

The equation has taken the linear log (or exponential) form and the interpretation is different than normal linear regression. When interpreting the information you have to apply an exponential form as the model is non-normal. For Poisson regression a one unit change in the predictor variable changes the expected count by the log of the regression coefficient; if the other coefficients in the model are held constant [28]. Another important note is that exponential coefficients are multiplicative. These are often difficult to interpret in the exponential form and are dependent on the change in the count variable. To illustrate, lets generate a quick example that uses the number of crashes at an intersection defined as the criterion variable (or count variable) and average daily traffic (ADT) as the only predictor. If the resulting coefficient was $e^{0.345}$ for ADT, that would be interpreted as $e^{0.345} = 1.41$ or the predicted effect for a one unit-change (increase) in ADT, results in a multiplicative effect (e.g., 1.41 times) on the number of crashes that occur at the intersection of interest. These multiplicative effects can be difficult to understand by the research field and it can be common to see researchers modify the results into a percentage format or risk rate [29]. Essentially, you take the exponential result and subtract one from it. Taking the previous example, $e^{0.345} = 1.41$, and subtracting one would result in 0.41. Multiply the outcome by 100 and you have a percentage influence of the predictor on the criterion variable. Conversely, if the predictor coefficient was negative, for example $e^{-0.345} = 0.708$, the risk rate would still be subtracted from the exponential result such that: 0.708-1 = -0.291, or a 29.1% decrease effect [30]. While the interpretation of exponential coefficients can seem overwhelming at first, a detailed explanation is essential in understanding the impact on crash rates using these statistical methods.

The results from a Poisson regression analysis can be a useful interpretation on the probability ratio or relative risk, however like the OLS linear regression model there are underlying assumptions that are made based on the distribution used. In Poisson regression, there are a number of assumptions that must be kept in mind, which include [28, 30]:

1. Underlying assumption is that the variance is equal to the mean,
2. The log of the criterion variable changes in a linear fashion with incremental increases in the predictor variable.
3. Changes in the rate are from the combined multiplied effects of predictors, and;
4. Observations are independent and do not influence each other.

While the Poisson regression method does provide a usable and useful model for count data, most of the vehicle crash data, and data in general, ends up violating the third assumption of the list [31]. Similar to other linear models in OLS, there are methods to identify if, specifically, the variance to mean assumption has been violated.

Overdispersion in Poisson Regression

A common violation in most Poisson regression models involves over dispersion of the data. Over dispersion occurs when the variance is larger than the mean, which violates the basic underlying structure of the Poisson regression model; recall $\mu = \lambda$, $\sigma^2 = \lambda$ [24, 32, 33]. In situations when overdispersion occurs the standard errors are under estimated [34]. This in turn can lead to over confidence in the results obtained through the statistical packages [32]. Over dispersion can be particularly effected by skewed variables at either end of the distribution. A similar, but less common effect can occur when the variance is less than the mean; referred to as under dispersion [35].

There are a number of ways to identify when over dispersion is present in the Poisson regression model. The most common and also the one utilized by the R package AER (Kleiber & Zeileis, 2008), is to test the Poisson regression model assumptions that the condition mean is equal to the variance, established as the null hypothesis. The alternate hypothesis is the variance does not equal the mean and that the model should be rejected as it does not meet the underlying assumptions. The test statistic used is a *t* -statistic, defined as asymptotically standard normal under the null [27, 33, 34]. The resulting hypotheses are:

1. $H_0 = E(X) = Var(X) = \mu$
2. $H_1 = Var(X) = \mu + \alpha * \text{trafo}$

α = constant (assumed to be zero if H_0 is true), $\alpha > 0$ = overdispersion, $\alpha < 0$ = underdispersion, trafo = transformation function, default =Null

The current research effort used the AER package to check for overdispersion in the poisson regression model. The current research tested for overdispersion during the analysis phase of the research effort.

Negative Binomial Distribution and Model

There are a few definitions for the negative binomial distribution. The first is a distribution where the trials are counted until an *r* th success [24, 25, 28]. This version is given in the equation (8) below where X is a random non-negative variable:

$$\Pr(X_r = k) = \binom{k-1}{r-1} p^r (1-p)^{k-r} \tag{6}$$

An alternative version of the equation is based on counts of failures prior to the r th success. The probability mass function for the negative binomial distribution is show in equation (9).

$$\Pr(X_r = k) = \binom{k+r-1}{k} (1-p)^r p^k \tag{7}$$

Where k = 0, 1, 2, 3….n, and

$E(X_r) = \frac{r(1-p)}{p}$ and $Var(X_r) = \frac{r(1-p)}{p^2}$

An important note is that the negative binomial distribution is an alternate to the Poisson distribution where the model provides an additional parameter so that the variance can take a different value compared to the mean. The addition of a parameter is achieved through the use of applying the Gamma distribution [26]. Recall under the Poisson distribution that the mean and λ are assumed to be equal. However, if we apply a different distribution to λ, then we can assume the differences in the model and the data are not uniform and are therefore heterogeneous [34]. A common naming convention, when allowing λ to be distributed as a gamma distribution, is the Gamma-Poisson mixture. The resulting negative binomial regression model incorporates the gamma functions and is presented in equation (10).

$$\Pr(X = k) = \frac{\Gamma(k+r)}{k!\Gamma(r)} \left(\frac{r}{r+\mu}\right)^r \left(\frac{\mu}{r+\mu}\right)^X, \quad k = 0, 1, 2, \ldots \tag{8}$$

Similar to the binomial distribution, the Poisson and negative binomial distributions converge when r approaches infinity (e.g., gets larger). The negative binomial distribution, similar to the Poisson regression, can be transformed and utilized as part of the GLM tool set to identify probability of count data that is handicapped and does meet the Poisson regression model assumptions [36]. The final regression model is similar to the Poisson regression model such that:

$$\ln \mu = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \tag{9}$$

Similar to the Poisson regression model the negative binomial model uses Maximum Likelihood Estimates to identify the parameter estimates and coefficients of the equation. The formulations of these are still being understood by the current author and thus have not been explicitly identified in the paper. For derivations of the MLE and the log link functions for the MLE for both the Poisson and negative binomial models the current author suggests Cameron and Trivedi, 1998; 2005, and Gardner, Mulvey, & Shaw, 1995 as a primer. Additional references for the MLE and derivations of the gamma distribution are available through a general search on the internet.

Rural Intersection Nighttime Crashes

In an effort to explore the models identified, the current research effort focused on predicting crashes at rural intersections. Identifying crash occurrence and predicting crash rates at rural intersections at night can provide guidance to roadway engineers by identifying potential issues at specific locations [37]. The data used in the current effort focused on those intersections that demonstrated high crash rates with and without roadway lighting. The data set also contained intersections with similar geometric features, but also had lower or zero crash occurrences. However, for the current data set, an addition measure was obtained that included the illuminance level from the roadway lighting (or not) from each of the intersections of interest. The intent of the data analysis was to identify a crash prediction model for these intersections and identify which factors contribute the greatest impact on rural intersection crashes.

Data Review and Cleaning

Prior to submitting the data to any statistical analyses, the data was reviewed based on the average illuminance metrics obtained during the data collection period. It was identified that some locations were incorrectly identified as having lighting, when in fact it did not. Conversely, some installations were updated and contained roadway lighting, when the crash database did not indicate lighting was present.

A set of illuminance cutoffs were established in order to correctly classify the average illuminance information and the presence of lighting. The cut offs were also visually verified during the data collection process when the measurements were being collected. If an intersection had an average illuminance level of below 1 lux and was also visually confirmed as having no working roadway light(s) or no lighting at all, the crash database was updated to reflect no lighting in the corresponding column value. However, if the lighting level was above 1 lux and was verified as having no lighting, when in fact it did, then it was acknowledged as having roadway lighting in the corresponding category.

A number of contributing factors were identified during the data collection process that influenced the reassignment of the lighting category variable. For example, if lighting was acknowledged at an intersection location, when in fact there was no lighting installation, it was likely that light trespass from other intersections was visible at that location, however it did not adequately light the intersection location. Conversely, it was apparent that new installations had been installed recently in some locations which reflects an overall improvement in the safety measures at that location.

A total of eleven intersections of the sixty-three were re-classified as having lighting when the average illuminance was below 1 and visually verified as not working or not present. Conversely, eight of 63 intersections were reclassified as having lighting present when it was marked as not present at the intersection. The reclassification resulted in a total of 37 intersections being classified as having lighting and average illuminance levels of greater than 1. The remaining 26 were classified as not having lighting (potentially even though a light was present but not working) and reflected an average lighting level of less than 1 lux (see e.g., Appendix B). The final data file was compiled into a comma-separated-values file format that was then imported into R (version 3.1.1).

Intersection Variables of Interest

The overall analysis initially used a Poisson regression model to predict nighttime crashes based on a number of factors. The primary variable of interest was the nighttime crash rates and this served as the dependent variable in the model. A number of predictor variables were entered into the model as potential predictors in the occurrence of nighttime crashes. These variables are shown in Table 8 below.

Table 8. Variable List and Descriptive Statistics

Rural Intersection Crash Data			
Variable	Mean (SD)	Minimum	Maximum
1. Total nighttime crashes	0.70 (0.98)	0	6
2. Total daytime crashes	5.21 (4.37)	0	19
3. Total nighttime crashes (with lighting)	0.61 (0.92)	0	6
4. Total nighttime crashes (no lighting)	0.94 (1.18)	0	4
4. Average Illuminance (lux)	3.91 (3.97)	0.07	18.42
5. Street Lights (Yes)	-	-	37
6. Street Lights (No)	-	-	26
7. Average Daily Traffic	6320	802	18527
8. Configuration T-intersection	-	-	38
9. Configuration X-intersection	-	-	25

Three additional variables included in the analysis was skewed intersection, at or near a curve in the roadway, and proximity to a rail road crossing (near).

Crash Prediction Modeling Results

Prior to running the Poisson and Negative Binomial regression models in R (version 3.1.1; 2014), a number of packages were installed beyond the base R package which provided the various models and resources for additional model testing. The packages used included MASS, pscl, pastecs, AER, QuantPsyc, and epicalc (R Core Team, 2014). For the Poisson regression model, the model type is specified as part of the GLM model included in the base R package. The model is specified by defining the "type=poisson".

In addition to running the poisson regression model in R, the analysis also assessed the effects of dispersion in the model. When comparing the residual deviance and the associated degrees of freedom, by rough estimation, the difference is greater than 1. Recall that the variance and mean are assumed to be equal in the Poisson regression. These rough results suggest that there may be overdispersion in the data and that further testing is required. For the current model a number of additional tests were applied that provided similar results. These alternative tests were done based on the packages available within R. The initial test compared the residual deviance value and residual degrees of freedom via a Chi-square test distribution. As stated above when reviewing the null and alternative hypothesis in dispersion testing, the chi-square test should not reject the null hypothesis if the variance is equal to the mean. However, in the current model $\chi^2 < 0.001$, rejecting the null hypothesis and suggesting the variance is greater than the mean. Additional tests (e.g., AER – dispersion Test; 38) also confirmed the presence of overdisperion in the model (dispersion = 1.35 > 1).

Negative Binomial Regression

When overdispersion is discovered in the data, a negative binomial model is an appropriate alternative model. The model supports a separate variance parameter and does not rely on the assumption that variance must equal the mean. The current data set was analyzed using negative binomial models through the use of the MASS package in R.

Variables

The negative binomial regression models used the number of crashes at night as the dependent variable. For the offset variable, the logarithm of the Average Daily Traffic Variable was used to control for exposure. The independent or predictor variables included intersection configuration (crossroad or 'T'), average illuminance (lux), and on or near a curve (yes or no). Each of these predictors was entered into each of the models for all intersections, lighted and unlighted intersections.

All Rural Intersections

To begin, the entire set of intersections was entered into the model in an effort to identify appropriate predictors for crash rates at night. In addition to running each individual variable, interactions were also included in the model. The predictors were entered into the model and the results of the model are presented in Table 9. Note that only the intercept and those predictors found to be significant in the model are presented in the table.

Table 9. Negative Binomial regression model results for all rural intersections.

Variable	Estimated Coefficients	Std. Error	Pr (>|z|)	Exp(β)
Intercept	-1.06	0.26	<0.001*	-
Average Illuminance (lux)	-0.08	0.04	0.04*	0.91
Intersection configuration (T)	1.10	0.28	<0.001*	3.03
Near a Curve (Yes)	1.02	0.26	<0.001*	2.79
Intersection Config (T) x Avg. Illum.	0.11	0.03	0.002*	1.13
Intersection Config (T) x Curve	-1.80	0.31	<0.001*	0.16

* Significant $p < 0.05$

As a reminder, recall that a Risk Ratio (RR) is established to measure the percent change in the dependent variable (e.g., response) when a unit increase in a continuous predictor variable is applied. For a categorical predictor variable, the unit increase is defined as the change from one level (type) to the next. The risk ratio is calculated as follows and will be utilized in interpreting the results of the analysis.

$$Risk\ Ratio = (\exp(\beta_k) - 1) \text{ x } 100\ (\%) \quad (10)$$

To begin, the result for average illuminance was significant and after calculating the risk ratio shows that a one lux increase in average illuminance results in a 9% decrease in the number of nighttime crashes. Recall that the range of illuminance values reflects those that were collected during the current research effort and they ranged between 0.07 – 18.42 lux. Furthermore, for a unit increase in intersection configuration, from ‘T’ to crossroad, there is an increase in nighttime crashes by 200%. While ADT was utilized as an offset variable, the risk of crashes occurring at these intersection types is substantially higher than at ‘T’ intersections. Similar effects were found for curve locations near an intersection. Results showed that a one unit increase from ‘Yes’ to ‘No’ curves near the intersection, increased the risk ratio of nighttime crashes by 178%. While this may appear counterintuitive, it may reflect additional caution that drivers engage in when scanning for traffic at night and it may also be an artifact of the data and the prevalence (or lack thereof) of curves in the dataset. Finally, a number of interactions were also significant in the data set. An important point is that the regular risk ratio cannot be employed when describing the interaction effects in the model. The interaction effect and related risk ratios requires calculating the components within the interaction term. The following formulas list how the risk ratios are calculated for these terms:

$$RR_{Int\ Confix\ (T)*Avg\ Illum.} = \exp(\beta_{Int\ Config\ (T)} + \beta_{Int\ Config\ (T)*Avg\ Illum}\ (Avg\ Illum)) \quad (11)$$

Table 10 provides the risk ratios for the calculated illuminance ranges associated with the data collection.

Table 10. Calculated Risk Ratios for Nighttime Crashes for Average Illuminance and ‘T’ Intersections

Average Illuminance (lux)	Risk Ratio
0	0
5	16.94
10	33.87
15	50.81
20	67.74

The interaction results are interesting such that at these specific intersections, there is an increased risk of nighttime crashes as illuminance increases. These results appear to be opposite to the notion of having more light at an intersection usually decreases the impact of crash risk.

A similar set of ratios was constructed for the second interaction effect where intersection type and proximity to a curve interacted. To begin, for 'T' intersections that were near a curve there was a predicted 3 times increase in nighttime crashes. Conversely, for cross road intersection locations that were near a curve, there was a 52% decrease in nighttime crashes. The effects for the impact of curves on intersection type was similar when reviewing the data from the curve standpoint. The impact of curves may influence nighttime driver behavior in different ways, such that addition time may be spend at crossroad intersections before proceeding, whereas drivers may not apply the same model at 'T' intersection locations near curves.

Lighted Intersection Locations

After the initial analysis the data was parsed into two separate components that contained lighted intersection information and unlighted information. Similar to the previous analysis, crash counts were examined for the lighted intersections only. Again, a negative binomial regression model was used. The results for the significant values and the intercept is displayed in Table 11.

Table 11. Negative Binomial regression model results lighted intersections only

Variable	Estimated Coefficients	Std. Error	Pr (>|z|)	Exp(β)
Intercept	0.26	0.31	0.39	-
Average Illuminance (lux)	-0.22	0.06	<0.001*	0.80
Intersection Configuration (T)	-2.35	0.37	<0.001*	0.10
Inter. Config. (T) x Avg. Illum.	0.40	0.06	<0.001*	1.48

* Significant $p < 0.05$

The results from the lighted intersections data only showed significant results for average illuminance, intersection configuration, and an interaction between intersection configuration and average illuminance. No other significant effects where found. As average illuminance increases there is a reduction in nighttime crashes by 20% at lighted intersection locations. Again, this is within the measurements ranges taken at the lighted intersection locations (e.g., 0.12-18.42). Intersection configuration was also significant for lighted intersection locations, however, a one unit increase in the predictor (from 'T' to cross-roads) lead to a reduction in predicted crash rates by 90%. Finally, an interaction between intersection configuration and average illuminance was also significant. Similar to before, a series of risk ratios were formulated to review the impact of lighting level on the intersection type and are presented in Table 12 .

Table 12. Calculated Risk Ratios for Nighttime Crashes for Average Illuminance and Lighted 'T' Intersections

Average Illuminance (lux)	Risk Ratio
0	0
5	0.71
10	1.42
15	2.13
20	2.84

Similar to the interaction for all intersections, the average illuminance risk ratios increased as the amount of average illuminance was increased. Again, this result goes counter to what other studies have shown with the benefits of lighting and may reflect the impact of the data set and lighting measurements taking during this study. A focus on specific intersection types and the lighting present at these locations would need to be assessed to confirm some of these findings.

Unlighted Intersection Locations

Following the lighted data analysis a similar negative binomial regression model was created for the unlighted data. Similar predictors were entered into the model and nighttime crash counts was the criterion variable. The results for the significant predictors and average illuminance for unlighted intersections is displayed in Table 13.

Table 13. Negative Binomial regression model results unlighted intersections only

Variable	Estimated Coefficients	Std. Error	Pr (>|z|)	Exp(β)
Intercept	0.02	0.20	0.93	-
Average Illuminance	-2.73	0.78	<0.001*	0.06

* Significant $p < 0.05$

The final analysis looked at the unlighted intersection locations and the effect of the predictor variables. Only average illuminance was significant in the model. The results showed that a one unit increase in the predictor (e.g., average illuminance) reduced the crash risk ratio by 94%. Again, this is for the unlighted intersections where the illuminance measurement ranged from 0.05-0.91 lux. The results show some influence of nighttime lighting, be it from light trespass from a nearby commercial area or a lighted intersection nearby, can impact some of the higher crash rate intersection locations. The lack of other significant relationships for unlighted intersection locations suggests that intersection configuration type does not impact the overall factors as much as lighting level.

Chapter 6
Discussion

The intent of the current research effort was to identify isolated rural intersection locations, measure the horizontal lighting levels at those locations, and analyze the impact of lighting levels on crash rates. In addition, based on the results of the analysis, potential recommendations or suggestions could be made regarding lighting intersection locations. The roadway lighting illuminance measurements taken and analyzed influenced crash predictions using five-years of crash data. The results showed an impact of lighting on crashes for both lighted and unlighted intersection locations. Other variables entered into the models also influenced crash predictions for lighted intersections, but less so for unlighted intersections (e.g., intersection configuration and proximity to a curve).

Rural Intersection Lighting

The full negative binomial regression model found a 9% reduction in the nighttime crashes for every unit (e.g., 1 lux) increase in the average illuminance (lux). When assessing just lighted intersection locations, a 1-lux increase in the average illuminance level decreased the nighttime crash rate by 20%. Finally, for unlighted intersections, a 1-lux increase in the average illuminance level resulted in a large 94% decrease in the nighttime crash rate. These results are presented across each of the analysis types in Figure 11.

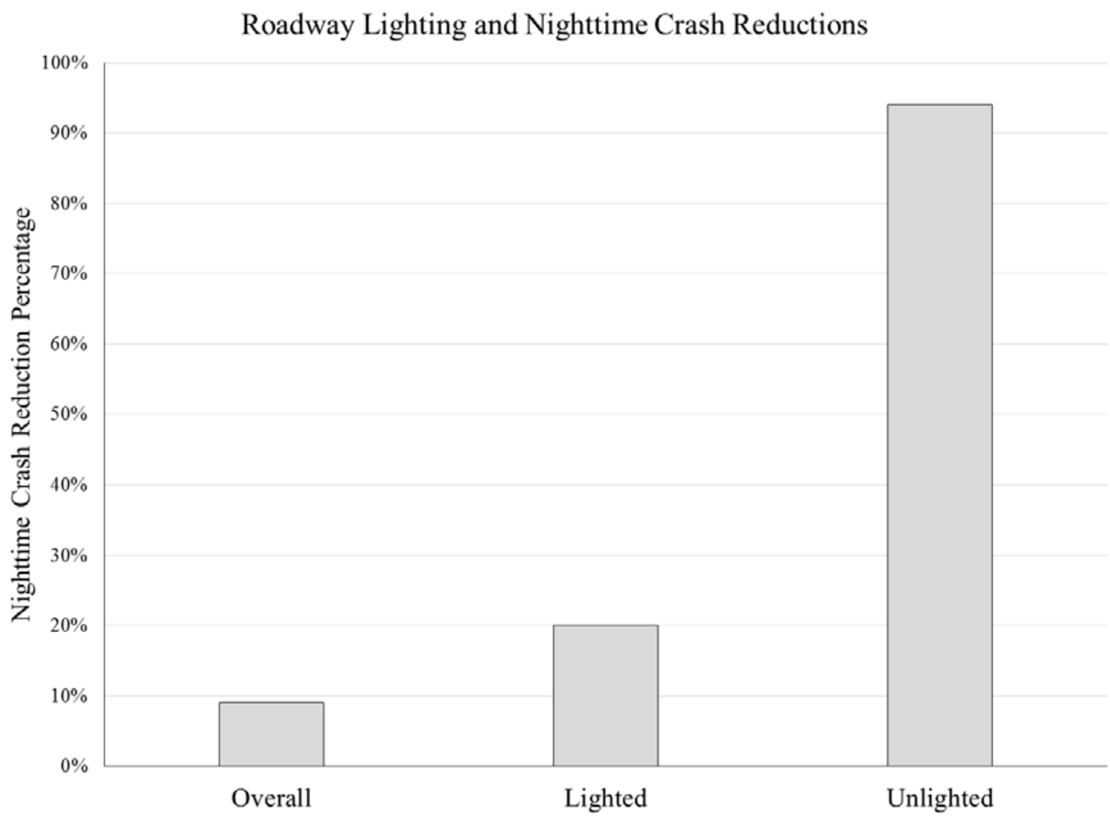

Figure 11. Crash Reductions as Derived from the Negative Binomial Regression Modeling

The primary information derived from the regression modeling is the influence of lighting overall. Minimal lighting, even ambient lighting at the unlighted locations, contributes to the driver's ability to identify roadway information at night and react accordingly. These results for average illuminance levels integrate with previous research and continue to confirm the benefits of roadway lighting [1, 2, 3, 4, 5, 20]. Isebrands et. al, [1, 4] identified a reduction in crash frequency of 36% between intersections that did not contain lighting and those that were fitted with lighting. The prediction effects found in the current study also found a reduction in nighttime crash predictions, that are perhaps not as high as those previously identified, but certainly significantly beneficial. The greatest impact was seen at unlighted intersections that contained no overall horizontal roadway lighting, but perhaps benefitted from ambient lighting near the intersection location. The amount of ambient lighting was visually beneficial to drivers and sufficiently reduced accident rates. While the actual ambient lighting levels may have assisted drivers, it may also reflect that drivers, given a small amount of light, can still adequately detect and avoid intersection crashes compared to lower levels of ambient lighting.

The extent to which roadway lighting at the lighted intersection benefitted drivers was less pronounced than unlighted intersection locations. The lighted intersections still had a reduction in nighttime crash rates of 20%; better than the overall comparison model. The beneficial impact of lighting may show different qualities as shown in this analysis. The lighting measurements taken at these intersection locations may suggest that there is a specific threshold or level at which the benefits of horizontal illuminance no longer provide a reduction in nighttime crash risk. This may be reflective of the amount of roadway lighting, lighting type, and intersection specification. For example, in Figure 12, the levels below 5 lux appear to incur higher crash rates and suggest that a minimal level around 5 lux may provide a minimum threshold. Overall, however, the use of roadway lighting did diminish nighttime crash risks at those locations were horizontal illuminance was measured.

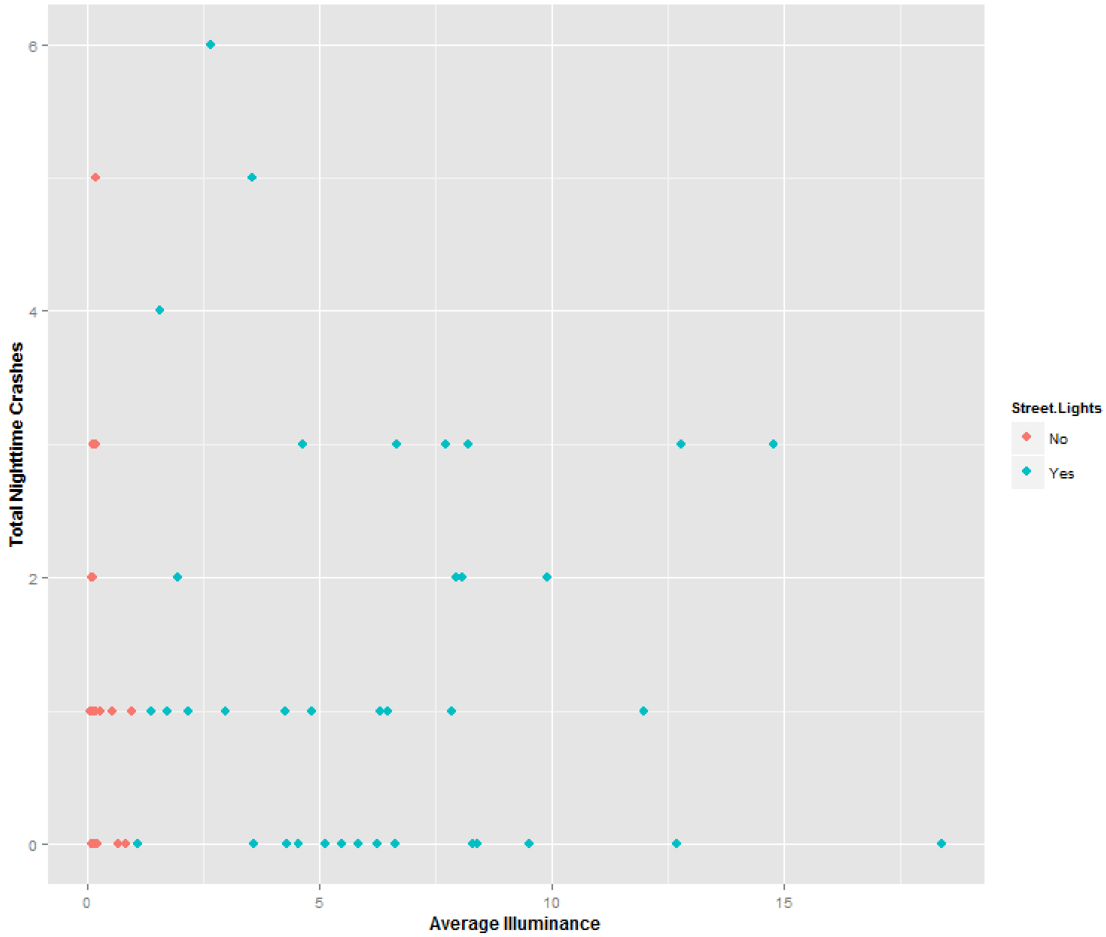

Figure 12. Average Illuminance Level and Nighttime Crash Rates for Lighted and Unlighted Intersections

Proximity of a Curve to an Intersection

The prediction data assessed the proximity of curves and the impact on the nighttime crash behavior. For the overall model (e.g., lighted and unlighted intersections), there was a high nighttime crash prediction value (e.g., 178%) for 'No curves near the intersection' contributing to nighttime crashes as intersection. The highly inflated prediction value is not well understood when reviewing the data. Upon first review, intersections situated near curves may provide drivers with a reason to stop, and fully scan the area prior to making a turn decision. However, having adequate sight distance, specifically at night, would be beneficial at an intersection, thus suggesting intersections near curves could be detrimental. This was not the case with the current dataset and prediction model and may reflect potentially an opposite effect for sight distance and a host of other contributing variables. For example, estimating the distance and approach of a vehicle, specifically at night, is problematic for most drivers [39] and in turn may contribute to the higher level crash prediction for those intersections not proximal to a curve. Conversely, the results may be an artifact of the data set used. While roadway lighting was a primary variable of interest and resulted in measurements at those intersection locations, proximity of a curve was not as extensively controlled for the current model. A total of 18 of the 63 intersections were classified as not having a curve near the location. This left the model with few examples of ‘No’ curve near an intersection, on top of which 11 had lighting. The remaining non-lit intersections (e.g., 7) had almost 1 crash per intersection. These values perhaps modified the prediction model and should be kept in mind when reviewing this data and applying to other areas.

Intersection Type

In the overall intersection illuminance model, the cross-roads were found to have a substantially higher crash rate, and to some extent highly inflated (e.g., 200%), when compared with the alternative intersection type (e.g., ‘T’ Intersection). Initially reviewing the data there were a greater number of intersections classified at ‘T’ when compared to crossroads (38 versus 25). The data is contrary to other research efforts [40] that found opposite results and linking ‘T’ intersections with a higher crash rate compared to crossroads. The contrary results may be attributed to simply having one less lane of traffic and roadway complexity to attend to when making a safe turn at an intersection location. A ‘T’ intersection requires drivers to come to a stop and visually scan left and right prior to making a turn decision. A crossroad adds an opposite lane for drivers to assess, maintain in memory, and then make a turn decision. The additional cognitive load may impact driver turn decisions at night and in turn contribute to higher crash predictions for those intersections with increased complexity. These factors in turn likely contributed to the increased prediction rates found in the overall illuminance model. Furthermore, those intersections with just no roadway lighting installed did not have a significant impact of intersection configuration compared to those that have lighting installed.

Chapter 7
Conclusions

The objective of this research effort was to quantify and document the lighting levels and impact of those lighting levels at isolated rural intersections. Intersection locations were chosen based on a number of parameters that included: Annual Average Daily Traffic, intersection type (T-intersection or cross-road intersection), intersection location (i.e., isolated rural), number of crashes, and county location. Horizontal illuminance was measured at each intersection location. The results were then entered into a serious of negative binomial regression models that identified a number of key characteristics. Based on the results obtained with the modeling and the data gathered a number of conclusions can be made:

- Overall, those intersections that contain roadway lighting had lower Night-to-day and Night-to-total crash rates for the 5 years of data assessed in the database.

- Intersections examined in this project and that contained lighting had slightly higher intersection crash rates compared to intersections that were not lit.

- The overall nighttime crash ratio was higher for cross-road intersection locations compared to 'T'-intersections. The results for lighted intersections only also found that cross-roads had higher nighttime crash ratios compared to 'T' intersections. No significant effects were found for unlighted intersections and roadway geometry.

- In the overall model, when average illuminance is increased by one-unit (e.g., 1 lux) the nighttime crash ratio was decreased by 9%. Furthermore, for those intersections that contained roadway lighting there was crash ratio decrease of 20% when average illuminance was increased by one-unit. The largest impact occurred for unlighted intersections, where a one unit increase in average illuminance (e.g., ambient light) resulted in a decrease of 94% for the crash ratio. Overall, the increase of average illuminance at intersections does decrease the occurrence of crashes at those intersections and serves as a valid crash mitigation strategy.

- Those intersections situation near a curve in the roadway had lower nighttime crash ratios compared to those intersection near a curve for the overall model. However, the effect of curve proximity to the intersection was not found for the lighted only model nor the unlighted model.

- Average illuminance and intersection configuration had significant interactions for the overall model and for the lighted intersections only model. The impact of intersection type was present such that those intersections containing lighting were primarily cross-roads as compared to those intersections that did not contain lighting (e.g., 'T' intersections). These effects likely overinflated the model estimates identified in the data analysis.

- According to the IESNA RP-8-14 recommendations, for the intersections identified in this project only 5 of the 37 lighted intersections met the minimum horizontal illuminance requirements of approximately 10 lux or higher (for the roadway type). Of those 5 intersections, two had no-crashes, one had one crash, and the remaining two intersections had 3 crashes each (below the maximum). Despite only a few intersections meeting the minimum level for IESNA recommendations, lower crash rates were still found for lighted intersections locations.

- Those intersections (e.g., 17 in total) having horizontal illuminance between 5-10 lux still had fewer nighttime crashes than intersections with a horizontal illuminance below 5 lux. With additional intersection monitoring data, a minimum threshold of 5 lux could be investigated for isolated intersections.

Recommendations

A framework for recommendations is presented and is based primarily on the data acquired as part of this project effort. These recommendations would require additional validation with additional horizontal, vertical, and luminance data collected at many more intersection locations across the state.

- Lighted intersections had reduced nighttime crashes compared to those intersections that were unlit. While subtle differences are apparent between each intersection, the suite of intersections chosen to be measured had similar ADT, configurations, and risk rating as identified through the risk rating stars. Again, lighting has been reconfirmed, in the current model, to be beneficial in reducing nighttime crashes. The availability of visual information helps reduce potential uncertainty when approaching a rural isolated intersections. The visual illumination also helps drivers identified critical information (e.g., stop signs) that may be missed all together.

- Increasing horizontal illuminance is effective in reducing the nighttime crash rate. The unlighted intersection model showed that a subtle increase in ambient illumination greatly reduced the nighttime crash ratio. Furthermore, those intersections that contained lighting also showed a marked decrease in the nighttime crash ratio as average illuminance increased.

- The majority if the lighting identified during the data collection process was High Pressure Sodium. However, alternative lighting was also identified for some of the data collection sites (e.g., Light Emitting Diode – LED). Overall lighting does contribute to a lower crash rate, the impact of the different type of lighting technologies was beyond the scope of the current project. The proposed benefits obtained from providing a LED roadway lighting set up include improved color rendering/color temperatures for improved object recognition, directionality, longevity, cost/benefit, and the potential to reduce lighting levels but potentially maintain visual performance. How these factors impact isolated intersections will require additional research and additional intersection lighting measurements to identify representative samples of current and “new” lighting set ups.

- Only two specific configuration types were used in the study and cross-road intersections were found to have significant impacts on nighttime crash predictions. However, to increase the generalizability to other intersections additional intersection types (e.g., offset, Y-intersections etc.) should be included in the model. The additional types of intersections may yield additional insight into lighting set ups and the impact on different crash rates.

- IESNA recommends levels of ~10 lux (average) maintained illuminance for isolated intersections. This level was only achieved for 5 of the 37 lighted intersections as measured. However, actual crash counts for those intersections between 5-18.42 lux were lower than those with less than 5 lux horizontal illuminance (including those intersections without lighting). Horizontal illumination at or near 5 lux should be investigated as a potential threshold for isolated rural intersection lighting.

Limitations

One limitation was the amount of intersections measured during the data collection effort. If a greater number of intersections were measured, the model and associated metrics may have yielded additional insight into nighttime crash predictions.

Another potential limitation is that only horizontal illuminance was collected at the intersections of interest. While horizontal illuminance is a primary method to assess the lighting requirements at current intersections, additional intersections and metrics that include vertical illuminance and luminance measurements can provide additional insight into isolated rural intersection locations and nighttime crash factors.

Finally, those intersections identified in the current research effort were recognized as already having lighting installed (and not). Intersection locations where lighting was installed may already be maximizing the effectiveness of mitigation strategies and may reflect other issues that cannot be rectified by roadway lighting. Furthermore, those intersections with lighting may have higher crash rates historically and may not reflect ‘normal’ crash rates at isolated rural intersections. Additional research with additional intersections may provide a much improved model.

Future Research

Overall, the results of the research effort identified that as average illuminance increased by one unit, the effect on nighttime crash ratios was a decrease of 9%. These results reconfirm the utility of lighting an intersection to provide a driver a safety benefit. However, the effectiveness of lighting at a minimum level appears to be somewhere around the 5 lux (with the current data). Validating a 'minimum' illuminance (and luminance) level will aid county and state engineers in determining where to first deploy roadway lighting in a cost effective manner. Additional research on these thresholds should also be investigated in an effort to find out where lighting levels above provide a safety benefit. These efforts can be investigated within a controlled environment before being validated and confirmed with crash data from around the state of Minnesota.

Finally, different lighting technologies that are currently emerging may yield visual performance benefits for drivers. The illuminance requirements for these lighting types may suggest even lower lighting levels than those currently employed or suggested. These technologies also have a benefit to reduce lighting costs in maintenance, energy, while providing similar performance to current HPS. Investigating these technologies within the real-world through lighting measurements and preliminary crash data will yield insight into future intersection lighting designs and crash risk.

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Appendix A
Rural Intersection County Engineer Questionnaire

Lighting Levels for Isolated Intersections Leading to Safety Improvements Questionnaire

General Questions

This section will help identify current and future isolated rural intersection information with respect to lighting requirements/additions.

1. What county do you provide roadway lighting for? *
2. How many isolated rural intersections does your county (area) currently maintain?

(Note: Isolated intersections are defined as intersections that are approximately 1 mile or more from an incorporated or developed area or from a signalized intersection. Intersections of interest are those that are between the public roads and do not include driveways or commercial entrances)

3. How many are unsignalized (in total)?
4. How many are stop sign controlled (all directions)?
5. How many are stop sign controlled (two-way)?
6. How many are uncontrolled?

Isolated rural intersection lighting

This section is to identify current and future lighting needs.

7. How many isolated rural intersections are lighted (in total)?
8. How many intersections are lighted and stop sign controlled (all-way)?
9. How many intersections are lighted and stop sign controlled (two-way)?
10. How many intersections are lighted and yield controlled?
11. How many intersections are lighted and uncontrolled?
12. How many of the isolated rural intersections have had lighting installed in the last year (in total)?
13. How many of the isolated rural intersections have had lighting installed in the last 5 years (in total)?
14. How many of the isolated rural intersections have had lighting installed in the last 10 years (in total)?
15. How were these installations funded? (e.g., MnDOT, county, combined funding from MnDOT/County etc.)
16. What warrants, standards, guidelines, or "rules of thumb" (or other) do you use in order to install lighting at isolated intersections?

(Please describe and reference any specific warrants/materials or other)

Rural intersection lighting installation information

This section attempts to identify "typical" installation information regarding rural intersection lighting.

17. At "typical" isolated intersections that are stop sign controlled (two-way) how many luminaires do you install / are installed?
18. At "typical" isolated intersections that are stop sign controlled (four-way) how many luminaires do you install / are installed?
19. At "typical" isolated intersections that have yield signs, how many luminaires do you install / are installed?

20. At "typical" isolated intersections that are uncontrolled how many luminaires do you install / are installed?
21. Please estimate the typical installation costs (e.g., average per light) for isolated intersection lighting.
22. Please estimate the typical maintenance costs (e.g., average per light) for isolated intersection lighting.
23. Please provide any additional costs beyond installation and maintenance (e.g., average per light) for isolated intersection lighting.
24. Have you encountered any limitations or obstacles that have prevented you from installing rural intersection lighting in the past?
25. What type of lamps are typically used for lighting isolated intersections?
26. Are there any Light Emitting Diode Installations/future installations that will use LED lighting?

Specific isolated intersection lighting information

The final section of the survey asks about recent isolated intersection installations. Please provide as much information as you can to help us understand where installations are taking place and the type of roadways and modifications that are occurring in the state.

These questions are repeated on the following page to identify more than one intersection installation. Please provide as much information about the intersection(s) as possible. The answers will help provide us with geometric, signage, sight-line information in an effort to better understand potential issues and solutions that lighting may provide.

27. What is the location of the intersection?
28. What is the Major roadway and its Speed limit?
29. What is the Minor roadway and its Speed limit?
30. When was the lighting added to the intersection (what date?)
31. What is the pavement type for the Major road?
32. What is the pavement type for the Minor road?
33. How is the intersection configured?
34. 34 What is the control type?
35. What is the roadway type?
36. Does the intersection have any channelization?
37. Were there any other improvements or modifications to the intersection beyond lighting?
38. Please provide any other information that will help us understand the use of lighting at rural intersection locations

Additional intersection information

If you've more than one intersection that has received lighting recently (within the last 2-3 years) please provide information about that intersection location.

39. What is the location of the intersection?
40. What is the Major roadway and its Speed limit?
41. What is the Minor roadway and its Speed limit?
42. When was the lighting added to the intersection (what date?)
43. What is the pavement type for the Major road?
44. What is the pavement type for the Minor road?
45. How is the intersection configured?
46. 34 What is the control type?
47. What is the roadway type?
48. Does the intersection have any channelization?

49. Were there any other improvements or modifications to the intersection beyond lighting?
50. Please provide any other information that will help us understand the use of lighting at rural intersection locations

Final questions

Thank you for taking the time to complete this survey.
We're interested in identifying any intersections that have received lighting as part of the improvement process. If you can provide a list of intersections that have received lighting and any intersections that are similar that do not have lighting we can add them to the future measurement portion of the project.

51. Do you have any intersections that we could measure the lighting level at for a future portion of this project?

52. Do you have any additional comments or suggestions to improve this survey or project?

Appendix B
Rural Intersection Lighting Measurement List

List of Isolated Rural Intersection Locations and Illuminance Data

ID	County	Location	Type	Config	Lighting?	Risk Rating	Mean Illuminance (Lux)
1	Carver	CSAH 34 AND USTH 212 WBL	Rural Thru Stop	X	Yes	★★★★	7.96
2	Carver	CSAH 33 AND CSAH 34	Rural Thru Stop	X	Yes	★★★★	1.31
3	Carver	CSAH 51 AND MNTH 5; CR 151	Rural Thru Stop	X	Yes	★★★	6.08
4	Carver	CSAH 30 AND CSAH 32	Rural Thru Stop	T	Yes	★★★	5.06
5	Carver	CSAH 33 AND MNTH 7	Rural Thru Stop	X	Yes	★★★★★	1.04
6	Carver	CSAH 20 AND CSAH 33 (SOUTH)	Rural Thru Stop	X	Yes	★★	7.54
7	Carver	CSAH 20 AND MNTH 25	Rural Thru Stop	T	Yes	★★★★	11.90
8	Dakota	CSAH 54 AND CSAH 91	Rural Thru Stop	T	No	★★	0.52
9	Dakota	CSAH 32 AND CSAH 71	Rural Thru Stop	T	Yes	★★	1.90
10	Dakota	CSAH 47 AND CSAH 85	Rural Thru Stop	X	Yes	★★★	0.19
11	Dakota	CSAH 47 AND MNTH 3	Rural Thru Stop	T	No	★★★★	11.97
12	Dakota	CSAH 54 AND CSAH 68	Rural Thru Stop	T	Yes	★★	0.18
13	Dakota	CSAH 23 AND CSAH	Rural Thru Stop	T	No	★★★	0.16

		80 (NORTH)					
14	Scott	CNTY 53 AND 280TH ST W MNTH-19	Rural Thru Stop	T	No	★	0.09
15	Scott	CSAH 11 AND 280TH ST W MNTH-19; LE SUEUR CSAH-30	Rural Thru Stop	X	Yes	★★★★	0.12
16	Scott	CSAH 2 AND PILLSBURY AVE CSAH-46	Rural Thru Stop	X	Yes	★★★★	3.48
17	Scott	CSAH 8 AND VERNON AVE CSAH-91	Rural Thru Stop	X	Yes	★★★★	2.57
18	Scott	CSAH 8 AND PANAMA AVE CSAH-23 (NORTH)	Rural Thru Stop	T	Yes	★★★★★	2.12
19	Scott	CSAH 12 AND MARSCHALL RD CSAH-17; 170TH ST E T-103	Rural Thru Stop	X	Yes	★★★★	1.72
20	Scott	CSAH 10 AND LANGFORD AVE MNTH-13	Rural Thru Stop	X	Yes	★★★★	0.64
21	Scott	CSAH 8 AND LANGFORD AVE MNTH-13	Rural Thru Stop	X	Yes	★★★★	6.08
22	Scott	CNTY 89 AND 280TH ST W MNTH-19	Rural Thru Stop	T	No	★★★	7.68
23	Scott	CSAH 15 AND S JCT CR-64 235TH	Rural Thru Stop	T	No	★★★	0.11

		ST W					
24	Scott	CSAH 2 AND HELENA BLVD MNTH-21	Rural Thru Stop	X	Yes	★★★★	0.12
25	Scott	CSAH 7 AND 280TH ST W MNTH-19	Rural Thru Stop	T	No	★★★★	0.78
26	Scott	CSAH 69 AND CHAPARAL AVE T-202 JACKSON PKWY MSAS-105	Rural Thru Stop	X	Yes	★★★★★	7.71
27	Sherburne	(80TH) 82ND AVE SE LT T-1580 80TH AVE SE RT CR-58	Rural Thru Stop	X	No	★★★★	0.06
28	Sherburne	MNTH-24 X-ING, CLEAR LAKE CORP LIM X-ING	Rural Thru Stop	T	Yes	★★★	0.91
29	Sherburne	(237TH) 241ST AVE NW X-ING T-442 LT CSAH-10 RT	Rural Thru Stop	T	No	★★★★	0.29
30	Sherburne	125TH AVE SE MNTH-25 X-ING	Rural Thru Stop	X	No	★★★	0.09
31	Sherburne	281ST AVE NW LT CR-42	Rural Thru Stop	T	No	★★★★	0.18
32	Sherburne	FREMONT AVE NW CSAH-4 X-ING	Rural Thru Stop	X	No	★★★★	0.05
33	Sherburne	237TH AVE NW RT CSAH-25	Rural Thru Stop	T	No	★★★★	0.06
34	Sherburne	160TH ST NW RT CSAH-30	Rural Thru Stop	T	No	★★★★	0.08

35	Washington	CSAH 19 AND MSAS-112	Rural Thru Stop	X	Yes	★★★	1.43
36	Washington	CSAH 19 AND MSAS-120	Rural Thru Stop	X	Yes	★★★	3.52
37	Washington	CSAH 20 AND LAMAR AVE S MSAS-103	Rural Thru Stop	T	Yes	★★★	4.11
38	Washington	CSAH 6 AND 31ST ST N MSAS-109	Rural Thru Stop	T	Yes	★	0.05
39	Washington	CSAH 17 AND MNTH-5 (WEST) STILLWATER BLVD N	Rural Thru Stop	T	Yes	★★★	5.56
40	Washington	CSAH 17 AND 39TH ST N MSAS-114	Rural Thru Stop	T	Yes	★	0.07
41	Washington	CSAH 14 AND CSAH-24	Rural Thru Stop	T	No	★★★★	0.09
42	Washington	CSAH 12 AND BOUTWELL RD N MSAS-122	Rural Thru Stop	T	Yes	★★★★	3.60
43	Washington	CSAH 15 AND MSAS-122	Rural Thru Stop		Yes	★	3.98
44	Washington	CSAH 15 AND CR-64	Rural Thru Stop		No	★★	0.10
45	Washington	CSAH 7 AND CSAH-15 (SOUTH)	Rural Thru Stop	T	No	★★★★	0.05
46	Washington	CSAH 7 AND PARKER ST MNTH-95	Rural Thru Stop	X	No	★★★	2.26
47	Washington	CSAH 3 AND 170TH ST N	Rural Thru Stop	T	No	★	0.07

		CSAH-4					
48	Washington	CSAH 4 AND USTH-61 FOREST BLVD CR-4A	Roundabout	X	Yes	★★★	18.42
49	Washington	CNTY 50 AND GOODVIEW AVE N MSAS-127	Rural Thru Stop	T	Yes	★★	0.06
50	Wright	MNTH-55 X-ING, 10TH ST SE AHD, T-90	Rural Thru Stop	X	Yes	★★★	8.24
51	Wright	MNTH-55 X-ING, 5TH ST SE T-105 BHD	Rural Thru Stop	X	Yes	★★★	9.51
52	Wright	MNTH-55 X-ING	Rural Thru Stop	X	No	★★★	7.47
53	Wright	CSAH-35 LT & BHD, CR-109 SEG-2 RT (NORTH)	Rural Thru Stop	X	Yes	★★★	4.81
54	Wright	CSAH-35 X-ING, CR-109 AHD (SOUTH)	Rural Thru Stop	X	No	★★★	6.31
55	Wright	CSAH-9 RT (NORTH)	Rural Thru Stop	T	Yes	★★★	12.67
56	Wright	MNTH-55 X-ING	Rural Thru Stop	X	Yes	★★★★	6.11
57	Wright	CSAH-37 X-ING	Rural Thru Stop	X	No	★★★	14.78
58	Wright	55TH ST NW X-ING T-457 LT CSAH-38 RT	Rural Thru Stop	X	Yes	★★★	0.06
59	Wright	MNTH-55 X-ING, OLIVER AVE NW CR-136 AHD	Rural Thru Stop	X	Yes	★★★★★	6.33

60	Wright	MNTH-24 X-ING	Rural Thru Stop	T	Yes	★★★★	12.68
61	Wright	CR-106 RT (NORTH)	Rural Thru Stop	T	Yes	★★★	9.88
62	Wright	CSAH-39 RT (NORTH)	Rural Thru Stop	T	Yes	★★★	9.28
63	Wright	CR-117 X-ING	Rural Thru Stop	X	No	★★★	6.49

Appendix C

Rural Intersection List, Location, and Crash Statistics

Rural Intersection Measurement List, Crash Rate, and Lighting Status

Intersection Number	Intersection Description	County	Crash Rate	Lighting*	Daytime* Crashes	Nighttime* Crashes
1	CSAH 34 AND USTH 212 WBL	Carver	0.4	Yes	8	2
2	CSAH 33 AND CSAH 34	Carver	2.1	Yes	9	1
3	CSAH 51 AND MNTH 5; CR 151	Carver	0.6	Yes	8	0
4	CSAH 30 AND CSAH 32	Carver	0	Yes	0	0
5	CSAH 33 AND MNTH 7	Carver	0.3	Yes	5	0
6	CSAH 20 AND CSAH 33 (SOUTH)	Carver	0	Yes	0	0
7	CSAH 20 AND MNTH 25	Carver	0.3	Yes	2	1
8	CSAH 54 AND CSAH 91	Dakota	0.2	No	2	0
9	CSAH 32 AND CSAH 71	Dakota	1	Yes	10	2
10	CSAH 47 AND CSAH 85	Dakota	1	No	5	1
11	CSAH 47 AND MNTH 3	Dakota	0.2	Yes	4	0
12	CSAH 54 AND CSAH 68	Dakota	0.7	No	7	3
13	CSAH 23 AND CSAH 80 (NORTH)	Dakota	0.2	No	2	1
14	CNTY 53 AND 280TH ST W MNTH-19	Scott	0	No	0	0
15	CSAH 11 AND 280TH ST W MNTH-19; LE SUEUR CSAH-30	Scott	0.1	No	1	0
16	CSAH 2 AND PILLSBURY AVE CSAH-46	Scott	1	Yes	12	1
17	CSAH 8 AND VERNON AVE CSAH-91	Scott	0.4	Yes	4	1
18	CSAH 8 AND PANAMA AVE CSAH-23 (NORTH)	Scott	0.3	Yes	2	1
19	CSAH 12 AND MARSCHALL RD CSAH-17; 170TH ST E T-103	Scott	0.5	Yes	7	1
20	CSAH 10 AND	Scott	0.2	No	3	0

Intersection Number	Intersection Description	County	Crash Rate	Lighting*	Daytime* Crashes	Nighttime* Crashes
	LANGFORD AVE MNTH-13					
21	CSAH 8 AND LANGFORD AVE MNTH-13	Scott	0.9	Yes	15	1
22	CNTY 89 AND 280TH ST W MNTH-19	Scott	0.6	Yes	10	1
23	CSAH 15 AND S JCT CR-64 235TH ST W	Scott	0	No	0	0
24	CSAH 2 AND HELENA BLVD MNTH-21	Scott	0.8	No	10	3
25	CSAH 7 AND 280TH ST W MNTH-19	Scott	0.3	No	2	0
26	CSAH 69 AND CHAPARAL AVE T-202 JACKSON PKWY MSAS-105	Scott	0.2	Yes	3	1
27	(80TH) 82ND AVE SE LT T-1580 80TH AVE SE RT CR-58	Sherburne	0.8	No	3	1
28	MNTH-24 X-ING, CLEAR LAKE CORP LIM X-ING	Sherburne	0	No	0	0
29	(237TH) 241ST AVE NW X-ING T-442 LT CSAH-10 RT	Sherburne	0.4	No	3	1
30	125TH AVE SE MNTH-25 X-ING	Sherburne	0.4	No	3	1
31	281ST AVE NW LT CR-42	Sherburne	1.4	No	4	1
32	FREMONT AVE NW CSAH-4 X-ING	Sherburne	0.7	No	10	0
33	237TH AVE NW RT CSAH-25	Sherburne	0.8	No	3	0
34	160TH ST NW RT CSAH-30	Sherburne	0.3	No	2	0
35	CSAH 19 AND MSAS-112	Washington	0.7	Yes	11	1
36	CSAH 19 AND MSAS-120	Washington	0.2	Yes	3	0
37	CSAH 20 AND LAMAR AVE S MSAS-103	Washington	0	Yes	0	0
38	CSAH 6 AND 31ST ST N MSAS-109	Washington	0	No	0	0

Intersection Number	Intersection Description	County	Crash Rate	Lighting*	Daytime* Crashes	Nighttime* Crashes
39	CSAH 17 AND MNTH-5 (WEST) STILLWATER BLVD N	Washington	0	Yes	1	0
40	CSAH 17 AND 39TH ST N MSAS-114	Washington	0.3	No	2	0
41	CSAH 14 AND CSAH-24	Washington	0.2	No	3	1
42	CSAH 12 AND BOUTWELL RD N MSAS-122	Washington	0.3	Yes	4	2
43	CSAH 15 AND MSAS-122	Washington	0.2	Yes	4	1
44	CSAH 15 AND CR-64	Washington	0.4	No	9	2
45	CSAH 7 AND CSAH-15 (SOUTH)	Washington	0.3	No	4	0
46	CSAH 7 AND PARKER ST MNTH-95	Washington	0.6	Yes	5	0
47	CSAH 3 AND 170TH ST N CSAH-4	Washington	2.1	No	10	4
48	CSAH 4 AND USTH-61 FOREST BLVD CR-4A * Roundabout	Washington	0.9	Yes	19	4
49	CNTY 50 AND GOODVIEW AVE N MSAS-127	Washington	0.3	No	1	0
50	MNTH-55 X-ING, 10TH ST SE AHD, T-90	Wright	0.4	Yes	13	0
51	MNTH-55 X-ING, 5TH ST SE T-105 BHD	Wright	0.4	Yes	11	1
52	MNTH-55 X-ING	Wright	0.2	Yes	5	0
53	CSAH-35 LT & BHD, CR-109 SEG-2 RT (NORTH)	Wright	0.5	Yes	4	0
54	CSAH-35 X-ING, CR-109 AHD (SOUTH)	Wright	1.3	Yes	8	0
55	CSAH-9 RT (NORTH)	Wright	0.2	Yes	1	0
56	MNTH-55 X-ING	Wright	0.5	Yes	10	0
57	CSAH-37 X-ING	Wright	0.5	Yes	3	0
58	55TH ST NW X-ING T-457 LT	Wright	0.4	No	2	0

Intersection Number	Intersection Description	County	Crash Rate	Lighting*	Daytime* Crashes	Nighttime* Crashes
	CSAH-38 RT					
59	MNTH-55 X-ING, OLIVER AVE NW CR-136 AHD	Wright	1	Yes	15	2
60	MNTH-24 X-ING	Wright	0.5	Yes	6	0
61	CR-106 RT (NORTH)	Wright	0.8	Yes	2	0
62	CSAH-39 RT (NORTH)	Wright	1.1	Yes	4	0
63	CR-117 X-ING	Wright	1.3	Yes	10	1

* As defined in the crash database received