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Safety and Cost Performance of Intersection Lighting

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16. Abstract

It has been reported that nationwide, about one quarter of the roadway travel commonly occurs after dark and half of the roadway traffic fatalities occurred at night. The nighttime traffic crash fatality rate is about three times the daytime traffic crash fatality rate. The problem may become worse at unlit or poorly lit critical roadway safety spots such as interchange, intersections, and railroad and highway crossing, particularly in adverse weather conditions. This study was conducted to investigate the lighting effects on crashes at Indiana intersections. The analysis of Indiana nighttime crash data to identify the contributing factors was conducted. The study intersection sites were selected based on crash frequencies and crash severities. Before and after field light tests were conducted to verify in-service light performance, including illuminance distribution and uniformity ratio. AGi32 simulation was also performed for three selected intersections to compare with field test results. In addition, the long term performance of demonstration luminaires at the I-74 & US 231 interchange was tracked and documented. This activity provides a better understanding of maintenance issues, cycles, and costs. Surveys to both State Highway Agencies (SHAs) and communities were conducted in order to identify perceptions from SHAs and the public toward lighting improvement. The community survey included questions such as the public attitudes to intersection lighting, effectiveness of lighting, visibility improvement, and safety improvement. To quantify safety effects of lighting at intersections, crash modification factors (CMFs) were developed by using two methodologies: before-and-after analysis and cross-sectional statistical analysis. The developed CMFs could be used to justify roadway lighting projects. Life Cycle Cost Analysis (LCCA) was conducted to determine the best lighting solution given a real project scenario. The analysis considered initial (luminaire and installation) cost, operation and maintenance cost, and energy cost.

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EXECUTIVE SUMMARY

SAFETY AND COST PERFORMANCE OF INTERSECTION LIGHTING

Introduction

It has been reported that, nationwide, about one quarter of roadway travel occurs after dark, and half of roadway traffic fatalities occur at night. The nighttime traffic crash fatality rate is about three times the daytime rate, with many crashes occurring at unlit or poorly lit critical roadway safety spots such as interchanges, intersections, and railroad and highway crossings, particularly in adverse weather conditions.

This study was conducted to investigate lighting effects on crashes at Indiana intersections. An analysis of Indiana nighttime crash data was completed to identify contributing factors. Study intersection sites were selected based on crash frequencies and severities. Before and after field light tests were conducted to verify in-service light performance, including illuminance distribution and uniformity ratio. AGi32 simulation was also performed for three selected intersections to compare with field test results. In addition, long-term performance of demonstration luminaires at the I-74 and US 231 interchange was tracked and documented. This activity provided a better understanding of maintenance issues, cycles, and costs. Surveys were sent to both State Highway Agencies (SHAs) and communities in order to identify perceptions from SHAs and the public about lighting improvement. The community survey included questions such as public attitudes toward intersection lighting, effectiveness of lighting, and visibility and safety improvement. To quantify the safety effects of lighting at intersections, crash modification factors (CMFs) were developed by using two methodologies: before-and-after analysis and cross-sectional statistical analysis. The developed CMFs could be used to justify roadway lighting projects. Life cycle cost analysis (LCCA) was conducted to determine the best lighting solution given a real project scenario. The analysis considered initial (luminaire and installation) cost, operation and maintenance cost, and energy cost.

Findings

The following tasks were completed during the course of this study:

- Illuminance values at the selected intersection sites were measured. The performance of new and existing luminaires was evaluated based on the measured luminance distributions.
- CMFs for various types of intersections were developed through the before-and-after analysis and cross-sectional statistical analysis. Since the cross-sectional analysis used a much larger data sample than the before-and-after analysis, lighting CMFs from cross-sectional analysis are deemed more representative for Indiana intersections.

This study evaluated new lighting projects with life cycle benefit and cost analysis and lighting retrofit projects with life cycle cost analysis. The benefits estimated in the new lighting project applied the CMF developed in this study, and the project was well justified from an economic perspective. During this study an Excel-based worksheet was developed to facilitate the life cycle analysis on new and retrofit lighting projects, and it is recommended that this worksheet be used as a standard procedure when life cycle cost analysis and life cycle benefit and cost analysis need to be performed by the agency.

Implementation

The illuminance-based evaluations and developed CMFs provide INDOT with useful tools for intersection lighting design and safety assessments. The life cycle cost methods, together with the application software, will enable INDOT to conduct project evaluations effectively. The research results also provide a rational basis for INDOT to develop or modify the standard related to intersection lighting.

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1. INTRODUCTION

1.1 Problem Statement

According to National Highway Traffic Safety Administration (NHTSA), in the year of 2014, there were 6,064,000 vehicle crashes in the states. Among them, approximately 70% of those crashes happened during the daytime and around 30% of crashes occurred during the nighttime. Traffic crashes are usually divided into fatal crashes, injury crashes, and property-damage-only (PDO) crashes. It has been reported that there were 15,168 nighttime fatal crashes, which account for about 51% of total fatal crashes. Given the fact that only 25–33% of the vehicle miles traveled (VMT) occur at night, the above statistics indicate that nighttime crash fatality rate is much higher and nighttime crashes are commonly more severe compared with the daytime.

Driving during the nighttime is inherently dangerous and demanding. Statistics has shown that although many factors such as alcohol, fatigue, and traffic density contribute to collisions at night, low luminance plays a major role (Hallmark et al., 2008; Plainis, Murray, & Pallikaris, 2006). Due to the potential effect of low visibility, drivers may not recognize hazardous objects, pedestrians, bicyclists, and traffic signs. Consequently, run-off-road, running stop sign, failure to yield right-of-way, wrong-way driving, pedestrian and bicycle crash may arise. The problem may become worse at unlit or poorly lit critical roadway safety spots such as interchanges, intersections, and railroad and highway crossing, particularly in adverse weather conditions.

Providing new lighting or improving existing lighting at intersections is one of the proven safety countermeasures of preventing crashes and reducing fatalities (Bullough, Donnell, & Rea, 2013; Isebrands et al., 2010). The improved visibility will reduce the glare of other light sources and enhance drivers' ability to obtain information quickly. In addition to traffic safety, the roadway lighting can also provide additional security and comfort for the public. Convincing evidence is also provided that lighting improvements lead to increasing pedestrian street use and reductions of crime, incivilities and fear at night in urban streets and residential settings (Painter, 1996).

In the year of 2014 in Indiana, statistics from Automated Reporting Information Exchange (ARIES) indicates that 18% of nighttime intersection fatal crashes happened at unlit sites, 70% at lit sites, and 12% during dusk and dawn. By contrast, the nation experienced 34%, 56%, and 10% of nighttime intersection fatal crashes at the lighting condition of not-lighted, lighted, and dusk and dawn correspondingly. To find out the reasons of this noteworthy difference between Indiana and the nation, Indiana's roadway lighting system, driver's behaviors, traffic flow pattern, geographic traits, and geometric design standards need to be investigated.

The performance of luminaire is generally evaluated by wattage, luminous efficacy (the ratio of lumen to wattage), correlated color temperature, color rendering index, operating life, and lumen depreciation. Currently, Indiana Department of Transportation (INDOT)'s roadway lighting system consists of high-pressure sodium (HPS) lamps. Because HPS lamps consume more energy, and have low color rendering ability, low lumen maintenance, and short life span, more cost-effective new lighting sources, particularly light emitting diode (LED) is suggested to replace HPS. With the maturity of new lighting technologies and their falling prices, their applications in roadway lighting are expected to rise considerably in the near future. Based on predictions from Navigant Consulting (2015), the current 53.3% of the street lighting sales by LED will become 94% in the year of 2023. Therefore, this study aims to evaluate the use of new lighting sources as a cost effective countermeasure improving traffic safety.

1.2 Research Approach and Main Tasks

The objectives of this study are threefold. First, this study evaluated the effect of nighttime lighting on traffic safety in Indiana. This is very useful for INDOT to recognize the nighttime crash issues and develop long-term strategies to address nighttime traffic safety problems. Second, this study assessed the in-service performance of new lighting technologies such as LED, plasma, and Ceramic Metal Halide (CMH) lights for area lightings. While new lights offer many advantages over the traditional HPS, it is necessary to gather field measurements to gauge the light performance of new light sources for successful applications, particularly at different types of intersections, including four-leg intersections, three-leg intersections, and roundabouts. Third, this study developed an economic methodology comparing new lighting candidates and identifying the most cost-effective lighting solution.

Specifically, the following tasks have been done assisting Indiana highway agencies evaluate whether new lighting source is the most cost effective countermeasures to various traffic scenarios.

1. The synthesis on nighttime crashes, new lighting technologies, and variables for selecting lighting sources to improve traffic safety at specific sites was conducted. Focus was on the publications by American Association of State Highway and Transportation Officials (AASHTO), INDOT, and Illuminating Engineering Society of North America (IESNA).
2. The analysis of Indiana nighttime crash data and site visiting to identify the contributing factors was conducted. Special emphasis was given to the Indiana State Police traffic crash data in the past years.
3. Potential test sites after consulting with INDOT Office of Traffic Safety and Office of Traffic Administration were identified. This work selected test sites in consultation with members of the Study Advisory Committee (SAC) for installing and evaluating new lights by taking into consideration the historic nighttime crash data, type of intersection, and LED, CMH, and plasma luminaires

currently available. Preference was given to intersections, including intersections that have poor safety histories and intersections where a new lighting system has been installed.
4. Before and after field light tests were conducted to verify in-service light performance, including illuminance distribution and uniformity ratio. AGi32 simulation was also performed for three selected intersections to compare with field test results. In addition, the long term performance of demonstration luminaires at the I-74 & US 231 interchange was tracked and documented. This activity provides a better understanding of maintenance issues, cycles, and costs.
5. Surveys to both State Highway Agencies (SHAs) and communities were sent in order to identify perceptions from SHAs and the public toward lighting improvement. The community survey included questions such as the public attitudes to intersection lighting, effectiveness of lighting, visibility improvement, and safety improvement.
6. To quantify safety effects of lighting at intersections, crash modification factors (CMFs) were developed by using two methodologies: before-and-after analysis and cross-sectional statistical analysis. The developed CMFs could be used to justify roadway lighting projects.
7. Life Cycle Cost Analysis (LCCA) was conducted to determine the best lighting solution given a real project scenario. The analysis considered initial (luminaire and installation) cost, operation and maintenance cost, and energy cost. With the CMF developed from last task, safety benefits were quantified to compare with costs. A software tool for LCCA analysis evaluating lighting options was developed in the meantime.

2. LITERATURE REVIEW

In transportation safety, the Crash Modification Factor (CMF) is commonly used to measure the effectiveness of a safety countermeasure or treatment. It is defined by Highway Safety Manual (HSM; AASHTO, 2010) as a multiplicative factor to compute the expected number of crashes after the countermeasure. It should be noted that sometimes the Crash Reduction Factor (CRF) is used as an alternative of CMF. CRF is defined as the percentage crash reduction that might be expected after the treatment (Bahar, Masliah, Wolff, & Park, 2007). The relationship between CMF and CRF can be stated as $CMF = 1 - (CRF/100)$. In the current version of HSM, the CMF for intersection lighting is only estimated using an empirical equation in terms of the proportion of total crashes for unlighted intersections that occur at night. It is therefore desired to develop CMF values for lighting at different types of intersections. In the past few years, two methods, before-and-after analysis and cross-sectional statistical analysis (Gross, Persaud, & Lyon, 2010), were applied to study the lighting effects at intersections. The main principles and applications of the two methods are illustrated in the following sections of this chapter. A brief summary of other methods is also discussed. At the end of this chapter, merits and demerits of each method are summarized.

2.1 Before-and-After Analysis

With a before-and-after analysis, a CMF value is determined by comparing the difference of crash frequencies between the before-period and the after-period. The "before-period" or "after-period" is defined as a certain time span before or after the treatment is carried out (Hauer, 1997). The basic form of the before-and-after analysis uses observational crash frequencies during before-period to predict after-period expected crash frequencies assuming the treatment is not implemented. The reduced crash frequencies of the observed after-period crash frequencies from the expected after-period crash frequencies are considered as the safety effects of the treatment. Although the before-and-after analysis is easy to use, the assumption that all other factors such as traffic, drivers' behavior, and road conditions remain unchanged is usually unrealistic. To separate effects of the treatment from other contributing effects, two improved algorithms based on the before-and-after analysis were developed, including the comparison group (CG) method and the empirical Bayes (EB) method (Gross et al., 2010).

Analyzing comparison group of sites by the CG method could separate non-treatment related effects and time trends, such as changing traffic volume from lighting effect. However, the potential issue of regression-to-the-mean (RTM) cannot be resolved. RTM is the phenomenon that observing abnormal high or low crash counts during the following years of the countermeasure. RTM bias may become significant if the analysis period is short. In other words, the CG method could overestimate or underestimate the safety effects of lighting. It is also hard to test the suitability of comparison group. It is assumed that comparison group and treatment group have the similar intersection characteristics, traffic volume, and crash counts in the before-period. Sometimes this assumption can be unreasonable if sample size is too small or two groups of sites are not ideally matched. The EB method accounts for observed changes due to regression-to-the-mean and safety changes due to time trends. However, the EB method has to use the overdispersion parameter to compute CMF. If crash data is not overdispersed, the approach may not be appropriate (Aul & Davis, 2006). This approach does not consider site selection bias, so different samples may yield inconsistent CMF values.

Walker and Roberts (1976) examined the before and after lighting effects of forty-seven rural at-grade intersections. They found that a 49% overall nighttime collision reduction after lighting. The before-and-after analysis conducted by Lipinski and Wortman (1976) indicated that installing illumination at rural at-grade intersections could reduce night accidents by 45% and reduce the ratio of night-to-total accidents by 22%. Box (1989) showed that roadway lighting reduced the overall crashes by 14% and the nighttime crashes by 36%. Fatal and injury reductions as high as 49% were realized through lighting as presented in two other studies (Green, Agent, Barrett, & Pigman, 2003; Schwab, Walton, Mounce, & Rosenbaum, 1982). A study performed by Presten and Schoenecker (1999) analyzed the before and after crash data of 3495 isolated rural two-lane through-stop intersections in Minnesota. The results of this study indicated the nighttime fatal crashes decreased 40% and the nighttime injury crashes decreased 26% after lighting was installed.

Hallmark et al. (2008) investigated the before and after crashes at 274 intersections in Iowa and found that the intersection safety was improved with lighting in terms of night-to-day and night-to-total crash ratios. Isebrands et al. (2010) analyzed 3-year before-period data and 3-year after-period data from 34 rural intersections in Minnesota. It was found through the study that with lighting the nighttime crash rate decreased 35%, the night-to-day crash ratio decreased 50%, and the night-to-total crash ration decreased 32%. In addition, the study also showed that reductions of 41% and 12% were realized for the nighttime fatal crashes and the nighttime injury/property damage crashes, respectively.

2.2 Cross-Sectional Statistical Analysis

The data used in before-and-after study is time-series data that consists of successive measurements on variables over specific time intervals. The before-and-after analysis relies on complete inventory data. However, collecting time-series data for the before-and-after analysis could be costly and time consuming since traffic volumes, intersection characteristics, and crash data within the analysis period need to be searched separately. If time-series data is not available, cross-sectional data could be used to quantify safety effects. Cross-sectional statistical analysis has been commonly used in transportation safety research to estimate the expected number of crashes on roadway segments, intersections, or interchanges (Lord & Mannering, 2010).

The cross-sectional statistical analysis can be used to analyze a large number of sites and variables related to safety. Poisson or negative binomial distribution is commonly assumed in the cross-sectional statistical analysis to estimate daytime and nighttime crashes. A Minnesota study (Gross & Donnell, 2011) applied the negative binomial regression method to analyze a four-year intersection crash data. Bullough et al. (2013) studied the lighting effects on intersection safety with the cross-sectional statistical analysis. In their study, the cross-sectional statistical analysis was utilized to reveal the crash reductions due to lighting at various types of intersections in urban, suburban, and rural areas. A New Zealand study (Jackett & Frith, 2013) applied this analysis method to analyze the relationship between luminance and safety at major intersections and found that the nighttime crashes decrease as the luminance increases. A study by Wanvik (2009) indicated that lighting not only reduced crashes, but also lowered the severities of crashes and reduced crash fatality.

When the cross-section method is used, efforts must be made in choosing appropriate statistical model and data collection in order to alleviate the biases in estimation. Simple regression models such as linear regression often produce biased estimations, while more complex models may overfit the data and yield impractical results. Therefore, crash data should be first analyzed to choose determine the most appropriate model. Adequate and proper design in data collection is essential for minimizing bias in the results of the analysis. Excluding key variables related to traffic safety, such as vehicle speeds and traffic volumes, often results in inaccurate safety evaluations. When repeated measurements, such as continuous yearly crash counts, were recorded at an intersection, it is important that the temporal and spatial correlations are examined during the analysis (Carter, Srinivasan, Gross, & Council, 2012).

2.3 Case-Control Analysis

A case-control analysis is commonly used to compare patients who have a disease or outcome of interest (cases) with patients who do not have the disease or outcome (controls), and looks back retrospectively to compare how frequently the exposure to a risk factor is present in each group to determine the relationship between the risk factor and the disease. The goal is to retrospectively determine the exposure to the risk factor of interest from each of the two groups of individuals: cases and controls. In this study, data for cross-sectional analysis is collected at a prescribed timing on a specific feature, such as lighting condition at an intersection, without knowing if there would be crashes or not. By contrast, case-control analysis selects sites based on crash outcomes and then determines the lighting effects on the crashes. Case-control analysis evaluates whether potential risk is disproportionately distributed between cases and controls, indicating the likelihood of the benefit by the countermeasure. Therefore, case-control analysis cannot be used to estimate crash frequencies, but can be used to reveal relative effects of treatments by odds ratio (OR) between groups of interests. Gross and Donnell (2011) verified that case-control analysis can analyze multiple treatments with respect to a single outcome but may incur overestimation or underestimation if confounding variables are not properly controlled.

It should be pointed out that there are many other methods for data analysis. However, through a primary review and evaluation of the available methods, it was determined that the methods discussed above were most appropriate for the intersection crash data available for this study. Table 2.1 summarizes advantages and disadvantages of the four analysis methods.

TABLE 2.1
Comparison of the Analysis Methods

Methodology	Advantages	Disadvantages
Before-and-After CG Method	Simple Account for time and traffic trends	Hard to handle regression-to-the-mean (RTM)
Before-and-After EB Method	Account for RTM and time and traffic trends	Can only use overdispersed data Inconsistent predictions by different sample Cannot consider spatial correlation Cannot specify complex model forms
Cross-Sectional Statistical Model	Predict crash frequencies	Omitted variable bias Hidden interactions among variables Cannot consider time and traffic trends Endogeneity
Case-Control Study	Study rare events Investigate multiple treatments	Cannot show causality Cannot discover differences within groups Only estimate one outcome per sample Estimation bias if confounding variables are not properly treated

3. CRASH DATA ANALYSIS

3.1 Crash Data

3.1.1 Crash Data Sources

The crash data in this study was obtained through several national and state databases as outlined below:

- Fatality Analysis Reporting System (FARS): This database of the National Traffic Safety Administration (NHTSA) is a national census of annual motor vehicle fatal traffic crashes that was created in 1975. The database includes those crashes that resulted in deaths within 30 days after the crash.
- General Estimates System (GES): Data from this system comes from crash reports by the police across the country. This system was established in 1988 and is widely used for traffic safety analysis.
- Automated Reporting Information Exchange System (ARIES): This is the Indiana traffic collision repository compiled by the Indiana law enforcement agencies. This system contains data for some key variables such as type of intersection, lighting condition, and numbers of injuries and fatalities.

3.1.2 Crash Classifications

Injury Severity. The National Safety Council (2007) published a standard for classifying motor vehicle traffic accidents or crashes from various aspects in order to provide a consistent language for the crash analysis across federal, state, and local jurisdictions. According to this standard, vehicle crashes are divided into five categories in terms of injury severity as follows.

1. K: Fatal crash;
2. A: Incapacitating injury crash;
3. B: Non-incapacitating evident injury crash;
4. C: Possible injury crash; and
5. O: Non-injury accident or PDO crash.

In practice, the three nonfatal crashes (A, B, and C) are often combined into one group. Thus, the following three categories are commonly used.

1. Fatal crash;
2. Nonfatal injury crash; and
3. Non-injury crash or PDO crash.

Light Condition. The common lighting conditions on roadways and at intersections used in the crash databases and in various studies include daylight, dark (not lighted), dark (lighted), and dawn/dusk. Dawn or dusk is the time period approximately 30 minutes before sunrise or 30 minutes after sunset. During the dawn and dusk periods, sunlight is not as bright as during the other time of the day, but is still sufficient for people to see objects within certain distance. It is therefore studied separately from daytime and nighttime periods.

3.2 Crash Comparison

3.2.1 Crash Trends

Ten-year crash data from 2004 to 2013 was retrieved, processed, and analyzed to reveal the patterns and trends of crashes. In order to reflect the effects of traffic volumes, crash rates per 100 million of crashes were calculated using Equation 3.1. The yearly crashes and corresponding crash rates are presented in Table 3.1. As shown in Table 3.1, within the ten year period, fatality rate and injury rate were in a generally decreasing trend with a few minor fluctuations.

$$Crash\ Rate = \frac{Number\ of\ Crashes}{100\ Million\ VMT} \tag{3.1}$$

In order to find the relative position of Indiana in comparison with the selected neighboring states in

TABLE 3.1
Yearly Crashes and Crash Rates

Year	Total Crash (1000)	Fatal Crash	Injury Crash (1000)	PDO Crash (1000)	Fatality	Injury (1000)	VMT (billions)	Crash Rate (per 100 M VMT)	Fatality Rate (per 100 M VMT)	Injury Rate (per 100 M VMT)
2004	6181	38253	1862	4281	42636	2788	2963	209	1.44	94
2005	6159	39189	1816	4304	43443	2699	2990	206	1.45	90
2006	5973	38588	1746	4189	42642	2575	3014	198	1.41	85
2007	6024	37248	1711	4275	41059	2491	3030	199	1.36	82
2008	5811	34017	1630	4146	37261	2346	2974	195	1.25	79
2009	5505	30797	1517	3957	33808	2217	2954	186	1.14	75
2010	5419	30196	1542	3847	32885	2239	2967	183	1.11	75
2011	5338	29757	1530	3778	32367	2217	2946	181	1.10	75
2012	5615	30800	1634	3950	33561	2362	2969	189	1.13	80
2013	5687	30057	1591	4066	32719	2313	2988	190	1.09	77

TABLE 3.2
Annual VMT Values of Selected States and the Nation

	Million Vehicle-Miles Traveled						
Year	**US**	**Indiana**	**Illinois**	**Kentucky**	**Michigan**	**Ohio**	**Wisconsin**
2003	2890893	72511	106536	46748	100756	108938	59615
2004	2962513	72713	109135	47322	103326	111654	60399
2005	2989807	71799	107706	47466	104052	110491	60017
2006	3014116	71215	106869	47742	104184	111247	59398
2007	3029822	71478	107483	48063	104614	110631	59493
2008	2973509	70973	106079	47534	101825	108302	57462
2009	2953501	76628	105846	47355	96769	110591	58157
2010	2966506	75761	105788	48007	97567	111836	59420
2011	2946131	76485	103234	48061	94754	111990	58554
2012	2968815	78923	104578	47344	94548	112715	59087
2013	2988323	78311	105297	46996	95132	112767	59486

TABLE 3.3
Annual Fatalities

Year	US	Indiana	Illinois	Kentucky	Michigan	Ohio	Wisconsin
2004	42636	947	1356	964	1159	1286	792
2005	43443	938	1361	985	1129	1323	815
2006	42642	899	1254	913	1085	1238	724
2007	41059	898	1249	864	1088	1257	756
2008	37261	814	1043	826	980	1190	605
2009	33808	693	911	791	871	1021	561
2010	32885	754	927	760	942	1080	572
2011	32367	750	918	721	889	1016	582
2012	33561	779	956	746	938	1123	615
2013	32719	783	991	638	947	989	543

terms of fatal crashes, the annual VMT and fatality values of these states as well as the national averages are presented in Tables 3.2 and 3.3. The annual fatality rates of the selected states, Indiana, and the nation are illustrated in Figure 3.1. The figure shows an apparent trend of crash rate decreasing in the nation, Indiana, and the neighboring dates. It can be seen in the figure that Indiana's fatality rate is in the middle among the six states.

3.2.2 Junction vs. Non-Junction

Roadway junctions the intersecting points of two or more roads, including intersections, interchanges, and railroad and highway crossings. The possibilities that crashes occur at roadway junctions are higher than on the non-junction roadway sections because of the increased traffic conflict points at junctions. Table 3.4 shows the annual fatal crashes on non-junction and junction roadway sections. It should be noted that the lengths of non-junction roadways are much greater than those of junctions because the junctions are only a very small portion of roadways. Therefore, even though the numbers of non-junction crashes are greater than those of junction crashes, the crash numbers at junctions in Table 3.4 are actually significantly greater with respect to the crashes per unit of roadway length.

To illustrate the high proportions of junction crashes, the percentages of the fatal crashes that occurred at junctions are plotted in Figure 3.2 and Figure 3.3. As can be seen in the figure, in five of the six states, more than 30% of the fatal crashes happened at junctions during the ten years. In other words, less than 70% of the fatal crashes occurred on non-junction roadway sections. Because of the dominating proportions of non-junction roadway lengths over junctions, the number of fatal crashes at junctions is in fact disproportionally large. This indicates that roadway junctions are highly important for traffic safety improvement.

As can be seen in Figures 3.2 and 3.3, five of the six states had higher percentages of the junction fatal crashes than the national average. Among the six neighboring states, Indiana was in the 5th place in non-junction fatal crashes and in the 4th place in junction fatal crashes.

Table 3.4, Figure 3.2 and Figure 3.3 contain the information on fatal crashes. To further investigate the details of the fatal crashes, the numbers of deaths or fatalities in these fatal crashes were calculated and are listed in Table 3.5. The yearly fatalities resulted from the fatal crashes in the six states are listed in Table 3.5. The fatality rates, in terms of number of deaths per fatal crash, can then be obtained based on the values in Tables 3.4 and 3.5. The fatality rates are plotted in Figure 3.4. The figure shows that

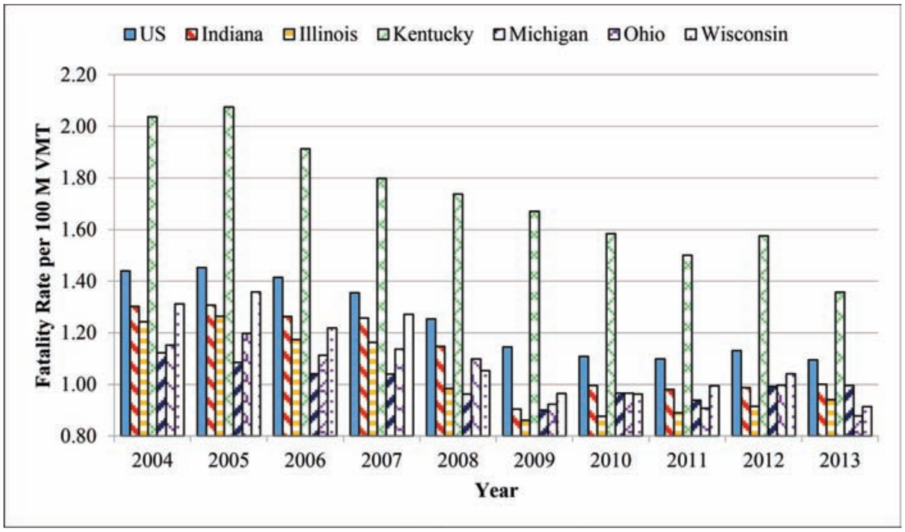


Figure 3.1 Fatality rates.

TABLE 3.4
Annual Fatal Crashes on Junction and Non-Junction Roadway Sections

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
					Non-Junction					
US	27442	28224	27975	27004	24800	22144	21148	20788	21351	20693
Indiana	575	611	588	586	518	408	469	463	491	499
Illinois	838	847	800	769	656	550	569	559	605	613
Kentucky	694	707	675	650	631	599	546	517	555	447
Michigan	754	735	738	702	667	559	569	558	533	572
Ohio	750	780	742	782	730	629	655	657	715	642
Wisconsin	474	479	481	490	417	353	345	346	367	334
					Junction					
US	10979	10968	10608	10420	9362	8707	9093	9029	9608	9310
Indiana	282	244	232	218	209	224	232	213	229	210
Illinois	384	386	336	357	294	282	289	275	280	281
Kentucky	160	178	162	153	120	131	147	152	139	143
Michigan	301	295	266	288	248	248	303	276	341	304
Ohio	413	443	399	379	369	316	328	284	307	275
Wisconsin	248	235	189	185	144	152	183	186	182	173

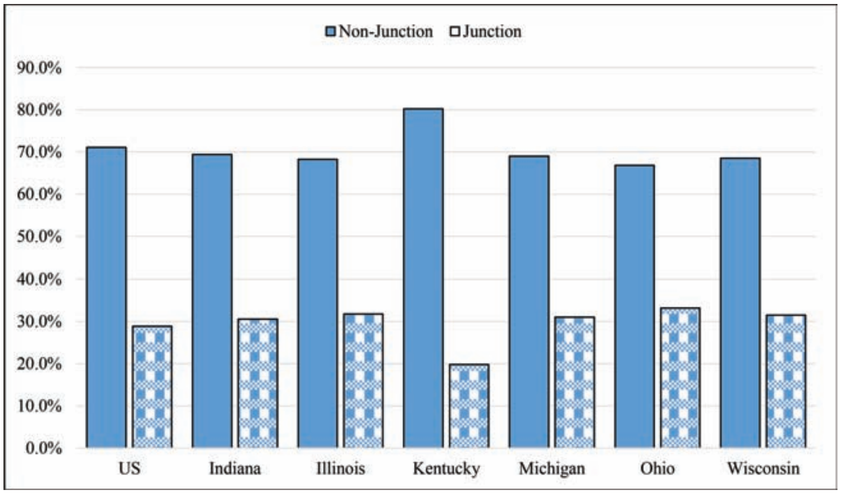


Figure 3.2 Average annual junction and non-junction fatal crashes.

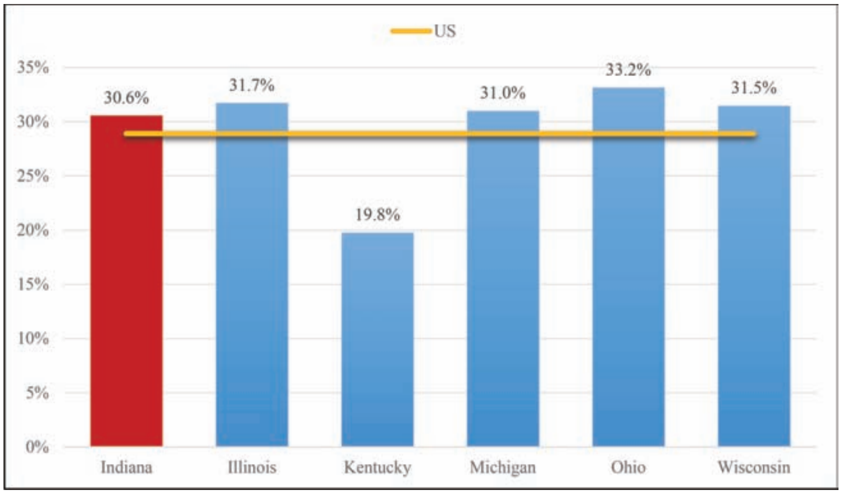


Figure 3.3 Proportions of fatal crashes in junction crashes (2004–2013).

TABLE 3.5
Number of Deaths from Fatal Crashes

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
					Non-Junction					
US	30853	31467	31037	29967	27253	24443	23115	22797	23386	22654
Indiana	646	672	652	657	585	453	507	519	534	549
Illinois	932	934	889	857	585	601	616	620	648	684
Kentucky	793	795	739	703	699	654	600	556	600	487
Michigan	840	806	792	768	713	596	612	601	574	614
Ohio	833	836	801	841	783	693	718	710	785	698
Wisconsin	516	547	519	551	450	395	377	378	408	354
					Junction					
US	11951	11973	11598	11281	10160	9428	9834	9634	10357	10018
Indiana	301	266	250	241	235	240	247	232	247	234
Illinois	421	429	365	391	235	310	311	297	308	306
Kentucky	171	190	174	161	126	137	160	164	146	151
Michigan	319	323	294	319	267	276	329	288	366	333
Ohio	453	485	437	414	408	329	361	307	336	291
Wisconsin	276	268	205	205	155	166	195	204	207	189

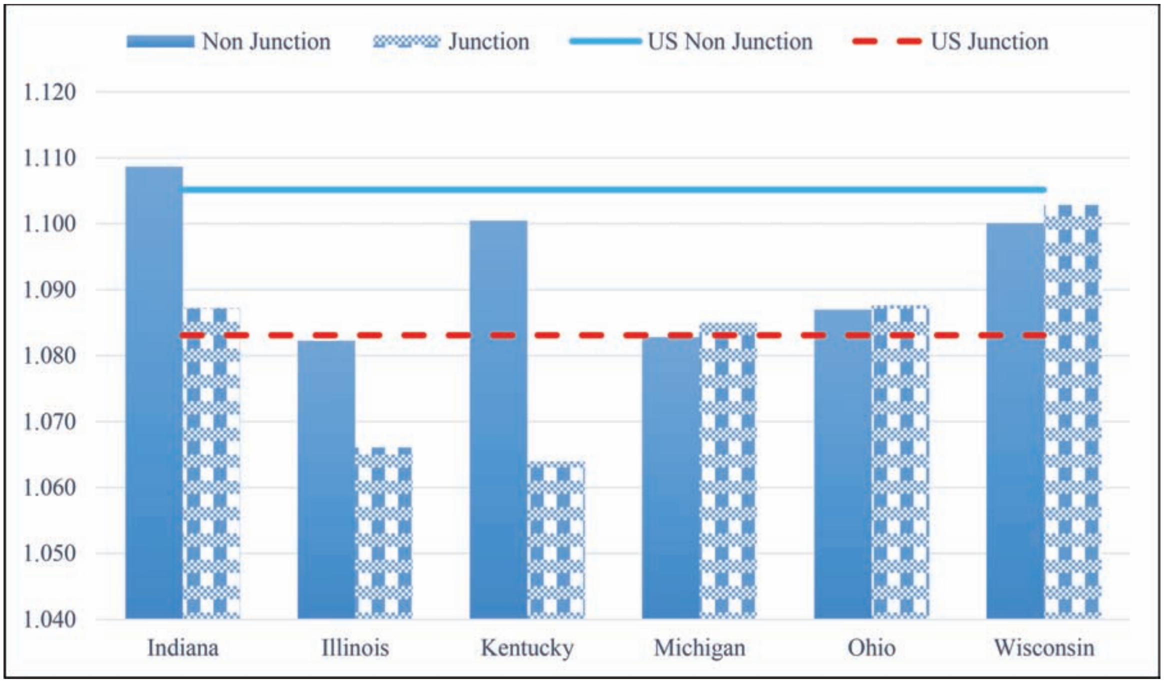


Figure 3.4 Average annual fatality rate by states.

TABLE 3.6
National Annual Crash Distributions

	Daylight		Dark (Lighted)		Dark (Not Lighted)		Dusk and Dawn	
Year	**Counts**	**%**	**Counts**	**%**	**Counts**	**%**	**Counts**	**%**
2004	4284089	69%	915038	15%	741339	12%	241567	4%
2005	4248360	69%	940158	15%	736768	12%	234612	4%
2006	4131647	69%	893291	15%	711670	12%	237636	4%
2007	4153063	69%	940243	16%	709291	12%	220455	4%
2008	3970423	68%	932815	16%	699236	12%	208371	4%
2009	3814948	69%	871405	16%	618083	11%	197222	4%
2010	3791849	70%	852389	16%	565535	10%	208280	4%
2011	3693589	69%	841410	16%	597451	11%	205181	4%
2012	3876875	69%	954628	17%	573882	10%	209254	4%
2013	3943510	69%	909371	16%	614819	11%	217205	4%
Average	3990835	69%	905075	16%	656807	11%	217978	4%

Indiana's fatality rates were higher than the national average values. Even though Indiana's numbers of crashes were relatively low among the six states, its crash fatality rates, especially non-junction fatality rate, were at the high end. In other words, the number of deaths per fatal crash was relatively high in Indiana.

3.2.3 Light Conditions

As discussed previously, traffic crashes can be divided into several categories according to the light condition. Table 3.6 presents the national annual crash counts as well as percentages under different light conditions. The values in the table indicate that most of crashes occurred during daylight period with a dominantly high percentage of 69%. This is understandable because approximately 75% of roadway travels take place during the daytime (Varghese & Shankar, 2007).

Similarly, the Indiana annual crash distributions are shown in Table 3.7. Compared to the national crash values in Table 3.6, the values in Table 3.7 exhibit that the proportions of Indiana's daytime crashes were lower and those of nighttime crashes were higher than the national values. It is interesting to note that in Indiana the percentage of dark-not-lighted crashes was higher and the percentage of dark-lighted crashes was lower than the national values. This may imply that roadway lighting in Indiana is more effective in safety improvement.

TABLE 3.7
Indiana Annual Crash Distributions

	Daylight		Dark (Lighted)		Dark (Not Lighted)		Dusk and Dawn	
Year	**Counts**	**%**	**Counts**	**%**	**Counts**	**%**	**Counts**	**%**
2004	136967	66%	29214	14%	30408	15%	10151	5%
2005	136628	66%	29245	14%	31186	15%	9719	5%
2006	124572	65%	26891	14%	30743	16%	9479	5%
2007	132380	65%	28830	14%	32656	16%	10001	5%
2008	132173	65%	29004	14%	33007	16%	10162	5%
2009	122826	65%	26125	14%	30629	16%	9087	5%
2010	127273	66%	25927	13%	30204	16%	8686	5%
2011	123194	66%	26413	14%	28743	15%	8789	5%
2012	124837	66%	25916	14%	28513	15%	8628	5%
2013	126098	66%	26787	14%	29632	15%	9241	5%
Average	128695	66%	27435	14%	30572	16%	9394	5%

TABLE 3.8
Fatal Crashes under Different Light Conditions

	Daylight	Dark (Not Lighted)	Dark (Lighted)	Dusk and Dawn
US	165986	99480	58033	13843
Indiana	3909	3008	229	347
Illinois	4700	2891	2012	346
Kentucky	4316	2274	505	398
Michigan	4605	2607	1560	433
Ohio	5507	2993	1650	416
Wisconsin	3027	1982	634	264

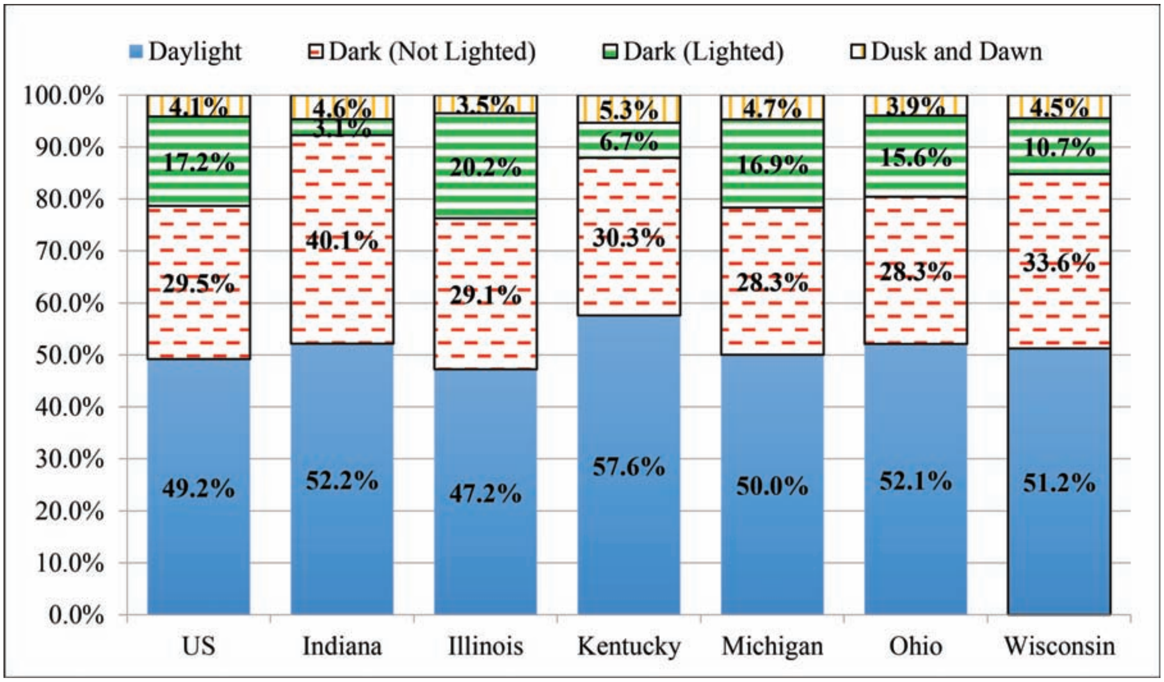


Figure 3.5 Proportions of fatal crashes under different light conditions.

Table 3.8 and Figure 3.5 show the fatal crashes and proportions of fatal crashes under different light conditions during the ten-year period from 2004 to 2013. It is clearly shown in Figure 3.5 that Indiana's fatal crashes the under dark-not-lighted condition had considerably high proportion than the neighboring states and the nation. In addition, the percentage of Indiana's dark-lighted fatal crashes was the lowest

TABLE 3.9
Nighttime Junction Fatal Crashes

	2006	2007	2008	2009	2010	2011	2012	2013	Total
					Dark (Not Lighted)				
US	1559	1509	1360	1250	1265	1219	1441	1344	10947
Indiana	83	46	60	60	63	58	59	60	489
Neighbor	195	206	183	151	171	157	188	159	1410
					Dark (Lighted)				
US	2457	2508	2239	2152	2156	2251	2332	2244	18339
Indiana	4	5	8	19	13	14	18	12	93
Neighbor	288	295	217	247	253	223	232	198	1953
					Dusk/Dawn				
US	436	397	359	354	379	342	419	405	3091
Indiana	9	15	8	10	6	8	13	16	85
Neighbor	52	55	36	29	54	47	44	42	359

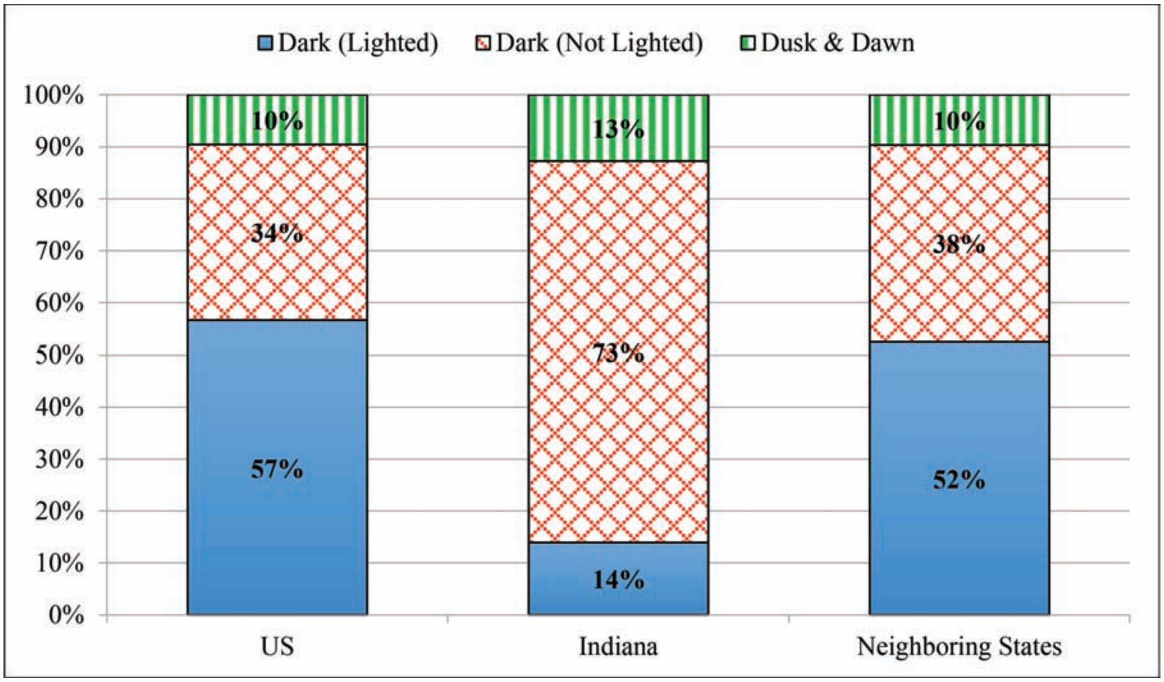


Figure 3.6 Junction nighttime fatal crash distributions.

among the selected states and the nation. Therefore, the crash data indicates that roadway lighting would be especially beneficial to Indiana's traffic safety.

Nighttime Junction Fatal Crashes. The main focus of this study is the effects of lighting on intersection safety. Therefore, the nighttime fatal crashes at junctions were of special interest in this study. Because fatal crashes in 2004 and 2005 are not available in the FAS database, only the nighttime junction fatal crash data from 2006 to 2013 was obtained as shown in Table 3.9. The proportions of junction fatal crashes in different nighttime periods are plotted in Figure 3.6. The figure displays that the proportions in Indiana are drastically different from the neighboring states and the nation. The percentage nighttime fatal crashes at Indiana junctions during the dark-not-lighted period is much higher than that in the neighboring states and the nation.

3.3 Lighting Effects on Indiana Nighttime Junction Crashes

The most recent five-year (2010–2014) crash data was retrieved from the Indiana ARIES database to study the lighting effects on nighttime roadway junction crashes. The crash data was analyzed to reveal the

TABLE 3.10
Crash Severities under Different Light Conditions

Crash Severity	Dark (Lighted)	Dark (Not Lighted)	Dawn/Dusk	Overall
Fatal Crash	160	168	41	369
Injured Crash	10894	4296	2802	17992
PDO Crash	38791	16301	10542	65634
Overall Crash	49845	20765	13385	83995
		Row Percent		
Fatal Crash	43.4%	45.5%	11.1%	100%
Injured Crash	60.5%	23.9%	15.6%	100%
PDO Crash	59.1%	24.8%	16.1%	100%
Overall Crash	59.3%	24.7%	15.9%	100%
		Column Percent		
Fatal Crash	0.3%	0.8%	0.3%	0.4%
Injured Crash	21.9%	20.7%	20.9%	21.4%
PDO Crash	77.8%	78.5%	78.8%	78.1%
Overall Crash	100%	100%	100%	100.0%
		χ^2 Test		
	DF	**Value**	**P-Value**	
	4	*98.6181*	*<0.0001*	

lighting effects in terms of crash severity, locality, junction types, and manner of collisions.

TABLE 3.11
Chi-Square Test on Light Condition and Crash Severity

Crash Severity	Dark (Lighted)	Dark (Not Lighted)	Dawn/Dusk
		Observed Counts	
Fatal	160	168	41
Injured	10894	4296	2802
PDO	38791	16301	10542
		Expected Counts	
Fatal	218.97	91.22	58.80
Injured	10676.96	4447.93	2867.11
PDO	38949.07	16225.85	10459.09
		Chi-square Statistics	
Fatal	15.88	64.62	5.39
Injured	4.41	5.19	1.48
PDO	0.64	0.35	0.66

3.3.1 Crash Severity

A total of 83,995 nighttime junction crashes were recorded from 2010 to 2014 in ARIES. These nighttime junction crashes are grouped according to their severities and light conditions as shown in Table 3.10. Also presented in Table 3.10 are the calculated percentages of the rows and columns along with the results of a χ^2 test.

The χ^2 test was performed to statistically determine if crash severities are associated with light conditions. In other words, it was to determine if light conditions affect crash severities. To test if crash severity and light condition are independent, the χ^2 test was conducted for the following hypotheses:

H_0: Crash severity is not associated with light condition,and

H_a: Crash seveity is dependent on light condition.

In the χ^2 test, the observed crash counts were compared with expected crash counts. The expected crash counts can be calculated with Equation 3.2. The observed crash counts and their corresponding expected values are shown in Table 3.11.

$$\text{Expected Counts} = \frac{\text{Row Total Counts} \times \text{Column Total Counts}}{\text{Grand Total Counts}} \tag{3.2}$$

With the observed and expected values in Table 3.11, the χ^2 was then calculated using the following equation:

$$\chi^2 = \sum \frac{(\text{Observed Counts} - \text{Expected Counts})^2}{\text{Expected Counts}} \tag{3.3}$$

The calculation with Equation 3.3 yielded $\chi^2 = 98.62$.

Since the number of light conditions is 3 and the number of severities is also 3, the degree of freedom for this test is then (3-1)(3-1) = 4. Based on the χ^2 distribution, $P\{(\chi^2(4) \leq (\chi^2(0.95; 4))=9.49$. Since $\chi^2 = 98.62 > P\{(\chi^2(4) \leq (\chi^2(0.95; 4))=9.49$, the null hypothesis is rejected. Thus, it was concluded that at a confidence interval of 95%, the crash severities were affected by the light conditions.

3.3.2 Locality

In a similar manner as in the previous section, the effects of localities on crashes were analyzed with χ^2 test. Table 3.12 lists different types of crashes under different combinations of locality and light condition. The χ^2 test concluded that localities along with light conditions had strong effects on crash severities.

TABLE 3.12
Crashes under Different Localities and Light Conditions

Locality	Dark (Lighted)	Dark (Not Lighted)	Dawn/Dusk	Overall
		All Crashes		
Rural	4839	11723	3389	19951
Urban	44977	9035	9992	64004
Overall	49816	20758	13381	83955
		Fatal Crashes		
Rural	17	113	23	153
Urban	143	55	18	216
Overall	160	168	41	369
		Injury Crashes		
Rural	1023	2396	737	4156
Urban	9867	1899	2065	13831
Overall	10890	4295	2802	17987
		PDO Crashes		
Rural	3799	9214	2629	15642
Urban	34967	7081	7909	49957
Overall	38766	16295	10538	65599
		χ^2 Test		
	DF	**Value**	**P-Value**	
	2	17706.1	<0.0001	

Figures 3.7 through 3.9 demonstrate the crash distributions in urban and rural areas under the three light conditions. Figure 3.7 shows the crash percentages under dark-lighted condition. Similarly, Figures 3.8 and 3.9 are those under dart-not-lighted and dawn/dusk conditions, respectively. It can be seen from the figures that the percentage of the fatal crashes in rural area under dark-not-lighted condition is significantly higher than that under dark-lighted condition. This may imply the importance of intersection lighting for safety improvement. In addition, the percentage of fatal crashes in rural areas during dawn/dusk period is also noticeably higher than that under dark-lighted condition.

3.3.3 Type of Roadway Junction

There are eight types of roadway junctions in the Indiana ARIES database as shown in Table 3.13. A χ^2 test was conducted to look into the effects of junction types on crashes. The test indicates that the types of roadway junctions are statistically correlated with crashes. The values in Table 3.13 show that four-leg, three-leg, and ramp junctions had the highest crash percentages, with 56.2%, 34.2%, and 5.4%, respectively. The crashes at lighted four-leg intersections experienced the highest percentages dark time crashes (60.9%) and dawn/dusk crashes (58.4%).

To further investigate the crash patterns at different intersections, the crash data was arranged in terms of

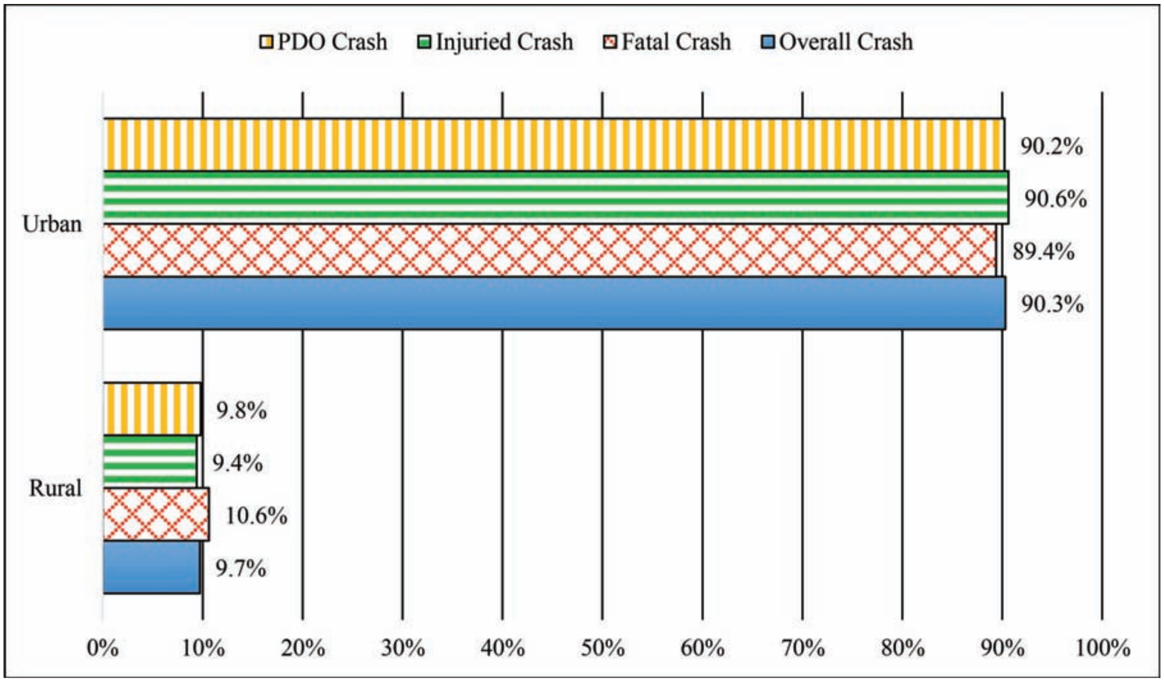


Figure 3.7 Crash percentages in urban and rural areas under dark-lighted condition.

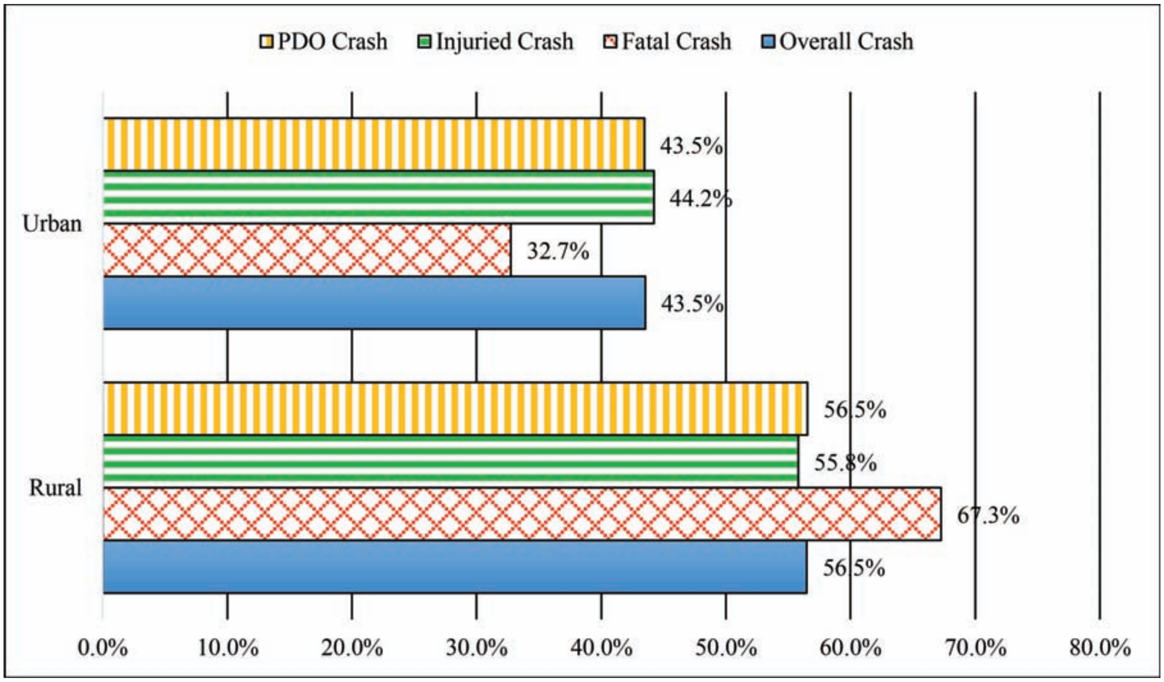


Figure 3.8 Crash percentages in urban and rural areas under dark-not-lighted condition.

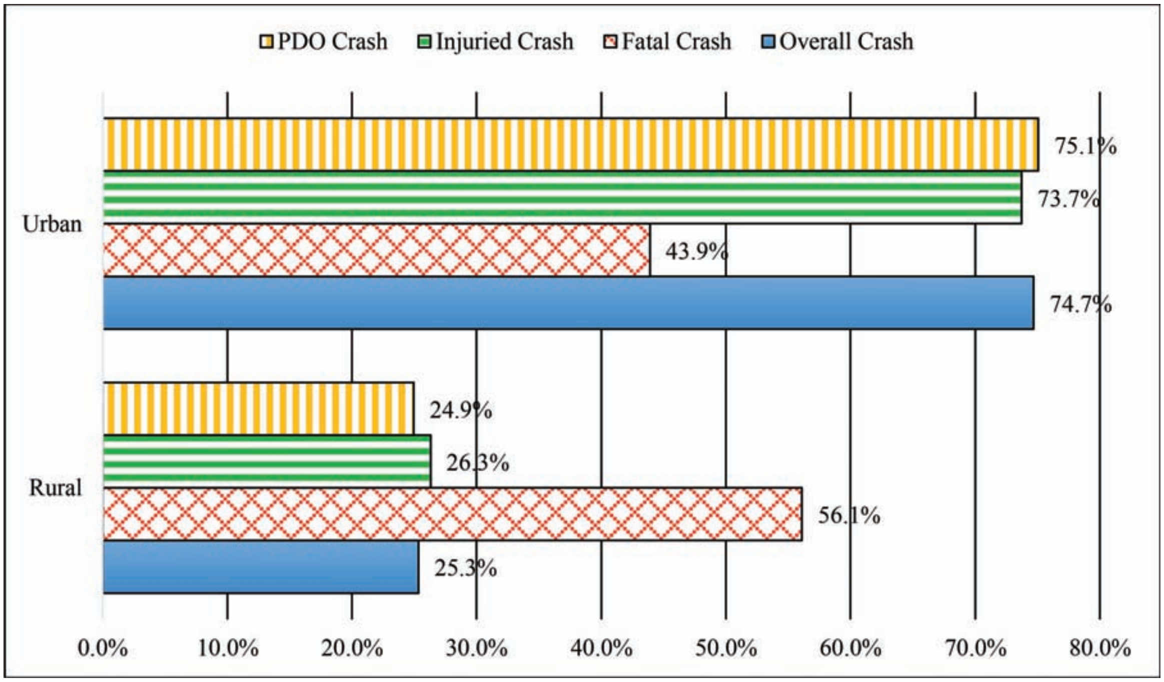


Figure 3.9 Crash percentages in urban and rural areas under dawn/dusk condition.

types of crashes, including fatal, injury, and property-damage-only (PDO), as displayed in Table 3.14. The percentages of different types of crashes at four-leg intersections and three-leg intersection are shown in Figures 3.10 and 3.11. Both figures indicate that that the under dark-not-lighted condition the fatal crashes outnumbered other types of crashes at four-leg and three-leg intersections, which further suggests the safety benefits from intersection lighting.

3.3.4 Primary Crash Causes

The ARIES database lists 50 primary causes of crashes. Table 3.15 shows all 50 primary causes and

TABLE 3.13
Crashes at Different Types of Roadway Junctions

Type of Junction	Light Condition Dark (Lighted)	Dark (Not Lighted)	Dawn/Dusk	Overall
Five Point Or More	522	107	81	710
Four-leg Intersection	30368	8982	7813	47163
Interchange	893	423	233	1549
Railroad Crossings	118	118	27	263
Ramp	2782	1026	722	4530
Three-leg Intersection	14471	9912	4331	28714
Traffic Circle/Roundabout	688	194	176	1058
Trail Crossings	2	3	2	7
Overall	49844	20765	13385	83994
Row Percent				
Five Point Or More	73.5%	15.1%	11.4%	100.0%
Four-leg Intersection	64.4%	19.0%	16.6%	100.0%
Interchange	57.7%	27.3%	15.0%	100.0%
Railroad Crossings	44.9%	44.9%	10.3%	100.0%
Ramp	61.4%	22.6%	15.9%	100.0%
Three-leg Intersection	50.4%	34.5%	15.1%	100.0%
Traffic Circle/Roundabout	65.0%	18.3%	16.6%	100.0%
Trail Crossings	28.6%	42.9%	28.6%	100.0%
Overall	59.3%	24.7%	15.9%	100.0%
Column Percent				
Five Point Or More	1.0%	0.5%	0.6%	0.8%
Four-leg Intersection	60.9%	43.3%	58.4%	56.2%
Interchange	1.8%	2.0%	1.7%	1.8%
Railroad Crossings	0.2%	0.6%	0.2%	0.3%
Ramp	5.6%	4.9%	5.4%	5.4%
Three-leg Intersection	29.0%	47.7%	32.4%	34.2%
Traffic Circle/Roundabout	1.4%	0.9%	1.3%	1.3%
Trail Crossings	0.0%	0.0%	0.0%	0.0%
Overall	100.0%	100.0%	100.0%	100.0%
χ^2 Test				
	DF	**Value**	**P-Value**	
	14	2505.2	<0.0001	

TABLE 3.14
Types of Crashes at Intersections

Type of Roadway Junction	Light Condition Dark (Lighted)	Dark (Not Lighted)	Dawn/Dusk	Overall
Fatal Crash				
Five Point Or More	1	2	0	3
Four-leg Intersection	93	76	27	196
Interchange	2	3	1	6
Railroad Crossings	1	9	1	11
Ramp	11	6	4	21
Three-leg Intersection	48	66	8	122
Traffic Circle/Roundabout	1	0	0	1
Trail Crossings	0	0	0	0
Overall	160	168	41	369

(Continued)

TABLE 3.14
(Continued)

	Light Condition			
Type of Roadway Junction	**Dark (Lighted)**	**Dark (Not Lighted)**	**Dawn/Dusk**	**Overall**
		Injury Crash		
Five Point Or More	125	34	24	183
Four-leg Intersection	7322	2118	1786	11226
Interchange	182	73	36	291
Railroad Crossings	29	22	4	55
Ramp	505	182	109	796
Three-leg Intersection	2649	1851	821	5321
Traffic Circle/Roundabout	81	15	22	118
Trail Crossings	1	1	0	2
Overall	10894	4296	2802	17992
		PDO Crash		
Five Point Or More	396	71	57	524
Four-leg Intersection	22953	6788	6000	35741
Interchange	709	347	196	1252
Railroad Crossings	88	87	22	197
Ramp	2266	838	609	3713
Three-leg Intersection	11771	7989	3502	23262
Traffic Circle/Roundabout	606	179	154	939
Trail Crossings	1	2	2	5
Overall	38790	16301	10542	65633

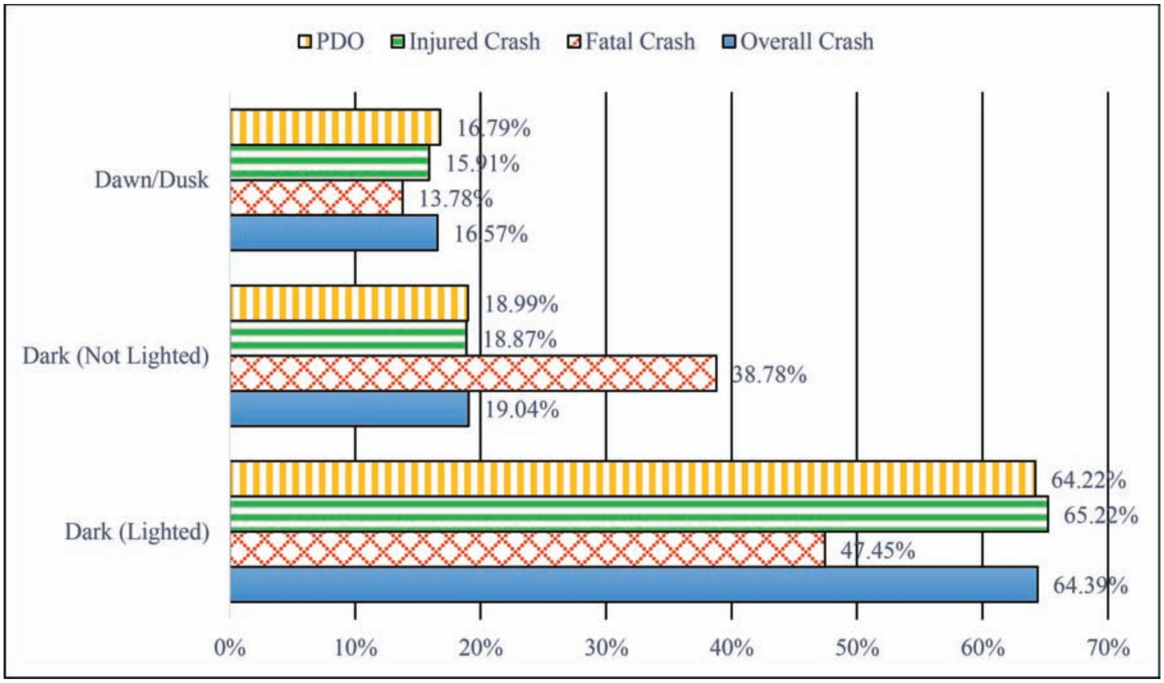


Figure 3.10 Crash distribution at four-leg intersections.

their related crashes. The χ^2 test result is also included in the table, which indicates that the crash causes are strongly correlated with light conditions. Figure 3.12 illustrates an example of some crash causes and the proportions of resulted crashes under different light conditions. It clearly shows that crashes from any causes would most likely occur under the dark-not-lighted condition.

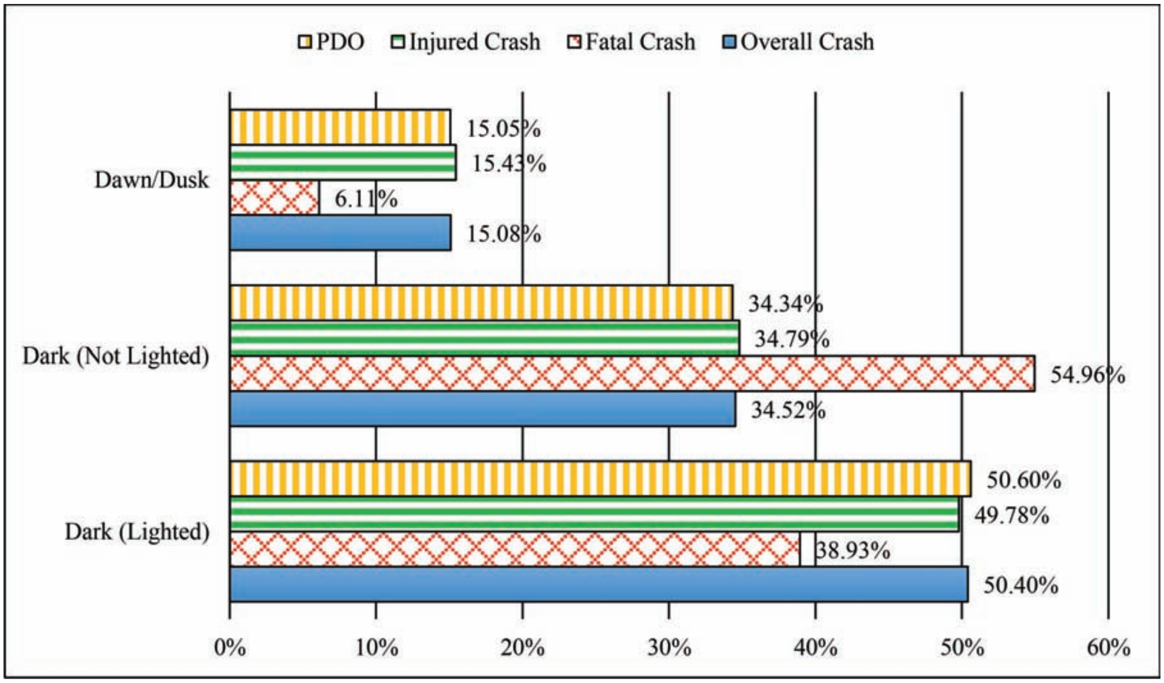


Figure 3.11 Crash distribution at three-leg intersections.

TABLE 3.15
Primary Causes of Crashes

#	Primary Factor	Dark (Lighted)	Dark (Not Lighted)	Dawn and Dusk	Total	Percent
1	Failure To Yield Right Of Way	11944	3749	3807	19500	23.33%
2	Following Too Closely	8208	2208	2677	13093	15.66%
3	Disregard Signal	4914	1168	1034	7116	8.51%
4	Ran Off Road Right	3064	2769	527	6360	7.61%
5	Others - Explain In Narrative	3624	1262	910	5796	6.93%
6	Speed Too Fast For Weather Conditions	2642	1369	719	4730	5.66%
7	Animal/Object In Roadway	679	3073	502	4254	5.09%
8	Improper Turning	2337	593	468	3398	4.07%
9	Unsafe Speed	1631	767	280	2678	3.20%
10	Unsafe Backing	1661	515	406	2582	3.09%
11	Driver Distracted	1279	465	402	2146	2.57%
12	Improper Lane Usage	1627	260	258	2145	2.57%
13	Unsafe Lane Movement	1208	270	238	1716	2.05%
14	Roadway Surface Condition	849	547	281	1677	2.01%
15	Left Of Center	757	327	129	1213	1.45%
16	Overcorrecting/Oversteering	491	258	103	852	1.02%
17	Improper Passing	348	170	140	658	0.79%
18	Driver Asleep Or Fatigued	286	182	89	557	0.67%
19	Brake Failure Or Defective	297	124	80	501	0.60%
20	Pedestrian Action	313	112	56	481	0.58%
21	Alcoholic Beverages	374	69	16	459	0.55%
22	View Obstructed	118	68	66	252	0.30%
23	Cell Phone Usage	141	62	20	223	0.27%
24	Driver Illness	142	49	28	219	0.26%
25	Wrong Way On One Way	157	15	14	186	0.22%
26	Headlight Defective Or Not On	87	57	6	150	0.18%
27	Tire Failure Or Defective	70	34	15	119	0.14%
28	Steering Failure	43	22	12	77	0.09%
29	Traffic Control Inoperative/Missing/Obscure	20	29	3	52	0.06%

(Continued)

TABLE 3.15
(Continued)

#	Primary Factor	Dark (Lighted)	Dark (Not Lighted)	Dawn and Dusk	Total	Percent
30	Accelerator Failure Or Defective	30	9	8	47	0.06%
31	Insecure/Leaky Load	18	13	9	40	0.05%
32	Obstruction Not Marked	19	18	3	40	0.05%
33	Holes/Ruts In Surface	20	13	5	38	0.05%
34	Engine Failure Or Defective	22	12	3	37	0.04%
35	Oversize/Overweight Load	19	8	5	32	0.04%
36	None	23	4	4	31	0.04%
37	Other Telematics In Use	19	5	3	27	0.03%
38	Other Lights Defective	7	10	1	18	0.02%
39	Glare	3	2	10	15	0.02%
40	Prescription Drugs	11	4	0	15	0.02%
41	Tow Hitch Failure	8	4	2	14	0.02%
42	Severe Crosswinds	5	6	2	13	0.02%
43	Lane Marking Obscured	4	5	0	9	0.01%
44	Illegal Drugs	5	0	0	5	0.01%
45	Passenger Distraction	3	2	0	5	0.01%
46	Road Under Construction	5	0	0	5	0.01%
47	Violation Of License Restriction	1	1	0	2	0.00%
48	Jackknifing	1	0	0	1	0.00%
49	Shoulder Defective	1	0	0	1	0.00%
50	Utility Work	1	0	0	1	
	Total	49536	20709	13341	83586	

χ^2 ***Test***

DF	Value	P-Value
98	8952.23	<.0001

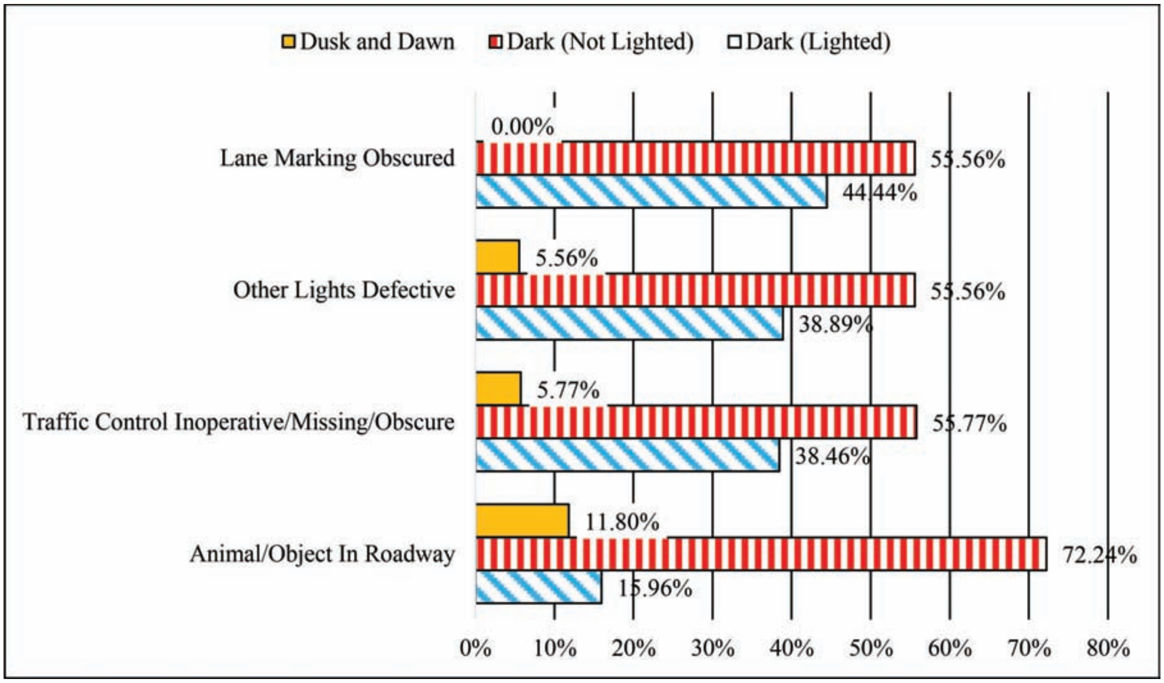


Figure 3.12 Crash distributions for various causes and light conditions.

TABLE 3.16
Manner of Collision under Different Light Conditions

Manner of Collision	Dark (Lighted)	Dark (Not Lighted)	Dusk and dawn	Total	Percent
Backing Crash	1888	605	447	2940	3.51%
Collision With Animal Other	4	12	2	18	0.02%
Collision With Deer	24	170	17	211	0.25%
Collision With Object In Road	18	12	2	32	0.04%
Head On Between Two Vehicles	4487	3288	885	8660	10.34%
Left Turn	4367	1007	1078	6452	7.70%
Left/Right Turn	944	256	262	1462	1.74%
Non-Collision	358	252	110	720	0.86%
Opposite Direction Sideswipe	1023	414	239	1676	2.00%
Other - Explain In Narrative	1494	793	312	2599	3.10%
Ran Off Road	4304	4143	929	9376	11.19%
Rear End	13018	3668	4029	20715	24.72%
Rear To Rear	69	22	16	107	0.13%
Right Angle	12253	4684	3788	20725	24.73%
Right Turn	1038	259	251	1548	1.85%
Same Direction Sideswipe	4407	1143	999	6549	7.82%
Total	49696	20728	13366	83790	

χ^2 Test

DF	Value	P-Value
30	4656.4	<0.0001

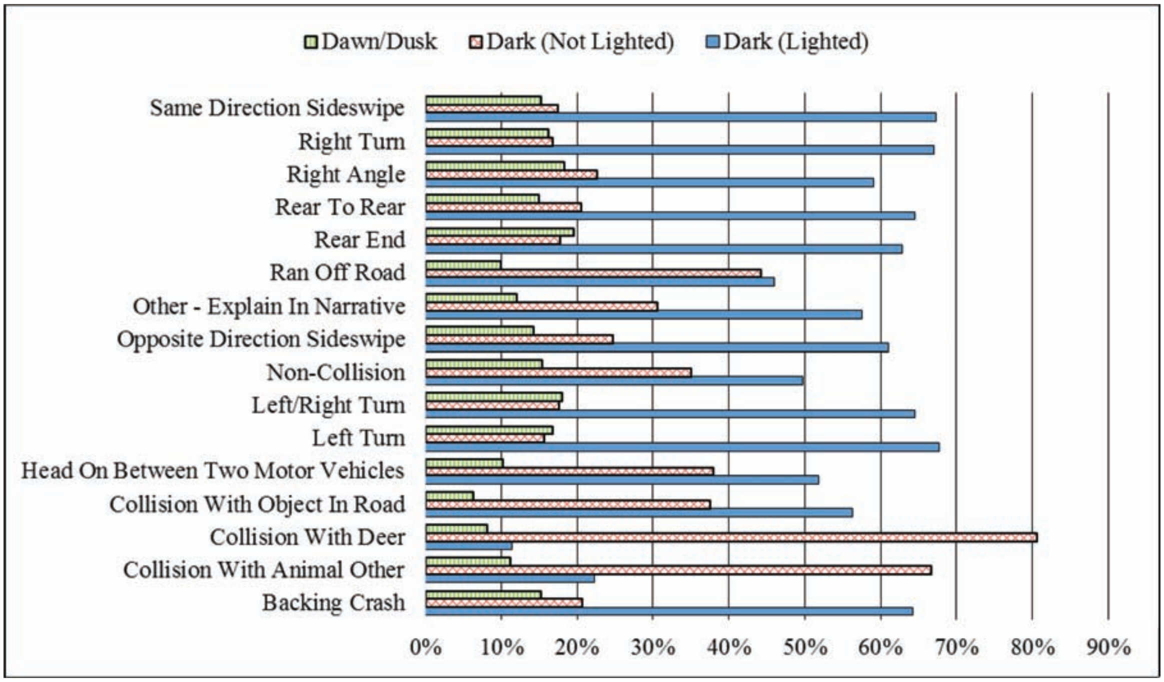


Figure 3.13 Crash distributions for different manners of collisions.

3.3.5 Manner of Collision

The manner of collision listed in Table 3.16 were also χ^2 tested. The test result indicates that manner of collision is statistically correlated with crashes under different light conditions. As shown in Table 3.16, the right angle, rear end, and head on collisions were the major types of collisions. The frequencies of the collision manners are displayed in Figure 3.13.

Table 3.17 presents the fatal crashes in terms of manners of crashes. It can be seen in the table that the top three manners of collisions with the highest fatal crashes are right angle, head on, and run off road.

TABLE 3.17
Fatal Crashes Corresponding to Manners of Collisions

Manner of Collision	Dark (Lighted)	Dark (Not Lighted)	Dusk/Dawn	Total
Backing Crash	1	0	0	1
Collision With Animal Other	0	0	0	0
Collision With Deer	0	0	0	0
Collision With Object In Road	1	0	0	1
Head On Between Two Vehicles	29	39	5	73
Left Turn	13	2	3	18
Left/Right Turn	0	0	0	0
Non-Collision	3	1	1	5
Opposite Direction Sideswipe	0	1	1	2
Other – Explain In Narrative	20	7	4	31
Ran Off Road	26	36	5	67
Rear End	15	20	4	39
Rear To Rear	0	0	0	0
Right Angle	45	60	18	123
Right Turn	0	0	0	0
Same Direction Sideswipe	6	2	0	8
Total	159	168	41	368

4. FIELD TESTING

4.1 Overview of Lighting Evaluation

4.1.1 Lighting Performance Indicators

The performance of a roadway lighting source is generally evaluated by photometric, colorimetric, temporal, cost, and energy-consumption indicators. Some key indicators are explained as below:

- *Illuminance:* The density of luminous flux falling on the pavement surface. It is measured in SI derived unit of lux (lx) or non-SI unit of foot-candle (fc).
- *Luminance:* The reflected luminous intensity from the pavement surface that is visible to the motorist's eye. It is measured in SI unit of candelas per square meter or non-SI unit of candelas per square foot.
- *Wattage:* This indicator is used to describe power consumption. The luminaire with high wattage may produces excess heat while the luminaire with low wattage may produce low level of brightness.
- *Luminous efficacy:* Defined as the ratio of luminous flux to power (wattage) and it measures how well the luminaire produces visible light.
- *Correlated color temperature (CCT) and color rendering index (CRI):* CCT, by Lighting Research Center, is "a specification of the color appearance of the light emitted by a lamp, relating its color to the color of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (K)." A lower CCT value indicates a warmer color appearance while a higher CCT value represents a cooler color appearance. CRI is used to demonstrate how well a specific lamp illuminates color compared with a reference light source on a scale from 0 to 100. CRI is often used when CCT is the same or close enough among different types of luminaires. The closer to 100 the CRI is, the better quality (trueness) of light the luminaire emits.
- *Lamp life:* For most lamp types, it is defined as the number of hours when 50% of a sample group of lamps have failed. For new lighting technologies such as LED, Plasma, and Induction lamps, it is defined as the number of hours when 50% of a sample group of lamps have been found with the initial luminous flux decreased to 70%. Longer operating life ensures greater economic and ecological advantages. Environmental factors and mechanical factors could affect the longevity of the luminaire.
- *Lumen maintenance:* Refers to the luminaire's ability to maintain its initial light output level throughout the course of the operating life. Since the light output of the luminaire depreciates over the life, an initial level of lighting higher than minimum maintained level is usually required.

4.1.2 Lighting Design Criteria

The Illuminating Engineering Society of North America (IESNA) developed three methodologies for the roadway lighting design based on photometric terms, which are illuminance, luminance, and small target visibility (STV). The concepts of illuminance and luminance are mentioned in previous section. Compared with the other two methodologies, the STV is a more complicated one measuring the luminance of the targets as well as the immediate background considering the adaptation level of the adjacent surroundings and the disability glare. The weighted average of the luminance of targets is equal to the STV.

The average maintained horizontal illuminance and uniformity ratio are two key design values. The average maintained horizontal illuminance is the average level of horizontal illuminance on the pavement area of calculation or measurement. For straight roadways, the area should cover one luminaire cycle, which is defined as the area between two poles along one side of the roadway. For intersections or other traffic conflict zones, the area of calculation or measurement has to be specified case by case. Uniformity ratio is defined as the ratio of average illuminance to the minimum illuminance in the

TABLE 4.1
AASHTO Road Surface Classifications

Class	Q_0*	Description	Mode of Reflectance
R1	0.10	Portland cement concrete road surface. Asphalt road surface with a minimum of 12 percent of the aggregates composed of artificial brightener aggregates.	Mostly diffuse
R2	0.07	Asphalt road surface with an aggregate composed of minimum 60 percent gravel. Asphalt road surface with 10 to 15 percent artificial brightener in aggregate mix.	Mixed (diffuse and specular)
R3	0.07	Asphalt road surface with dark aggregates; rough texture after some months of use.	Slightly specular
R4	0.08	Asphalt road surface with very smooth texture.	Mostly specular

*Q_0 Representative Mean Luminance Coefficient.

TABLE 4.2
AASHTO Illuminance Design Values for Continuous Roadway Lighting

Roadway Classification	General Land Use	Average Maintained Illuminance (fc)				Minimum Illuminance	Uniformity Ratio
		R1	R2	R3	R4		
Principal Arterials – Interstate and other freeways	Commercial	0.6 to 1.1	0.6 to 1.1	0.6 to 1.1	0.6 to 1.1	0.2	3 or 4
	Intermediate	0.6 to 0.9	0.6 to 0.9	0.6 to 0.9	0.6 to 0.9	0.2	3 or 4
	Residential	0.6 to 0.8	0.6 to 0.8	0.6 to 0.8	0.6 to 0.8	0.2	3 or 4
Principal Arterials – Others	Commercial	1.1	1.6	1.6	1.4	As Uniformity Ratio allows	3
	Intermediate	0.8	1.2	1.2	1.0		3
	Residential	0.6	0.8	0.8	0.8		3
Minor Arterials	Commercial	0.9	1.4	1.4	1.0		4
	Intermediate	0.8	1.0	1.0	0.9		4
	Residential	0.5	0.7	0.7	0.7		4
Collectors	Commercial	0.8	1.1	1.1	0.9		4
	Intermediate	0.6	0.8	0.8	0.8		4
	Residential	0.4	0.6	0.6	0.5		4
Local	Commercial	0.6	0.8	0.8	0.8		6
	Intermediate	0.5	0.7	0.7	0.6		6
	Residential	0.3	0.4	0.4	0.4		6

area. Lower uniformity ratio indicates less frequent contrasts on the lighted roadway segments so that road users are allowed to perceive roadway conditions continuously with less discomforts. However, if the uniformity ratio is too low when the brightness is low, the visibility could be reduced, making it difficult for drivers to distinguish objects and roadway features.

Tables 4.1 and 4.2 are the road surface classifications and the roadway illuminance design values specified by AASHTO. Although no specific design values are provided for intersection lighting, AASHTO suggests that "special conditions may make somewhat different illuminance levels desirable or necessary." Three design indicators are recommended in the AASHTO standard, including average maintained illuminance, minimum illuminance, and uniformity ratio. Lighting designers can choose design values based on roadway classification, general land use, and road surface classifications.

The IESNA illuminance design values for roadway lighting are presented in Table 4.3. IESNA also provides the illuminance design values for urban street intersections as shown in Table 4.4. Different from the AASHTO specifications, IESNA design values do not include minimum illuminance values. Table 4.5 is the INDOT (2013) recommended illuminance design values.

This study adopts illuminance design values from INDOT design manual. The minimum average maintained illuminance is set as 0.8 fc for all types of intersections. The maximum uniformity ratio allowed is 6 for roundabout and 4 for other types of intersections. Since no value is specified for the minimum illuminance by INDOT, a minimum illuminance of 0.2 fc for continuous roadway lighting from AASHTO standard is considered in this study as the minimum lighting requirement.

TABLE 4.3
IESNA Illuminance Design Values for Continuous Roadway Lighting

Roadway Classification	Pedestrian Conflict Area	Minimum Maintained Average Values (fc) R1	R2 & R3	R4	Uniformity Ratio
Freeway Class A	–	0.6	0.9	0.8	3
Freeway Class B	–	0.4	0.6	0.5	3
Expressway	High	1.0	1.4	1.3	3
	Medium	0.8	1.2	1.0	3
	Low	0.6	0.9	0.8	3
Major	High	1.2	1.7	1.5	3
	Medium	0.9	1.3	1.1	3
	Low	0.6	0.9	0.8	3
Collector	High	0.8	1.2	1.0	4
	Medium	0.6	0.9	0.8	4
	Low	0.4	0.6	0.5	4
Local	High	0.6	0.9	0.8	6
	Medium	0.5	0.7	0.6	6
	Low	0.3	0.4	0.4	6

TABLE 4.4
IESNA Illuminance Design Values for the Intersection of Continuously Lighted Urban Streets for R2 and R3 Pavement Classifications

Functional Classification	Average Maintained Illumination at Pavement by Pedestrian Area Classification (fc) High	Medium	Low	Uniformity Ratio
Major/Major	3.4	2.6	1.8	3
Major/Collector	2.9	2.2	1.5	3
Major/Local	2.6	2.0	1.3	3
Collector/Collector	2.4	1.8	1.2	4
Collector/Local	2.1	1.6	1.0	4
Local/Local	1.8	1.4	0.8	6

TABLE 4.5
INDOT Recommended Illuminance Design Values

Roadway Classification	Average Maintained Illuminance (fc)	Uniformity Ratio
Interstate Route or Other Freeway	0.8	4
Expressway	1.1 to 1.6	3
Intersection or City Street	0.8	4
Weigh Station or Rest Area Ramp	0.6	4
Weigh Station or Rest Area Parking Area	1.0	4
Roundabout	0.8 to 3.4	3 to 6

4.2 Field Illuminance Measurement

4.2.1 Test Site Selection

In order to select appropriate intersection sites for this study, the crashes at intersections between 2008 and 2013 were identified from the ARIES database using the longitude and latitude values. The crashes at the thousands of intersections identified were further analyzed to divide them into crashes at different time periods, including nighttime crashes. Then the intersections were ranked on the basis of number of nighttime crashes using SAS, a statistical software.

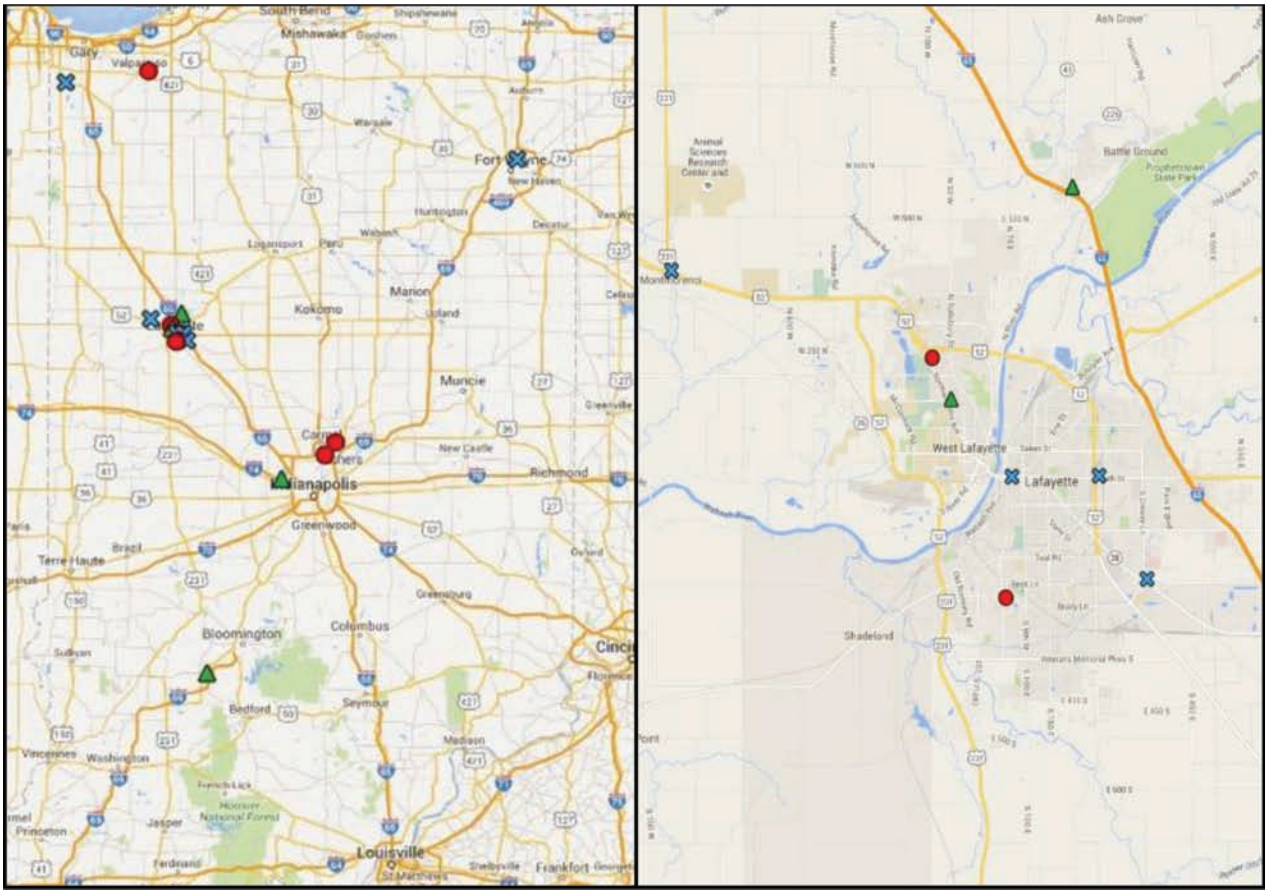


Figure 4.1 Locations of test intersections.

Because traffic volume is directly related to crash rate, efforts were therefore made to obtain AADT for the 40 top ranked intersections through the INDOT Interactive Traffic Count Map. With the AADT values of the intersections, the crash rates were calculated as number of crashes per million vehicle miles traveled. The intersections were also ranked in terms of crash rates.

Crash severity is one of the most commonly used measures of highway safety (Golembiewski & Chandler, 2011). A crash severity index can be calculated using Equation 4.1. After the intersection severity indexes were obtained, the intersections were ranked according to severity indexes.

$$Severity\ Index = \frac{\alpha_F F + \alpha_I I + \alpha_{PDO} PDO}{N} \qquad (4.1)$$

Where,

F = total number of fatal crashes at the intersection;

I = total number of injury crashes at the intersection;

PDO = total number of property-damage only crashes at the intersection;

N = total number of crashes at the intersection; and

á$_F$, á$_I$, á$_{PDO}$ = severity parameters for fatal, injury, and PDO crashes, respectively. Empirical values (á$_F$ = 12, á$_I$ = 3, á$_{PDO}$ = 1) were used in this study (FHWA, 2011).

The final ranking was then made by combining the three ranking, i.e., rankings by number of crashes, crash rates, and severity indexes. The Study Advisory Committee (SAC) selected 13 intersections and one interchange based on the final ranking as listed in Table 4.6. Among the 13 intersections, five were selected as lighting replacement intersections and the rest were used as control sites with no lighting changes. The interchange lighting consists of three high mast towers.

The locations of the test sites are displayed in Figure 4.1. The four-leg, three-leg, and roundabout intersections are represented in Figure 4.1(left) by blue cross, green triangle, and red circle, respectively. Figure 4.1(right) is a map of Lafayette and West Lafayette, where the majority of the test sites are located.

4.2.2 Luminaire Installation

The lighting replacement at the five intersections and one interchange were made in different dates between December 2014 and November 2015 as shown in Table 4.7. The new luminaires installed at the test intersections include GE LED 260W, Stray Light Plasma 270W, Holophane LED 168W, Horner LED 80W, and Philips Ceramic Metal Halide (CMH) 210W. Of the three at the US 231 and I-74 interchange, new luminaires were installed on two of them. The Cree

TABLE 4.6
Test Intersections for Lighting Evaluation

Site #	City	Road	Intersecting Rd	Intersection Type	Existing luminaire	Proposed New Luminaire
1	Fort Wayne	E. Coliseum Blvd	Coldwater	Four-leg	HPS 400W	LED 260W
2	Lafayette	SR 38 E	Creasy Ln	Four-leg	HPS 250W	Plasma 270W
3	St John(Lake)	US 231	US 41	Four-leg	HPS 250W	Cree LED*
4	Wes Lafayette	US 231	US 52	Four-leg	HPS 250W	LED 168W
5	Lafayette	South St	S 4th St	Four-leg	LED 109W	No Change
6	Brownsburg	US 136	Connector	T/Y	HPS 250W	LED 80W
7	West Lafayette	Northwestern	Cherry Lane	T/Y	HPS 200W	No Change
8	West Lafayette	SR 43	I-65 N Exit Ramp	T/Y	HPS 400W	CMH 210W
9	Carmel	Hazel Dell Pkwy	E 131ST	Roundabout	LED 142W	No Change
10	Carmel	96TH ST	Westfield	Roundabout	MH 250W	No Change
11	Valparaiso	Sturdy Rd	Laporte Ave	Roundabout	LED 80W	No Change
12	Wes Lafayette	Yeager Rd	Northwestern	Roundabout	MH 250W	No Change
13	Lafayette	Poland Hill Rd	Twyckenham	Roundabout	LED 130W	No Change
14	Crawfordsville	US 231	I-74	Interchange	HPS 1000W	T1: LED 240W; T2: LED 392W; T3: CMH 375W

*Luminaires at Site 3 were replaced with Cree LED when this study was near complete.

TABLE 4.7
New Luminaire Installation Dates

Site #	City	Intersecting Roads	Existing Luminaire	New Luminaire	Installation Date
1	Fort Wayne	E. Coliseum & Coldwater	HPS 400W	GE LED 260W	July 2015
2	Lafayette	SR 38 & Creasy Lane	HPS 250W	Stray Light Plasma 270W	July 2015
4	West Lafayette	US 231 & US 52	HPS 250W	Holophane LED 168W	November 2015
6	Brownsburg	US 136 & Connector	HPS 250W	Horner LED 80W	November 2015
8	West Lafayette	SR 43 & I-65 N Exit	HPS 400W	Philips CMH 210W	July 2015
14	Crawfordsville	US 231 & I-74	HPS 1000W	T1: Cree LED 240W; T3: GE CMH 375W	T1:2015; T3: December 2014

LED 240W luminaires were installed to replace HPS 1000W lamps on Tower 1 (T1), and the GE CMH 375W luminaires were installed to replace HPS 1000W lamps on Tower 3 (T3).

During the installation of new luminaires at sites 2, 8, and 14, the research team was present to observe the installation processes. The main observations are outlined as follows.

Site 2: SR 38 & Creasy Lane Intersection in Lafayette

- Stray Light Plasma 270W (Figure 4.2) luminaires were installed to replace the existing HPS 250W lamps.
- Removal of the existing HPS luminaires and installation of the Plasma luminaires were easy, but the Plasma luminaires were relatively heavy to lift.
- It took about 30 minutes to complete the removal of the existing luminaire and installation of a new luminaire at each pole.
- It took about four hours to complete the luminaire replacements of four poles, including traffic control set up and lunch time.
- The new lighting system had interference with the traffic signals. This problem was solved during the night through electric rewiring.

Site 8: SR 43 & I-65 N Exit Ramp in West Lafayette

- Philips CMH 210W (Figure 4.3) luminaires were installed to replace the existing HPS 400W lamps.
- The electrical wires of the new luminaires were not readily connectable with the existing system. It took some time for wiring connections.
- It took about 45 minutes for the luminaire to be replaced at one pole and about four hours (including the labor lunch time) to complete all the replacements at the three poles.

Site 14: US 231 & I-74 Interchange in Crawfordsville

- Cree LED 240W luminaires were installed to replace HPS 1000W lamps on Tower 1.
- On Tower 2, the burnout drivers and two broken Global Tech LED 392W luminaires were replaced with new ones as shown in Figure 4.4. The luminaires were then properly sealed to solve water accumulation problems. The work was completed on Tower 2 in about one hour
- GE CMH 375W luminaires were installed to replace HPS 1000W lamps on Tower 3 (Figure 4.5).
- A motor was used to connect the moving fixture inside tower to move the luminaires down and up during the installations on all towers.

Figure 4.2 Field installation at Site 2, plasma head, and plasma driver.

Figure 4.3 Field installation at Site 8, CMH lamp, and CMH ballast.

- It took about 1.5 hours to replace HPS with CMH 375W on Tower 3. The installation of new luminaires was relatively easy.
- Connecting new devices with the existing lighting fixtures was not straightforward and took extra time to complete.

4.2.3 Illuminance Measurements

Konica Minolta T-10 illuminance meter shown in Figure 4.6 was used to measure the illuminance levels at the selected study sites. The illuminance meter can be used to measure the illuminance of continuous and intermittent light sources.

The illuminance measurements were conducted in accordance with the IESNA standards of LM-50 Photometric Measurement of Roadway and Street Lighting Installations and RP-8 Roadway Lighting. For the measurement of continuous roadway lighting, test area should cover at least one luminaire cycle as shown in Figure 4.7. The measurement layout in the figure is a typical grid setup on a two-way two-lane roadway segment. One luminaire cycle refers to the luminaire coverage section between two adjacent lighting poles along one side of roadway. The tested lighting pole should be placed as the center of the luminaire cycle in the layout of the illuminance measurements. The test area should extend half of the luminaire cycle on both sides from the centered lighting pole. Within each luminaire cycle, test points were set up in the following way.

Figure 4.4 Luminaire installation on Tower 2 at Site 14.

Figure 4.5 Luminaire installation on Tower 3 at Site 14.

Figure 4.6 Konica Minolta illuminance meter T-10.

- The roadway lanes in the test area were divided into subareas with longitudinal and transverse lines.
- It is recommended in the standards that the transverse lines be spaced at a maximum distance of 16.4 feet or 5 meters along the longitudinal lines from the tested pole. In this study, the spaces between the transverse lines were 8 feet or 16 feet at the test sites, depending on the actual intersection characteristics.
- At the interchange of US 231 and I-74, the spaces between adjacent measurement points were 40 feet for the illuminance measurements of the high mast towers.

As illuminance measurements at intersections normally involve roadway curvatures and corners, the measurement layouts could not strictly follow the standards. Therefore, use of pole spacing as the luminaire cycle was not applicable if a lone lighting pole was located at a corner of the intersection. In this study, the illuminance

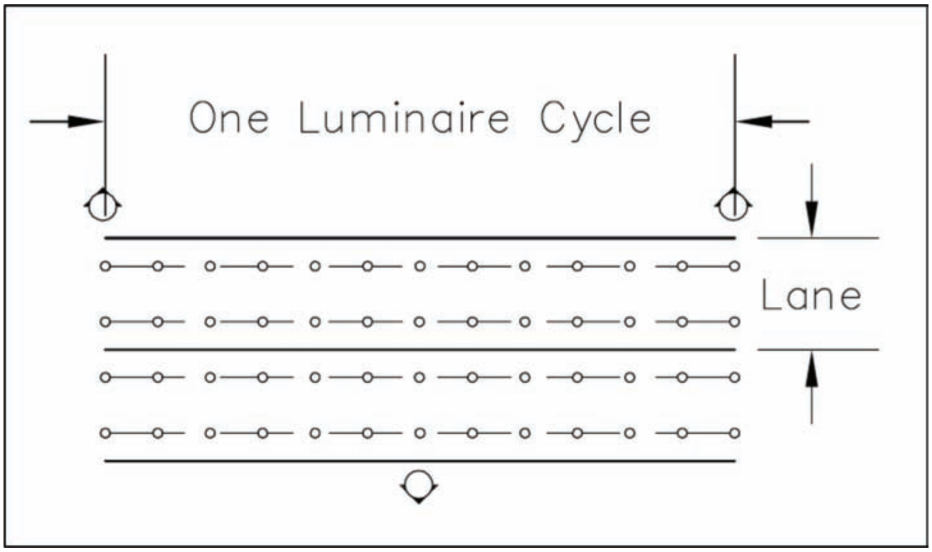


Figure 4.7 Layout of illuminance measurements.

Figure 4.8 Traffic control setup, test grid setup, and illuminance measurements.

levels of an intersection with a corner lighting pole were measured from the pole to a distance of 96 feet from the pole on both sides of the pole. If the illuminance level was less than 0.1 fc at a distance less than 96 feet from the pole, the measurement would stop at the low illuminance point. The number of measurements at each study site was generally above 100. The measurements were time consuming and labor intensive, including traffic control, marking test points, and measuring and recording illuminance values. Figure 4.8 illustrates traffic setup, testing grid marking, and illuminance measuring.

4.3 Illuminance Measurements and Lighting Simulation

Filed measurements of illuminance must be conducted during night times and traffic controls are required at intersections. In addition, the use of the illuminance meter under low air temperature may affect the accuracy of the illuminance measurements. Therefore, it would be challenging and impractical to conduct illuminance measurements in the winter. As shown in Table 4.8, the field measurements at the study sites were scheduled and conducted during non-winter dates as much as possible.

TABLE 4.8
Study Site Information and Illuminance Measurement Dates

Site #	City	Road 1	Road 2	Type of Intersection	Test Date	New Lighting Simulation
1	Fort Wayne	E. Coliseum Blvd	Coldwater Rd	Four-leg	10/22/14 and 3/14/16	N/A
2	Lafayette	SR 38 E	Creasy Lane	Four-leg	6/28/15 and 2/4/16	Yes
3	St John(Lake)	US 231	US 41	Four-leg	6/23/15	N/A
4	Wes Lafayette	US 231	US 52	Four-leg	6/28/15 and 2/4/16	Yes
5	Lafayette	South St	S 4th St	Four-leg	4/15/15	N/A
6	Brownsburg	US 136	Connector Rd	Three-leg	4/21/15 and 11/23/15	Yes
7	Lafayette	Northwestern Ave	Cherry lane	Three-leg	4/14/15	N/A
8	Lafayette	SR 43	I-65 N Exit Ramp	Three-leg	6/28/15 and 2/4/16	N/A
9	Carmel	Hazel Dell Pkwy	E 131th St	Roundabout	5/12/15	N/A
10	Carmel	96th St	Westfield Blvd	Roundabout	5/12/15	N/A
11	Valparaiso	SR 130E	Sturdy Rd	Roundabout	6/23/15	N/A
12	Wes Lafayette	Yeager Rd	Northwestern Ave	Roundabout	4/14/15	N/A
13	Lafayette	Poland Hill Rd	Twyckenham Blvd	Roundabout	4/15/15	N/A
14	Crawfordsville	US 231	I-74	Interchange	12/8/2015 (also measured in 2013 and 2014 in a previous study)	N/A

Among the 14 study sites, six of them (Sites 1, 2, 4, 6, 8, and 14) had new luminaires installed. Therefore, at these six sites, illuminance measurements were conducted twice, one before luminaire installation and one after. For the rest of the eight sites, only one measurement was made. In addition, the illuminance values were calculated for Sites 2, 4, and 6 with the lighting design and simulation software, AGi32. The reason for using AGi32 for the three sites was that the required intersection geometric files and luminaire IES files were available for these three intersections. The results of the illuminance measurements and the AGi32 calculations are discussed in the following.

4.3.1 HPS and LED at Site 1 – Coliseum Boulevard East & Coldwater Road in Fort Wayne

Site 1 is a four-leg intersection located in Fort Wayne as shown in Figure 4.9. The tested lighting pole is marked by a symbol of sun in the map. At this site, the existing HPS 400W lamps were replaced with LED 260W luminaires. The photos of the old and new luminaire lighting are shown in Figure 4.10.

Figure 4.11 shows the 3D illuminance footprints at Test Site 1. There are 4 lanes at this intersection from Lane 1 (L1) to Lane 4 (L4). L1 is closest to the lighting pole and L4 is farthest. The symbol “1/4 L1” denotes the first quarter longitudinal line along L1 and “3/4 L2” means the second quarter longitudinal line along L2. The tested lighting pole is located at 0 feet on x-axis and there are other two poles located at 88 feet and at -180 feet from the tested lighting pole. All the measured illuminance values are higher than 0.2 fc for both HPS 400W and LED 260W luminaires. Figure 4.12 shows the values of illuminance measurements along the longitudinal direction. The illuminance curves are not symmetric in the two sides of the tested lighting pole. This can be attributed to the effects of the adjacent lighting poles. It should be noted that the measured illuminance values indicate that the LED luminaires produced sufficient lighting with much less electricity consumption.

4.3.2 HPS and Plasma at Site 2 – SR 38 & Creasy Lane in Lafayette

Figure 4.13 is the map of the intersection at Site 2 in Lafayette. This is a four-leg intersection with two through lanes and one left turning lane at each direction. The existing HPS 250W lamps were replaced with Plasma 270W at this intersection. Figure 4.14 shows the nighttime views of the two types of luminaires. In addition to the illuminance measurements of the HPS and Plasma luminaires, the illuminance distribution of the Plasma luminaires was also calculated with AGi32. The measured and calculated illuminance values are plotted in Figure 4.15. Within the measured distance of 120 feet, the percentages of illuminance values of greater than 0.2 fc are 94%, 53%, and 88% for HPS, Plasma, and calculated Plasma, respectively. This implies that the Plasma luminaires produced a smaller light spread than the HPS ones. It also indicates that the AGi32 calculations of illuminance levels were not as accurate as desired for this particular case. The reason for the noticeable difference was not clear. A likely cause could be the loss of lighting effectiveness due to dirtiness of the luminaires. Figure 4.16 shows the values of measured and calculated illuminance along the longitudinal direction.

4.3.3 HPS at Site 3 – US 231 & US 41in St. John (Lake)

Site 3 is a four-leg intersection with HPS 250W lighting lamps. Figure 4.17 shows an aerial photo and a night time view of the HPS lighting. The measured illuminance values are plotted in Figure 4.18. It is shown in the figure that the illuminance values are symmetrically distributed along the two sides of the lighting pole. The illuminance distributions along the longitudinal direction are illustrated in Figure 4.19.

4.3.4 HPS and LED at Site 4 – US 231 & US 52 in West Lafayette

This is a four-leg intersection in West Lafayette with four lighting poles at the four corners of the intersections. Figure 4.20 is the map of the intersection. The existing HPS 250W lamps were replaced with LED 168W at this intersection. Figure 4.21 shows the nighttime views of the two types of luminaires. In addition to the illuminance measurements of the HPS and LED luminaires, the illuminance distribution of the LED luminaires was also calculated with AGi32. The measured and calculated illuminance values are plotted in Figure 4.22. The percentages of illuminance values of greater than 0.2 fc are 97%, 89%, and 73% for HPS, LED, and calculated LED, respectively. Therefore, the HPS luminaires yielded a larger lighting area with illuminance level above 0.2 fc. It also indicates that the AGi32 calculations of illuminance levels were not as accurate as desired for the LED luminaires. Figure 4.23 shows the values of measured and calculated illuminance along the longitudinal direction. Although the LED luminaires produced a smaller lighting area than the replaced HPS, the illuminance levels of the LED were comparable to those of the HPS. This is meaningful as the LED luminaires consume less energy than the HPS lamps.

4.3.5 LED at Site 5 – South Street & South 4th Street in Lafayette

As shown in Figure 4.24, it is a four-leg intersection with LED 190W luminaires. Figures 4.25 and 4.26 illustrate the luminance distributions. The illuminance levels were all above 0.2 fc. The non-symmetric pattern displayed in Figure 4.26 was caused by an adjacent lighting pole located about 80 feet away from this lighting pole.

4.3.6 HPS and LED Luminaires at Site 6 – US 136 and Connector Road in Brownsburg

This is a T intersection as shown in Figure 4.27. The LED 80W luminaires were installed to replace the existing HPS 250W. The night time lighting of the two types of luminaires is displayed in Figure 4.28. The illuminance values of the LED luminaires were calculated with AGi32 in addition to the filed measurements. Figure 4.29 and Figure 4.30 illustrate the distributions of the measured and calculated illuminance values. Within the 232-foot-wide measurement area, the percentages of illuminance values of greater than 0.2 fc are 100%, 77%, and 59% for HPS, LED, and calculated LED, respectively. Similar to the other study sites, there is a significant difference between the AGi32 calculations of illuminance values and the measured values for the LED luminaires. The maximum illuminance values are 4.5 fc for HPS, 2.3 fc for LED, and 3.2 fc for calculated LED.

4.3.7 HPS at Site 7 – Northwestern Avenue & Cherry in West Lafayette

This is a T intersection with HPS 200W lighting as shown in Figure 4.31. Figures 4.32 and 4.33 present the illuminance distributions. The non-symmetric pattern displayed in Figure 4.33 was caused probably by a lighting pole adjacent to the lighting pole under study. Within the measurement area of 168 feet from the lighting source, 94% of the illuminance values were above 0.2 fc.

4.3.8 HPS and CMH at Site 8 – SR 43 & I-65 North Exit Ramp in Lafayette

This is a T intersection as shown in Figure 4.34. CMH 210W luminaires were installed on the lighting pole to replace the existing HPS 400W lamps. Figure 4.35 shows the nighttime views of the two types of lightings. Figures 4.36 and 4.37 present the illuminance distributions. All 108 measured illuminance values are above 0.2 fc for both types of luminaires. It is clear that with much lower power of the CMH 201W, the new luminaries provided sufficient lighting at the intersection.

4.3.9 LED at Site 9 – Hazel Dell Parkway & East 131 Street in Carmel

This roundabout junction in Carmel was lighted with LED 142W as shown in Figure 4.38. The measured illuminance values around the lighting pole are plotted in Figures 4.39 and 4.40. Within the 150 feet measured distance, 63% of the illuminance values were above 0.2 fc.

4.3.10 LED at Site 10 – 96th Street & Westfield Boulevard in Carmel

At this roundabout (Figure 4.41), there were four lighting poles with MH 250W luminaires at the time when the illuminance was measured. The illuminance values were very low, only 22% were above 0.2 fc and the maximum measured illuminance value was only 0.37. It was found that the MH 150W luminaires were to be replaced because of their old age. The luminaires were replaced with new LED luminaires after the measurement.

4.3.11 LED at Site 11 – SR 130 East & Sturdy Road in Valparaiso

At this roundabout (Figure 4.44), the area between two lighting poles with LED 80W luminaires were measured for the illuminance. The two lighting poles were 104 feet apart and the illuminance distributions are shown in Figures 4.45 and 4.46. As can be seen in Figure 4.46, the measured illuminance in the range between -40 feet and 112 feet were all above 0.2 fc.

4.3.12 MH at Site 12 – Yeager Road & Northwestern Avenue in West Lafayette

This is a roundabout junction lighted with MH 250W luminaires. The photo map and the night view of the lighting are shown in Figure 4.47. The illuminance levels were measured in an area with two lighting poles. Figures 4.48 and 4.49 are the illuminance distributions within a distance range of 176 feet. Majority of the measured illuminance values (85 out of 92) were above 0.2 fc with a maximum illuminance value of 1.39 fc.

4.3.13 LED at Site 13 – Poland Hill Road & Twyckenham Boulevard in Lafayette

This is a roundabout junction lighted with LED 130W luminaires. The photo map and the night view of the lighting are shown in Figure 4.50. Figures 4.51 and 4.52 are the illuminance distributions within a distance range of 192 feet. Of the measured illuminance values, 87% were above 0.2 fc with a maximum illuminance value of 2.63 fc.

4.3.14 HPS, LED, and CMH at Site 14 – US 231 & I-74 in Crawfordsville

There are three high mast towers at this interchange as shown in Figure 4.53. On each tower, there are six luminaires. On Tower 1 (T1), LED 240W luminaires were installed to replace the HPS 1000W lamps. On Tower 3, CMH 375W luminaires were installed to replace the HPS 1000W. On Tower 2 (T2), LED 392W were installed in 2013 for a previous study. Therefore, illuminance values for T2 were measured in 2013, 2014, and 2015.

The layouts for illuminance measurements are illustrated in Figure 4.54. The measurement points were spread on the circles 40 feet apart around the tower. As shown in the layouts, the measurements were made along six directional lines (N, S, NW, SE, NE, and SW) for T1 and T3, and along eight directional lines (N, S, W, E, NW, SE, NE, and SW) for T2. This was because there were some geometric limitations around T1 and T3 in the field.

Figure 4.55 shows the illuminance distributions for the LED 240W and HPS 1000W luminaires at T1. All of the measured illuminance values were above 0.2 fc in all directions for both types of the luminaires. It should be noted that with six luminaires on the tower, six LED 240W luminaires would save considerable amount of electricity usage in comparison with six HPS 1000W lamps.

Figure 4.56 presents the illuminance distributions of three years for LED 392W luminaires at T2. As indicated by the maximum illuminance values in the past three years (1.746 fc, 1.668 fc, and 1.227 fc), the lighting efficiency gradually decreases with time. It should be noted that the burned out drivers observed in 2014 could also be a factor contributing to the drop in illuminance.

The illuminance distributions at T3 are plotted in Figure 4.57 for the HPS and CMH luminaires. One of the six CMH luminaires was out of order when the measurements were made. Because of this, the illuminance values of the two types of luminaires are not directly comparable.

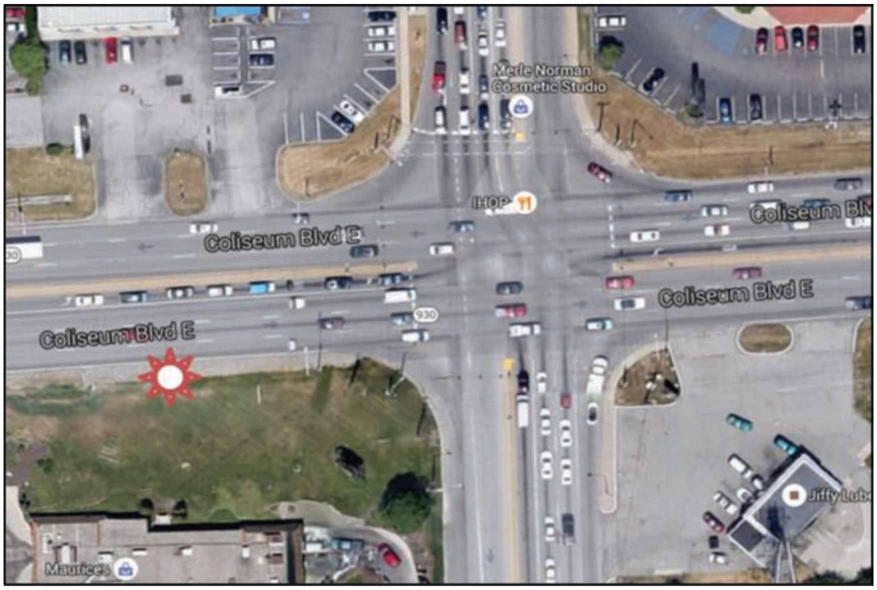
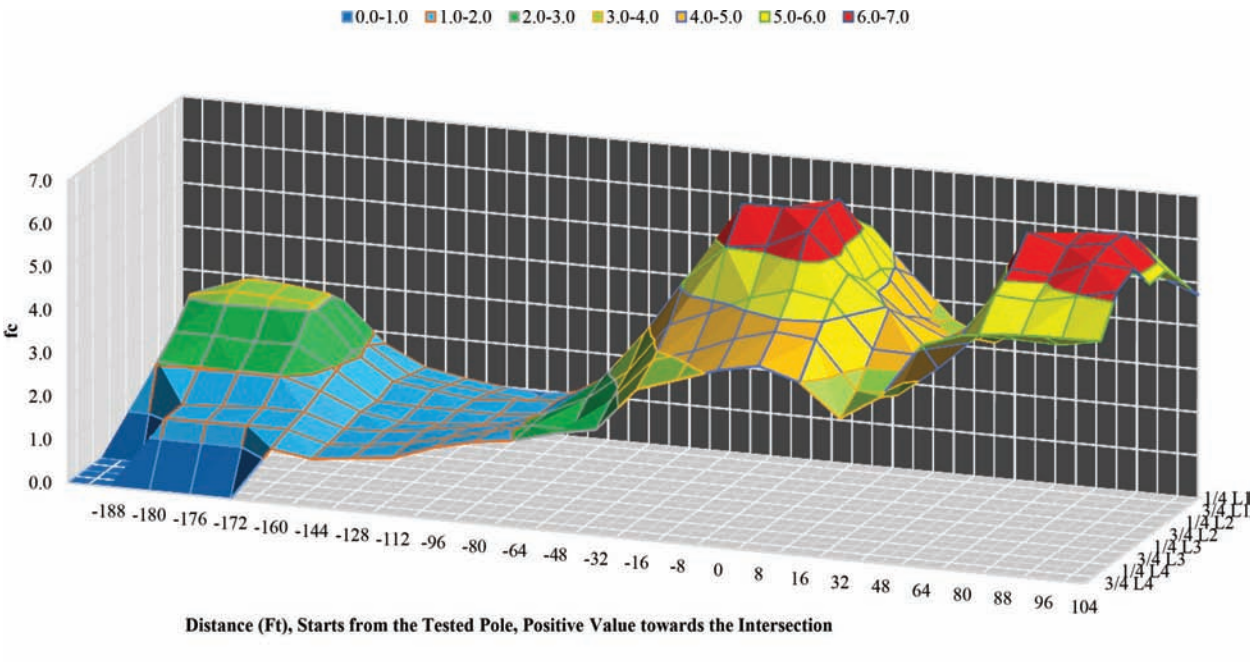
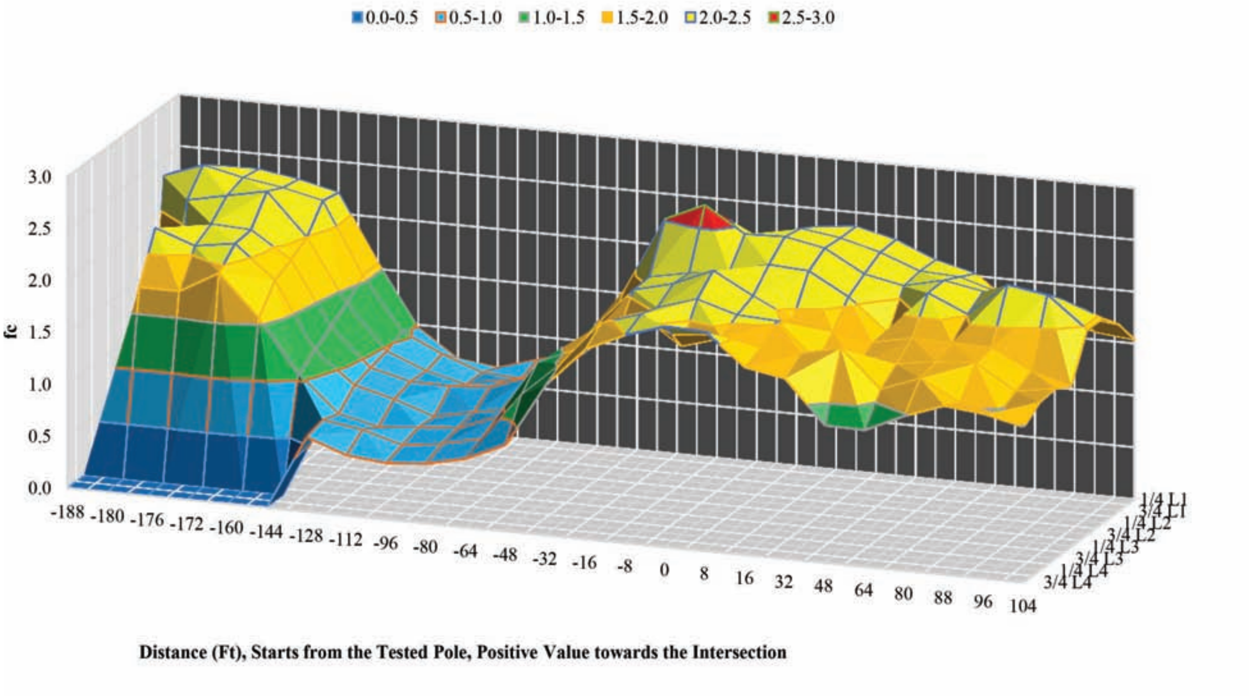


Figure 4.9 Map of Test Site 1.

Figure 4.10 HPS 400W (left) and LED 260W (right) at Test Site 1.

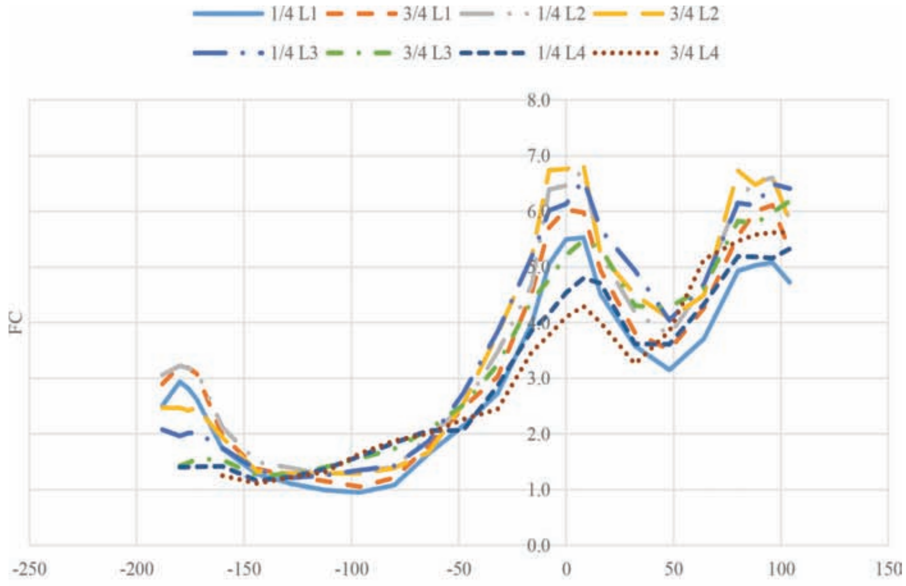


(a) HPS 400W

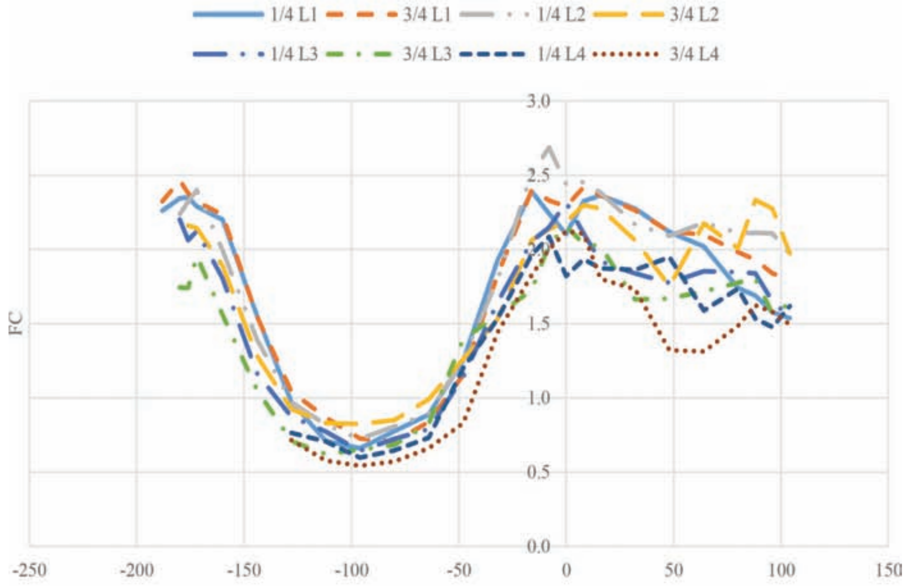


(b) LED 260W

Figure 4.11 Illuminance footprints at Site 1.



(a) HPS 400W



(b) LED 260W

Figure 4.12 Longitudinal illuminance distributions at Site 1.

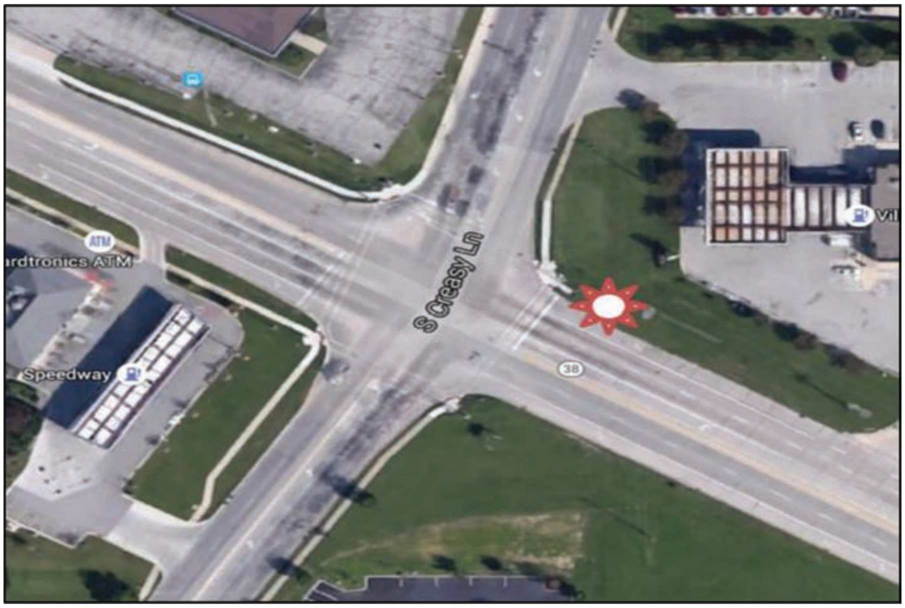
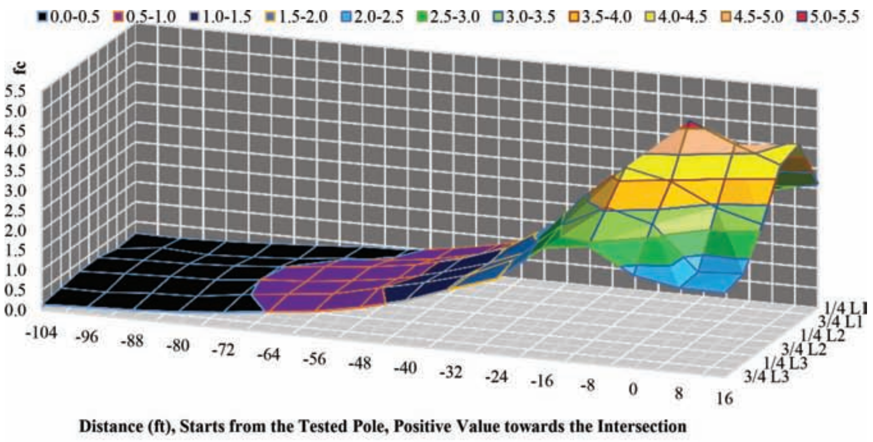
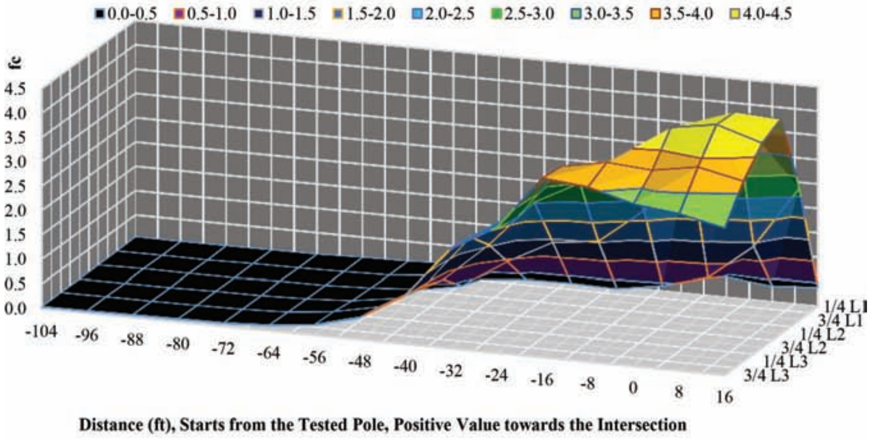


Figure 4.13 Map of Test Site 2.

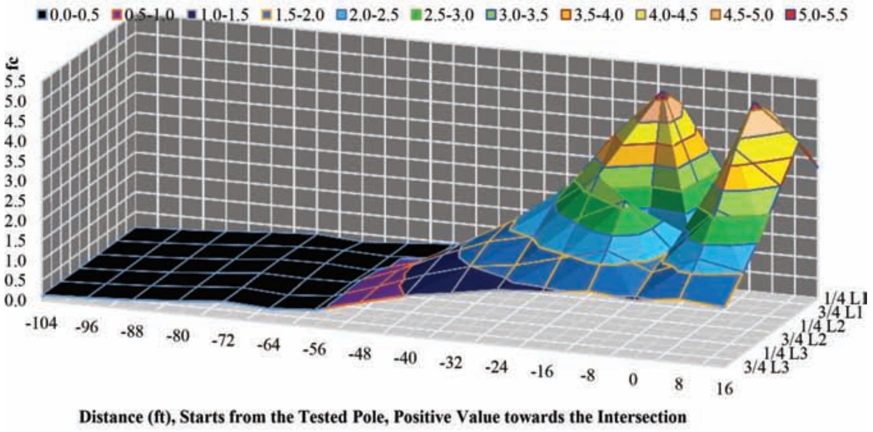
Figure 4.14 HPS 250W (left) and plasma 270W (right) at Test Site 2.



(a) HPS 250W

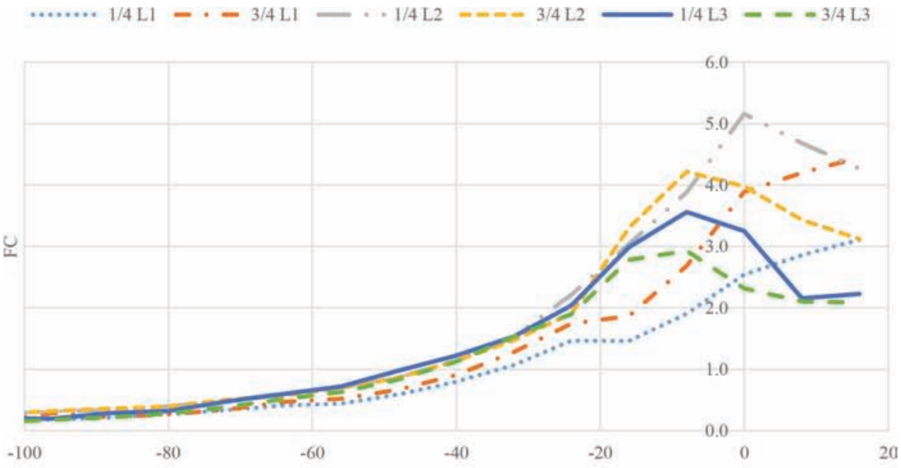


(b) Plasma 270W

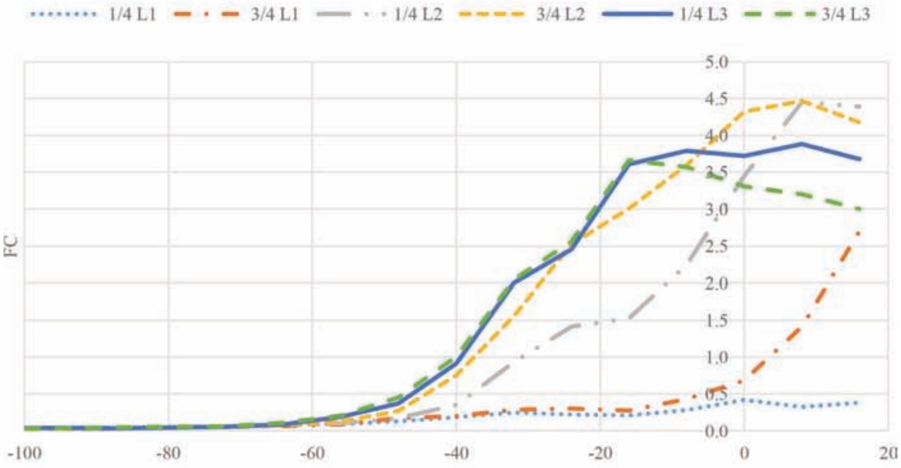


(c) AGi32 Calculated Illuminance of Plasma 270W

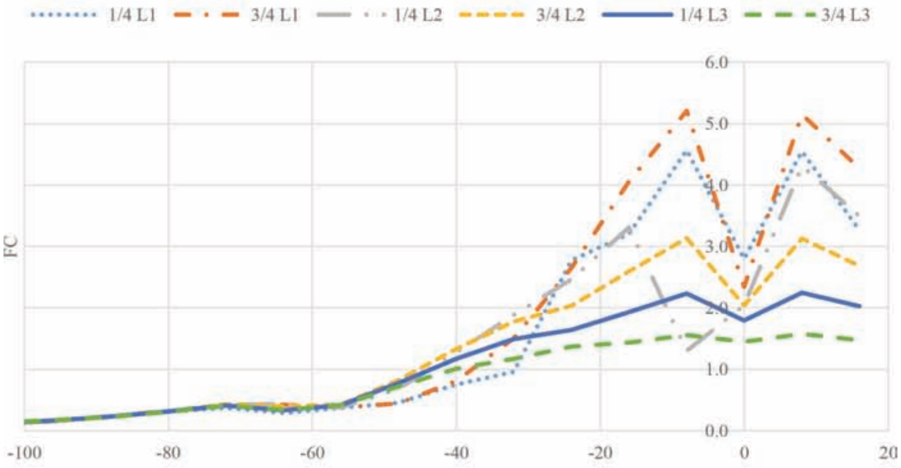
Figure 4.15 Illuminance footprints at Site 2.



(a) HPS 250W



(b) Plasma 270W



(c) AGi32 Calculated Illuminance of Plasma 270W

Figure 4.16 Longitudinal illuminance distributions at Site 2.

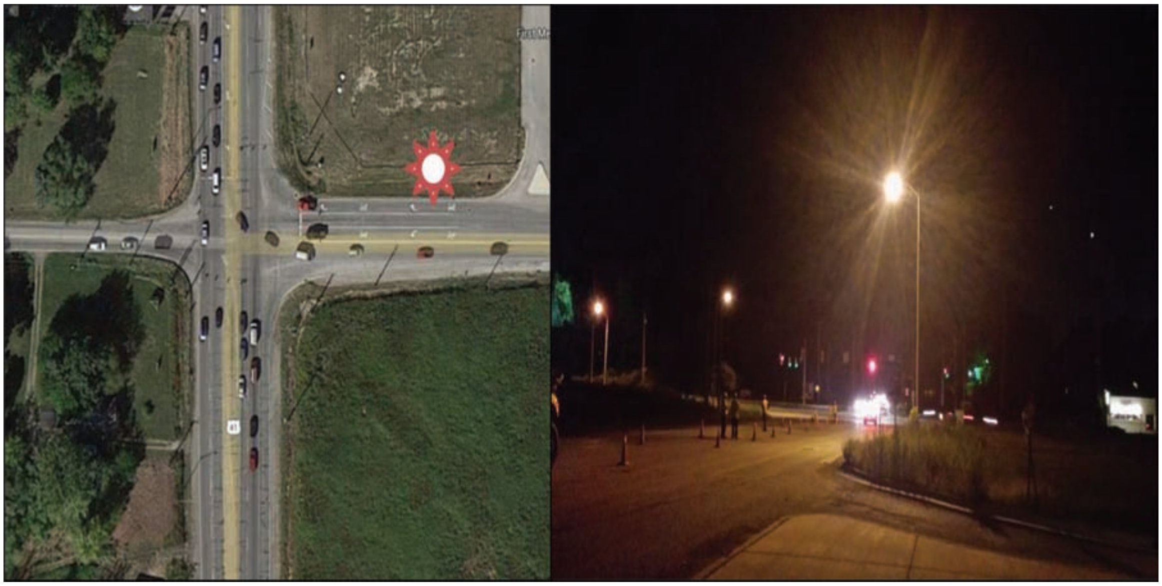


Figure 4.17 Map of Test 3 and HPS 250W.

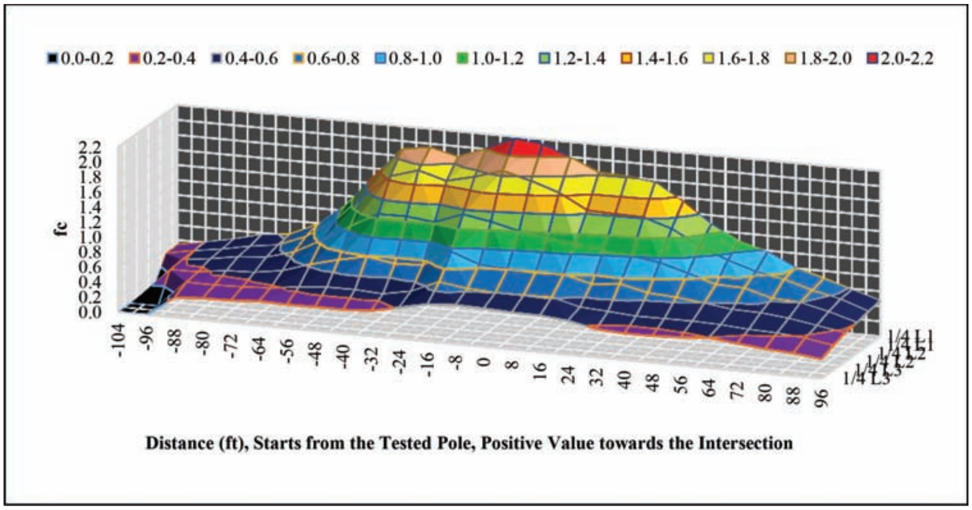


Figure 4.18 Illuminance footprints at Site 3.

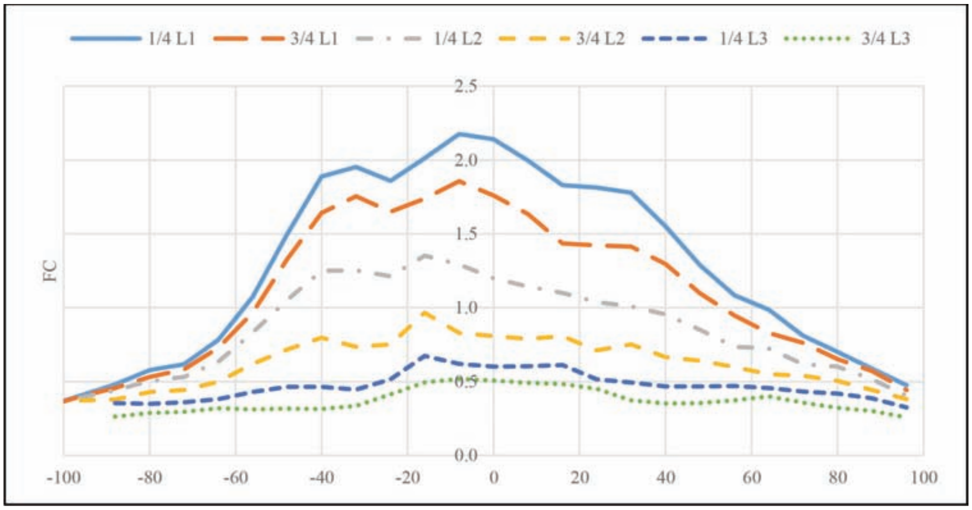
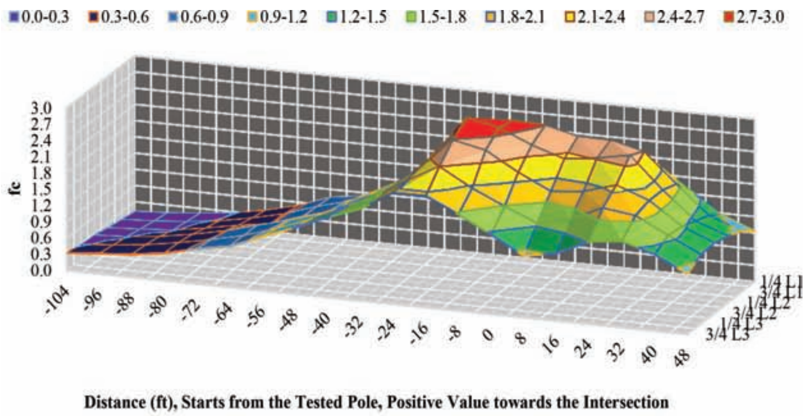


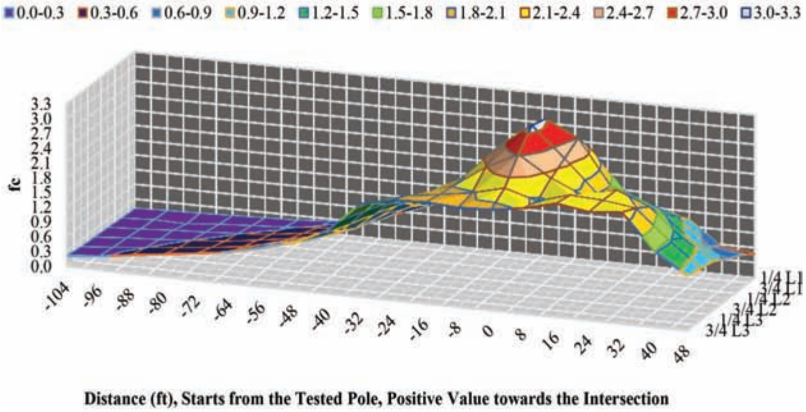
Figure 4.19 Longitudinal illuminance distributions at Site 3.

Figure 4.20 Map of Test Site 4.

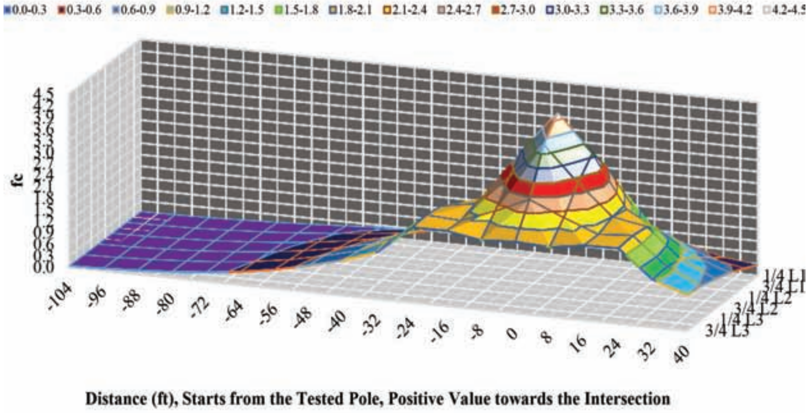
Figure 4.21 HPS 250W (left) and LED 168W (right) at Site 4.



(a) HPS 250W

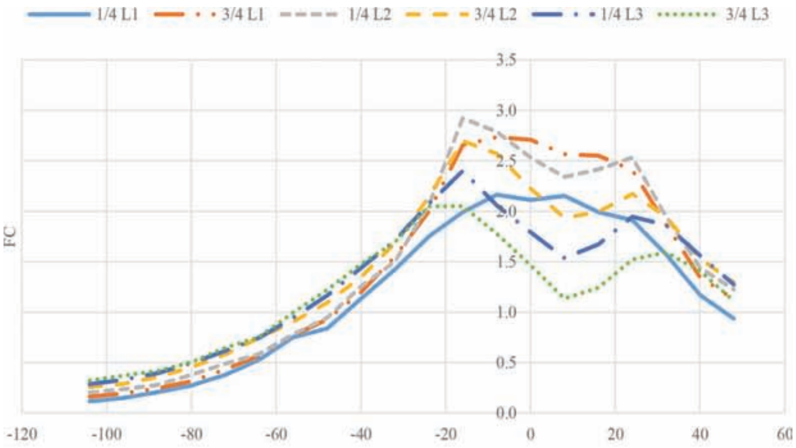


(b) LED 168W

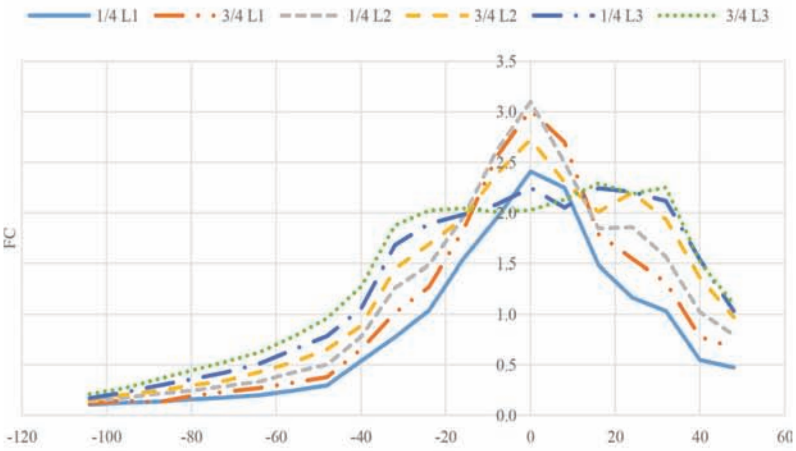


(c) AGi32 Calculated LED 168W

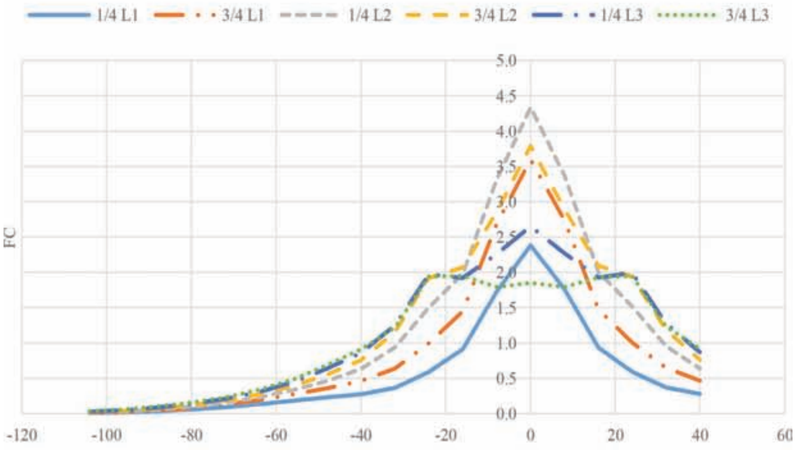
Figure 4.22 Illuminance footprints at Site 4.



(a) HPS 250W



(b) LED 168W



(c) AGi32 Calculated LED 168W

Figure 4.23 Longitudinal illuminance distributions at Site 4.

Figure 4.24 Map of Test Site 5.

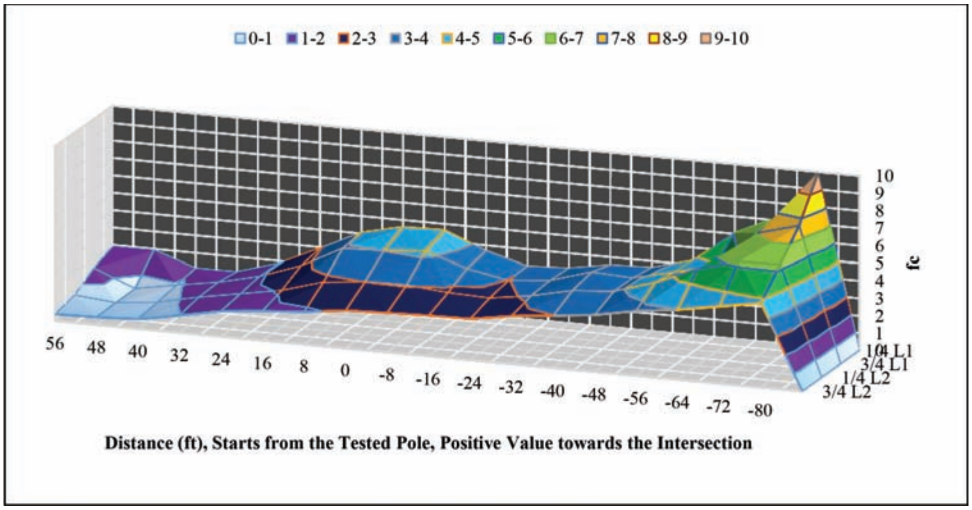


Figure 4.25 Illuminance footprints at Site 5.

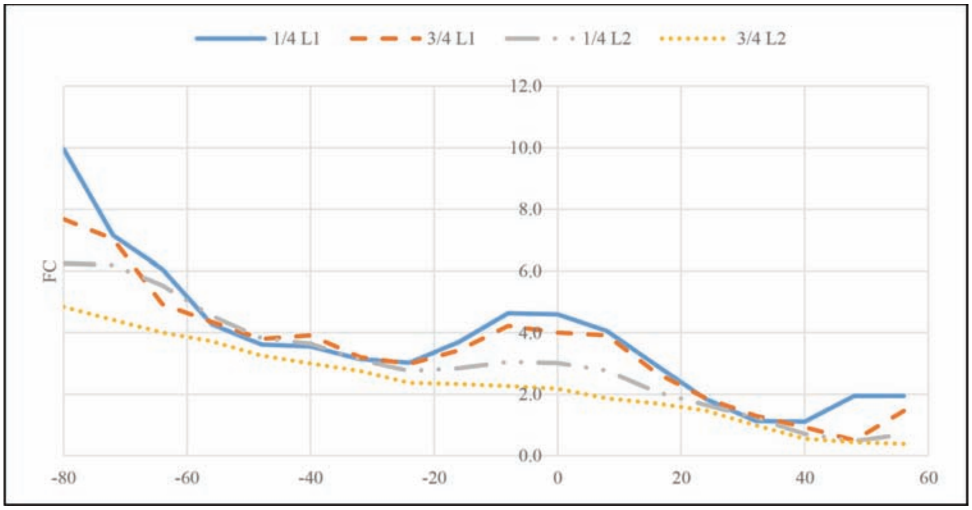


Figure 4.26 Longitudinal illuminance distributions at Site 5.

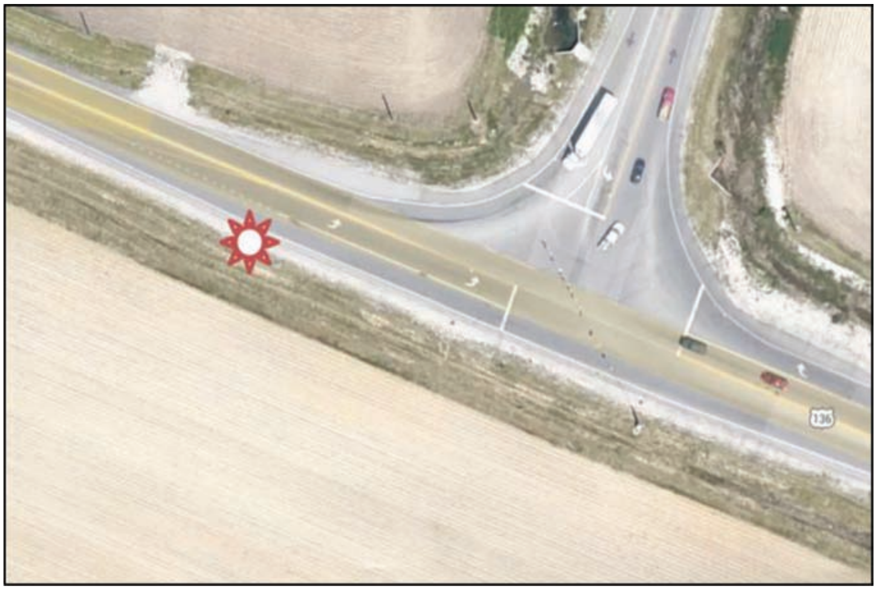
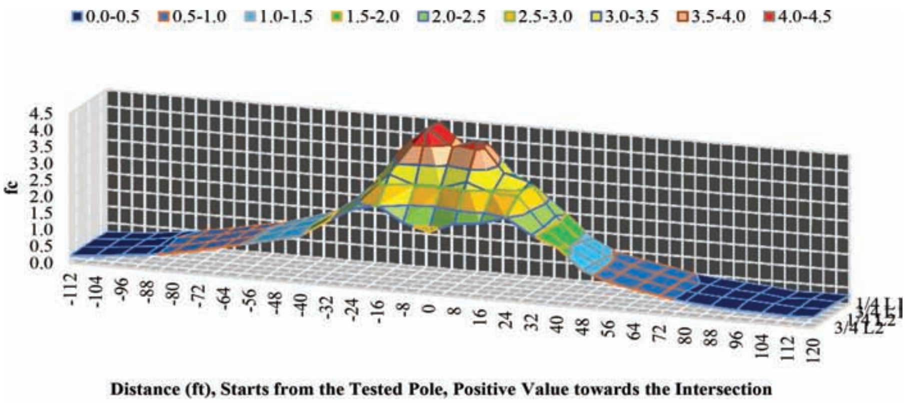
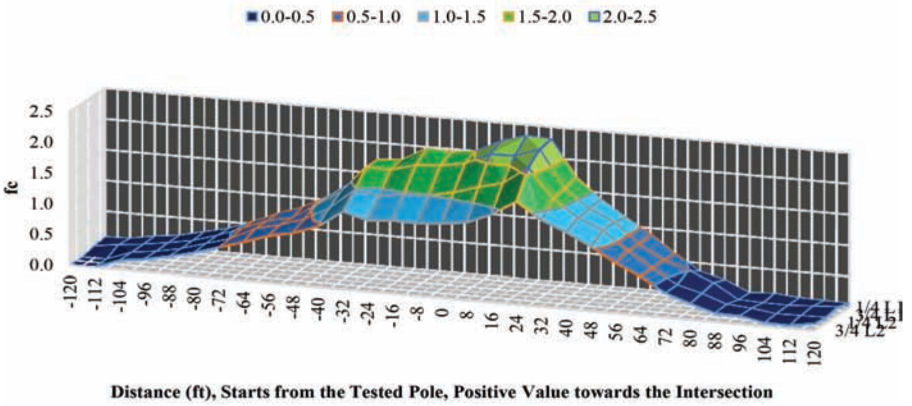


Figure 4.27 Map of Test Site 6.

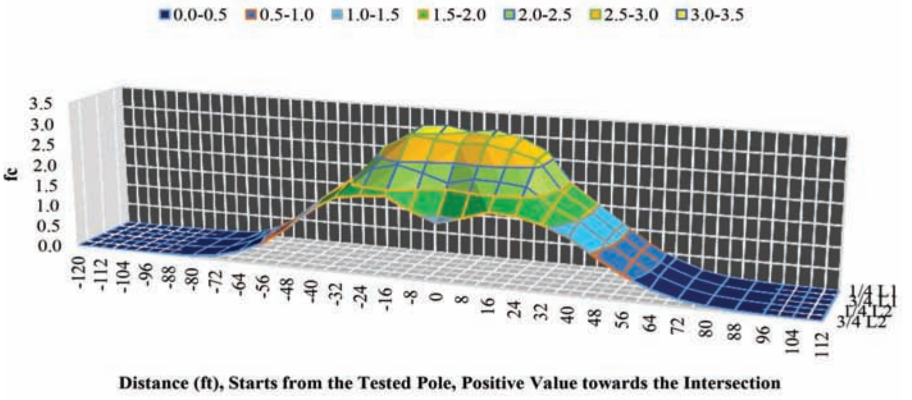
Figure 4.28 HPS 250W (left) and LED 80W (right) at Test Site 6.



(a) HPS 250W

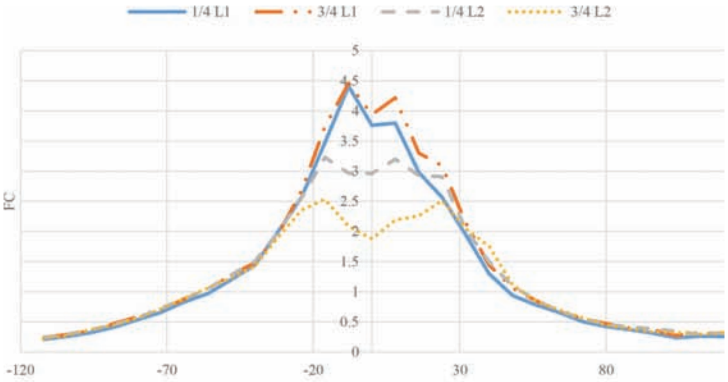


(b) LED 80W

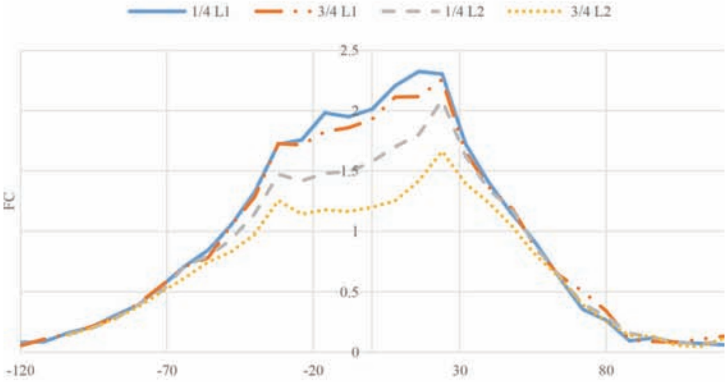


(c) AGi32 Calculated LED 80W

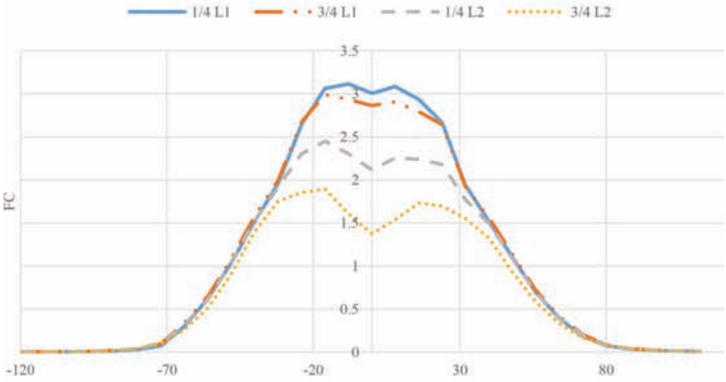
Figure 4.29 Illuminance footprints at Site 6.



(a) HPS 250W



(b) LED 80W



(c) LED 80W Simulated

Figure 4.30 Longitudinal illuminance distributions at Site 6.

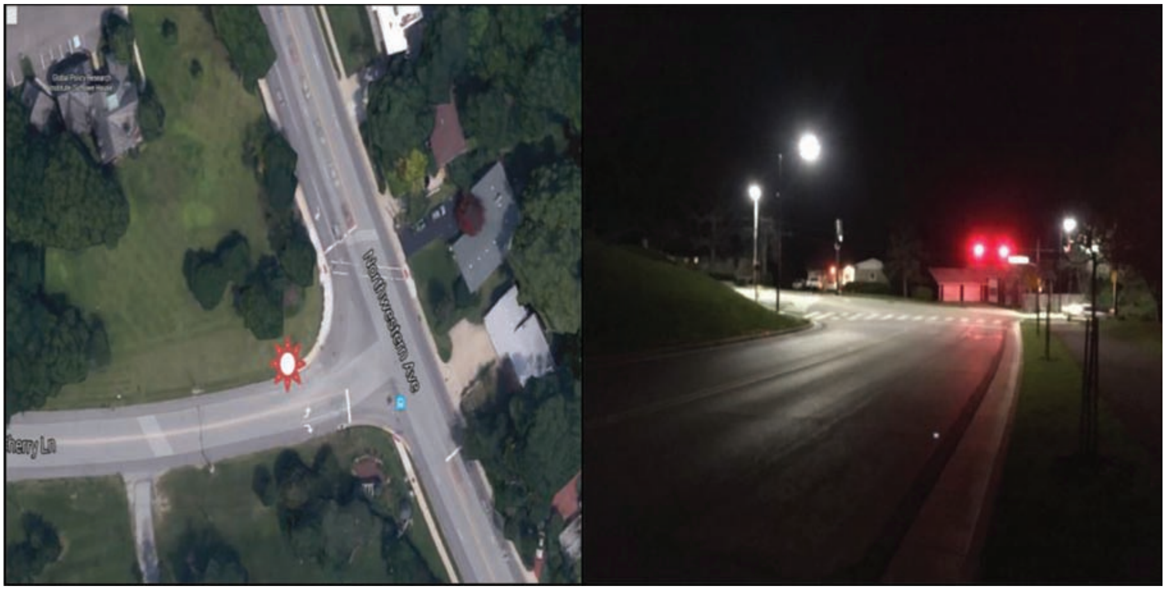


Figure 4.31 Map of Test Site 7 and nighttime HPS 200W lighting.

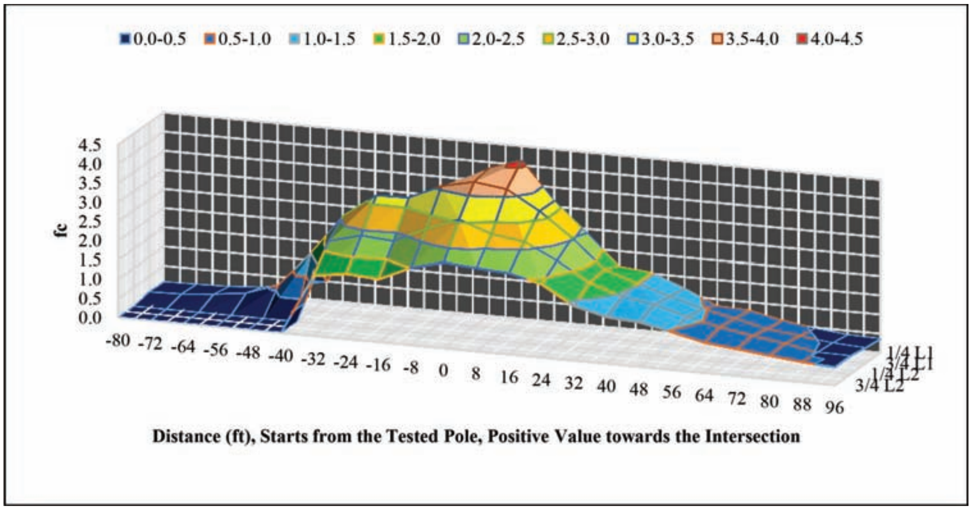


Figure 4.32 Illuminance footprints at Site 7.

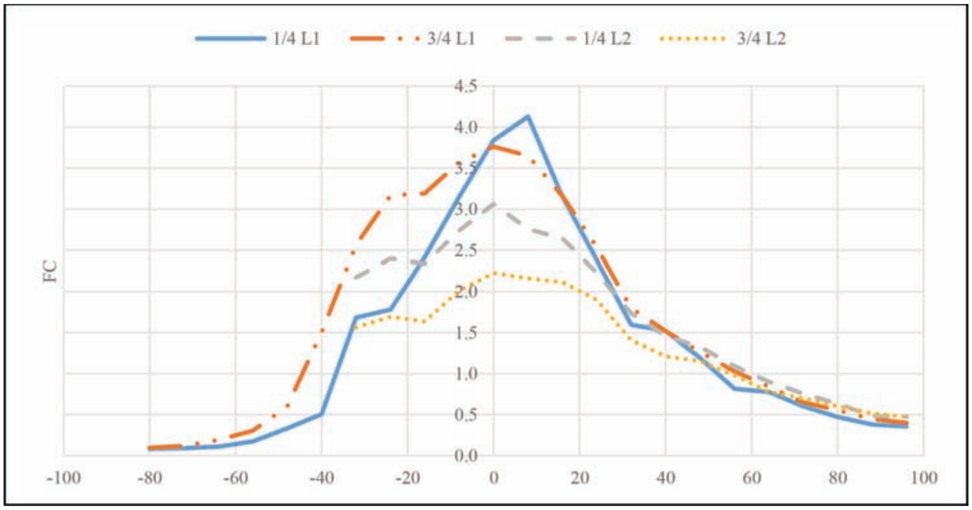


Figure 4.33 Longitudinal illuminance distributions at Site 7.

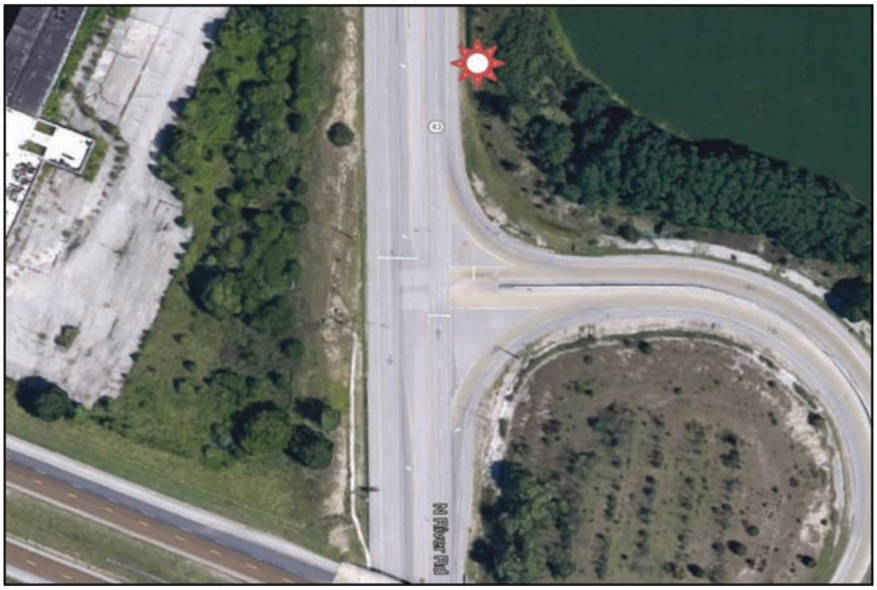
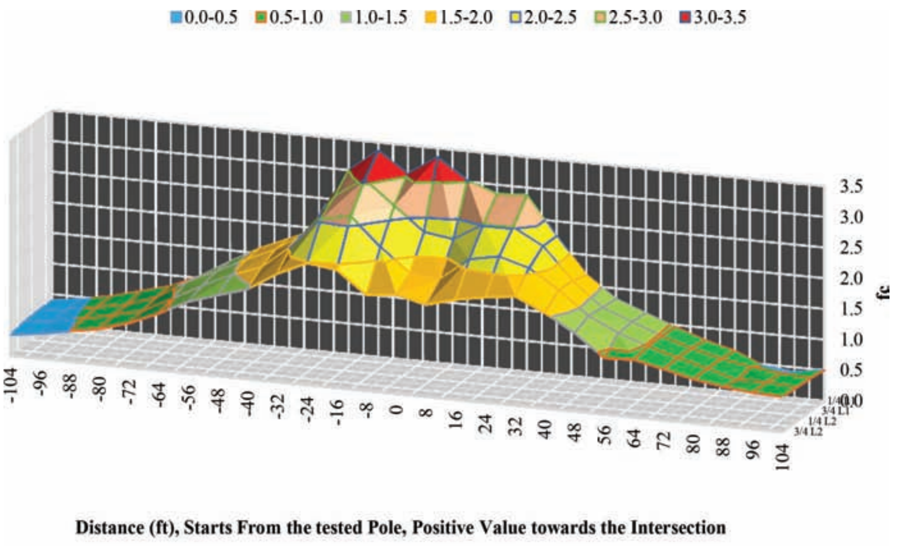
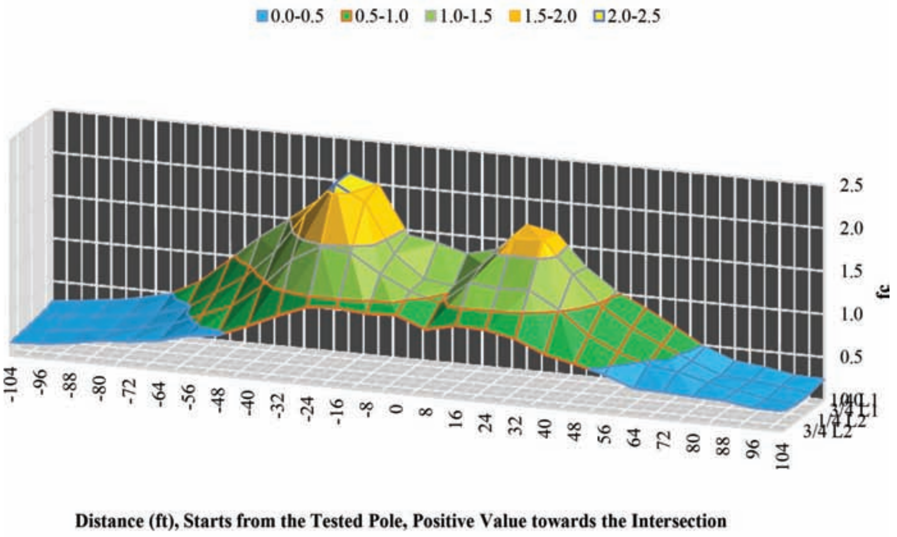


Figure 4.34 Map of Test Site 8.

Figure 4.35 HPS 400W (left) and CMH 210W (right) at Test Site 8.

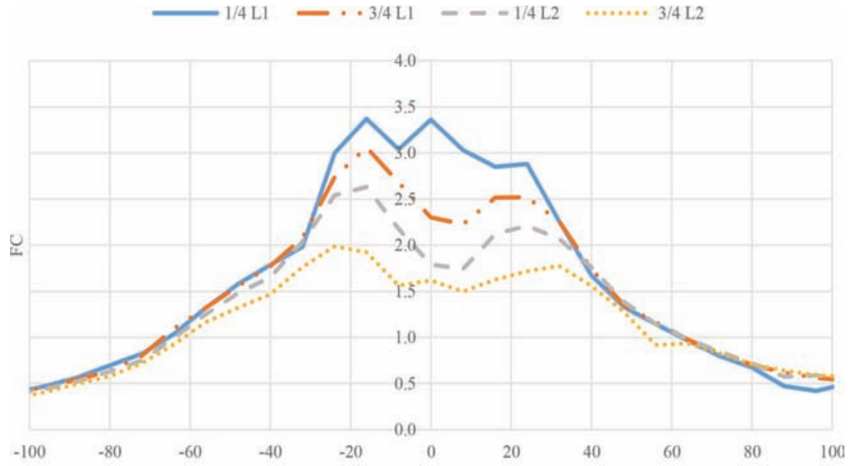


(a) HPS 400W

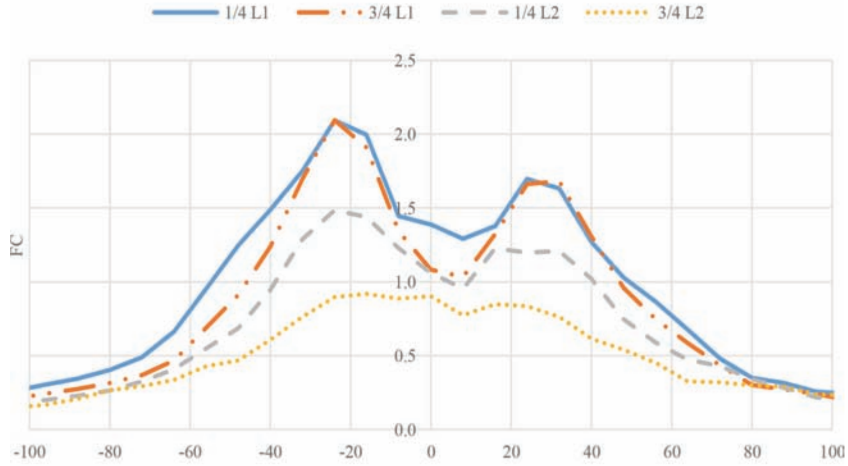


(b) CMH 210W

Figure 4.36 Illuminance footprints at Site 8.



(a) HPS 400W



(b) CMH 210W

Figure 4.37 Longitudinal illuminance distributions at Site 8.

Figure 4.38 Map of Test Site 9 and nighttime LED 142W lighting.

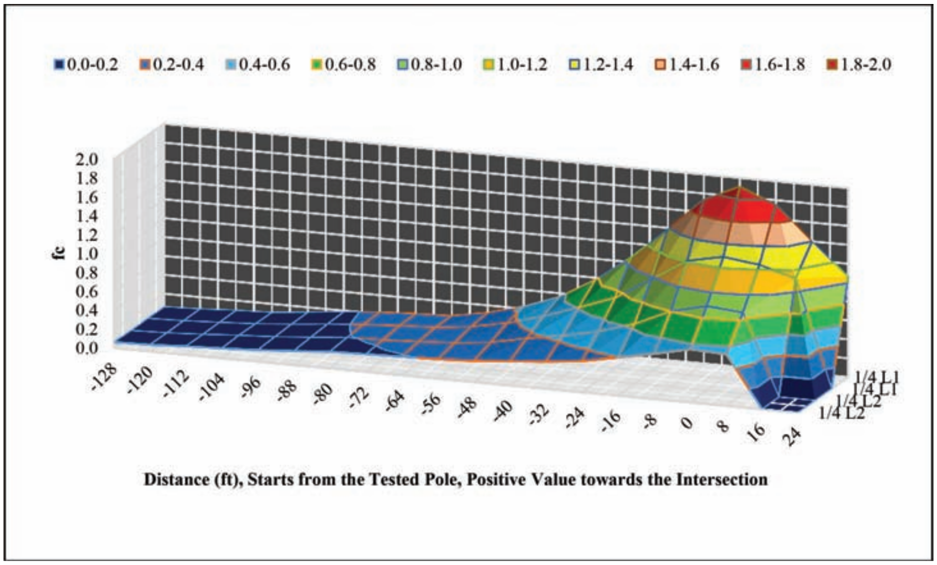


Figure 4.39 Illuminance footprints at Site 9.

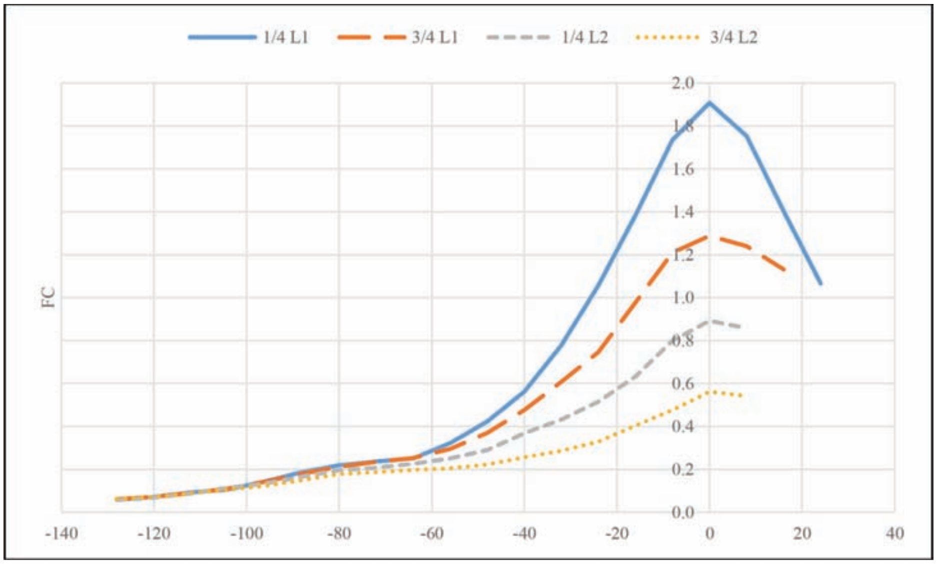


Figure 4.40 Longitudinal illuminance distributions at Site 9.

Figure 4.41 Map of Test Site 10 and MH 250W lighting.

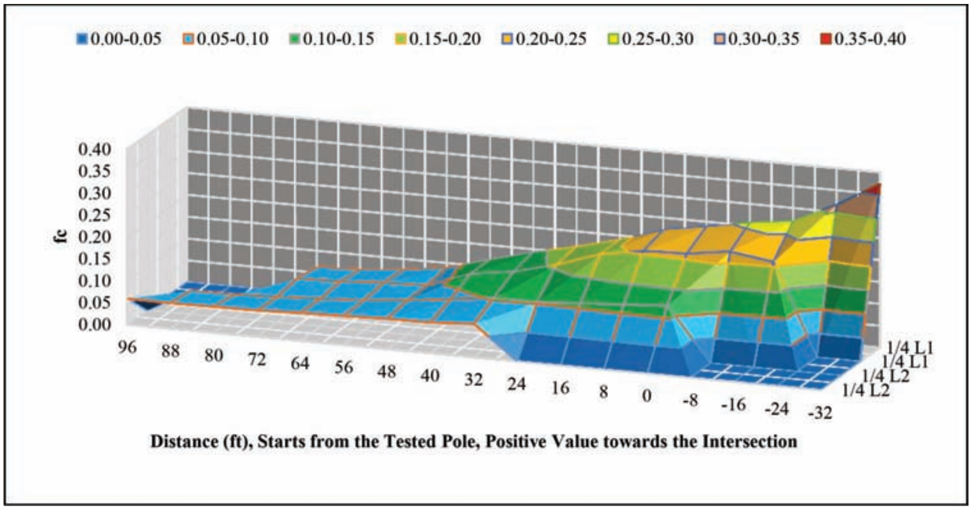


Figure 4.42 Illuminance footprints at Site 10.

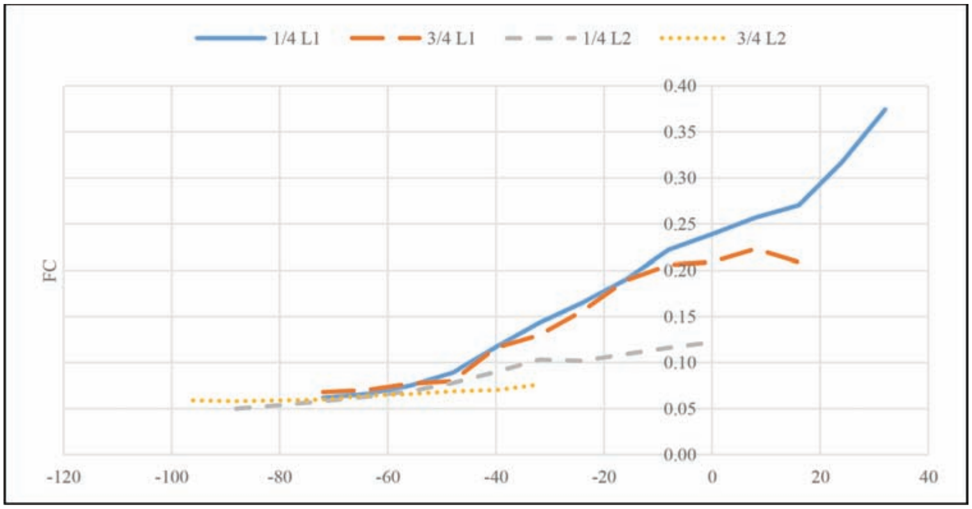


Figure 4.43 Longitudinal illuminance distributions at Site 10.

Figure 4.44 Map of Test Site 11 and nighttime LED 80W lighting.

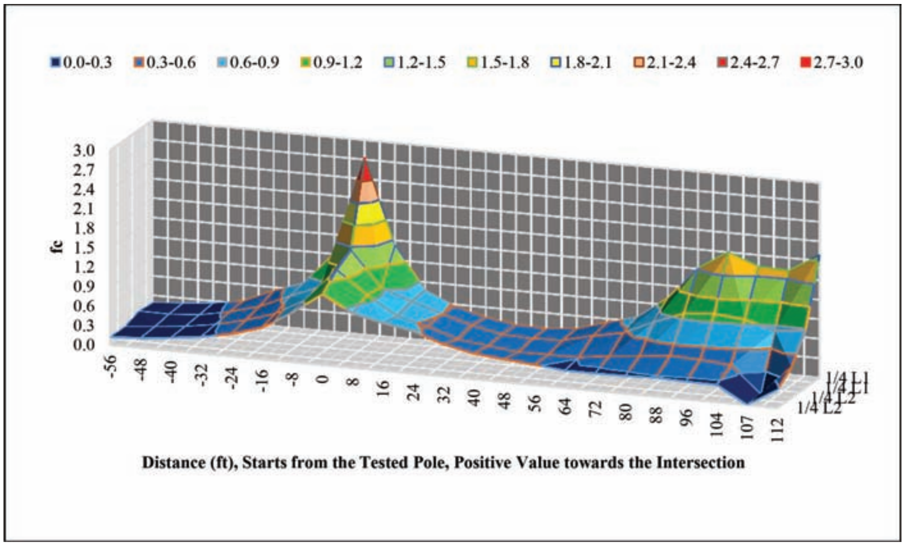


Figure 4.45 Illuminance footprints at Site 11.

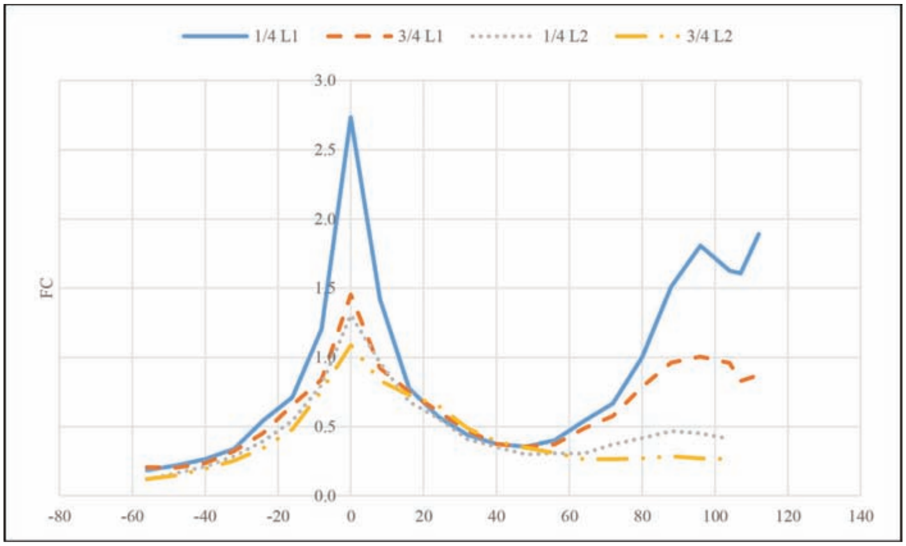


Figure 4.46 Longitudinal illuminance distributions at Site 11.

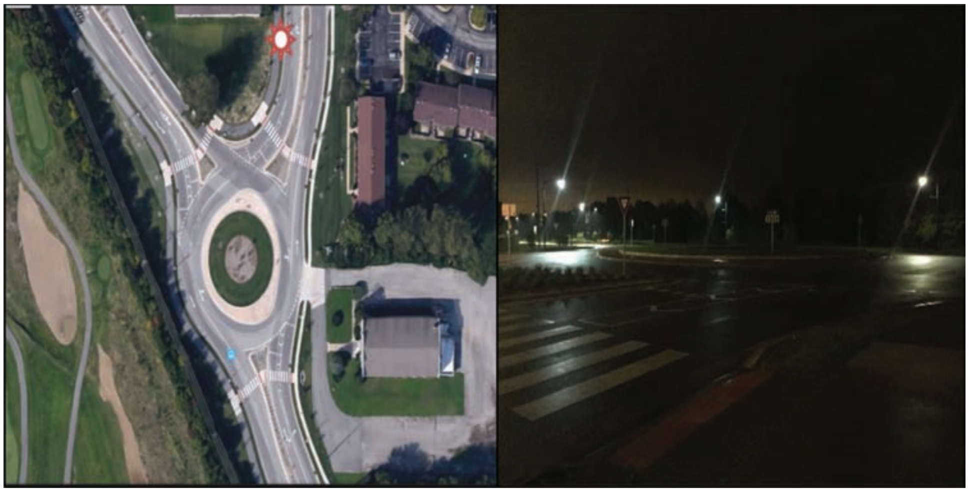


Figure 4.47 Map of Test Site 12 and nighttime MH 250W lighting.

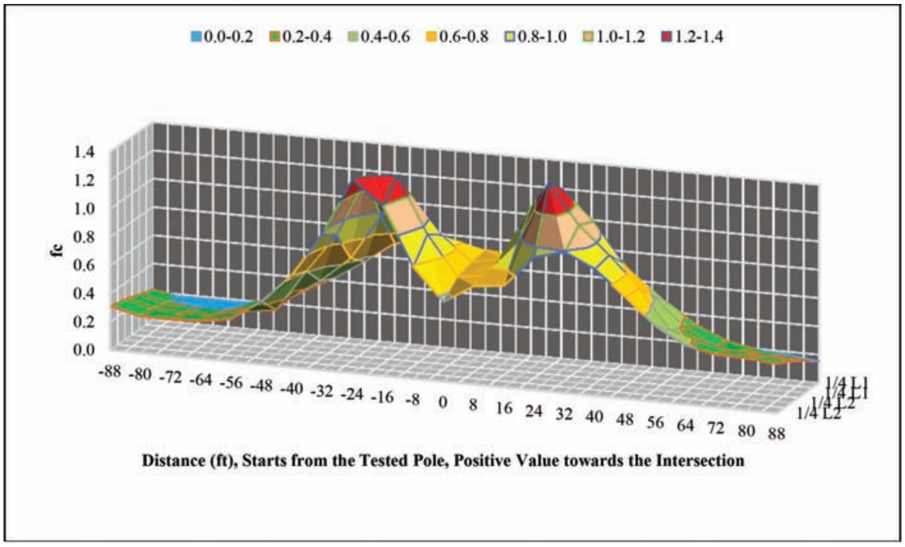


Figure 4.48 Illuminance footprints at Site 12.

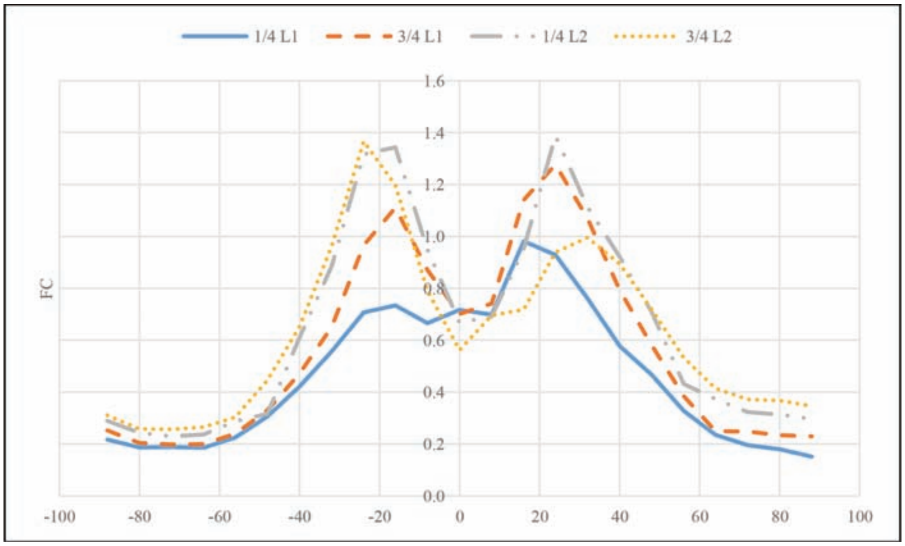


Figure 4.49 Longitudinal illuminance distributions at Site 12.

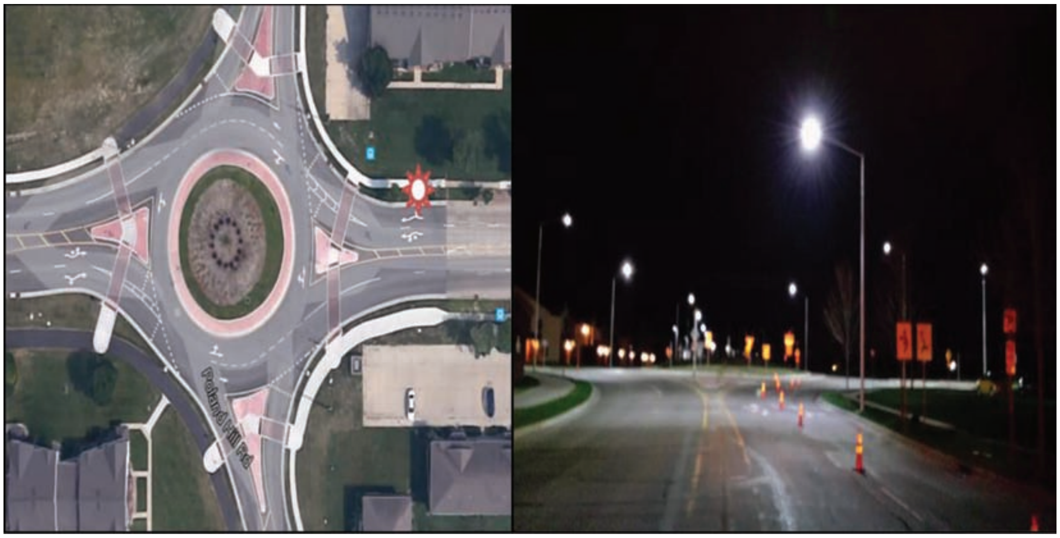


Figure 4.50 Map of Test Site 13 and nighttime LED 130W lighting.

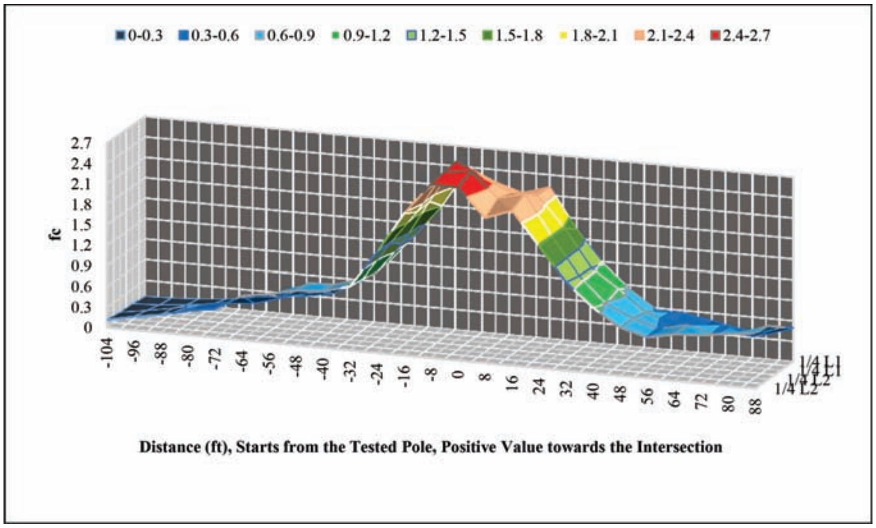


Figure 4.51 Illuminance footprints at Site 13.

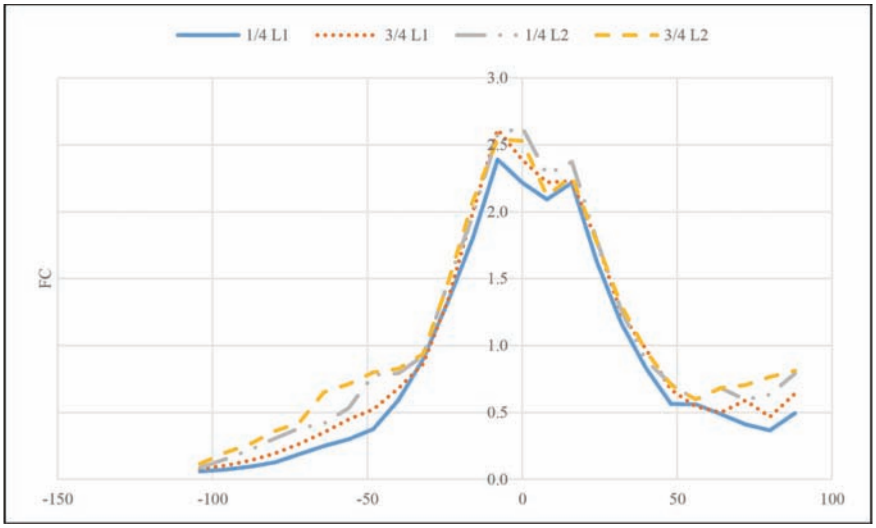


Figure 4.52 Longitudinal illuminance distributions at Site 13.

Figure 4.53 Map of Test Site 14.

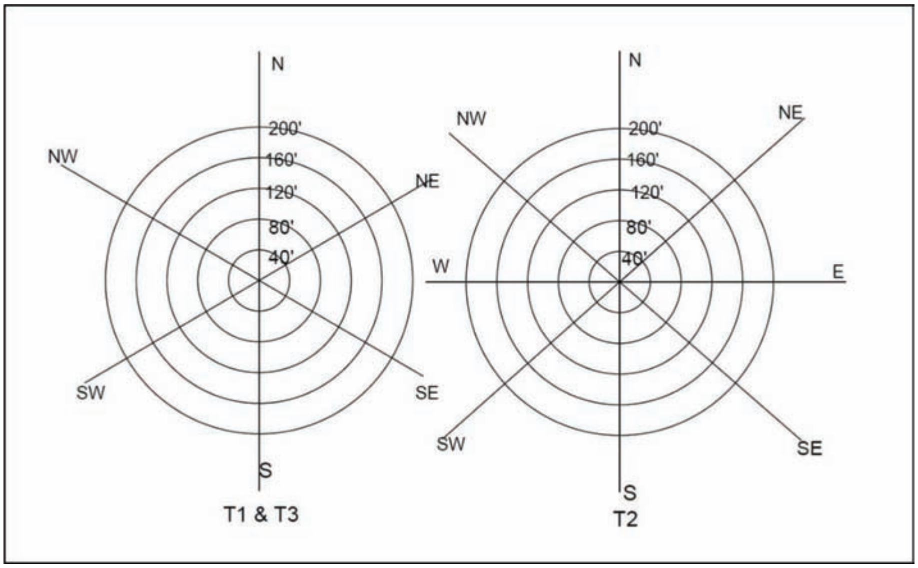
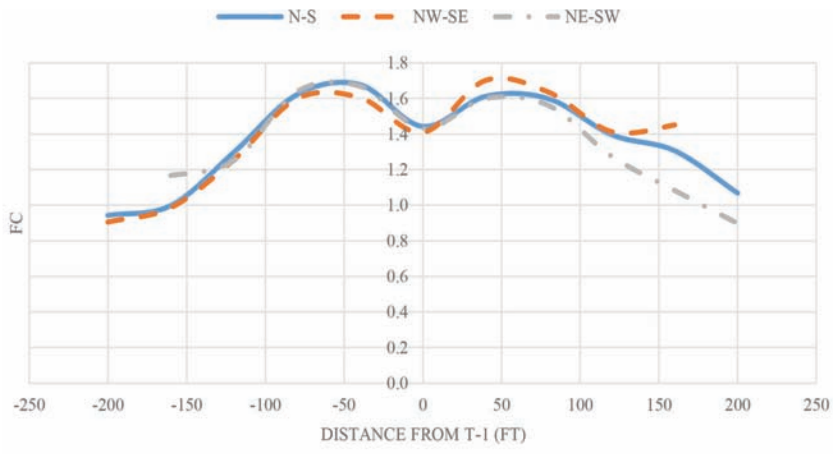
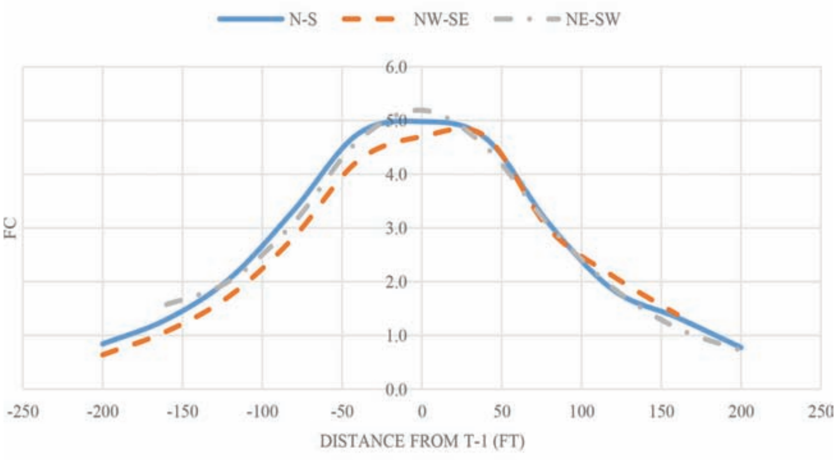


Figure 4.54 Layouts for illuminance measurements at Site 14.

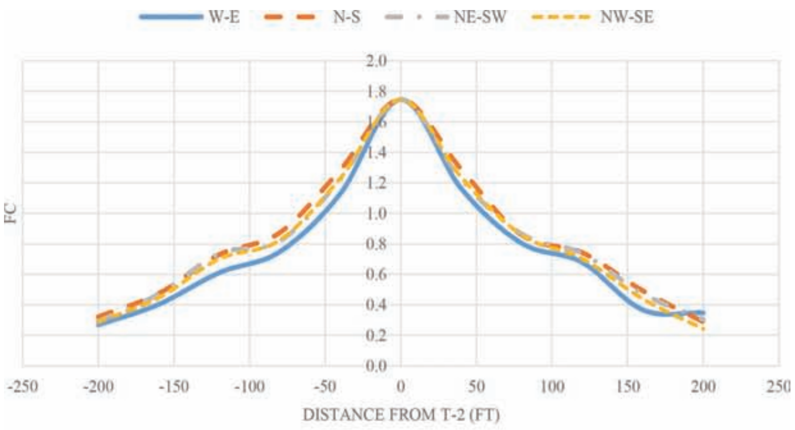


(a) LED 240W

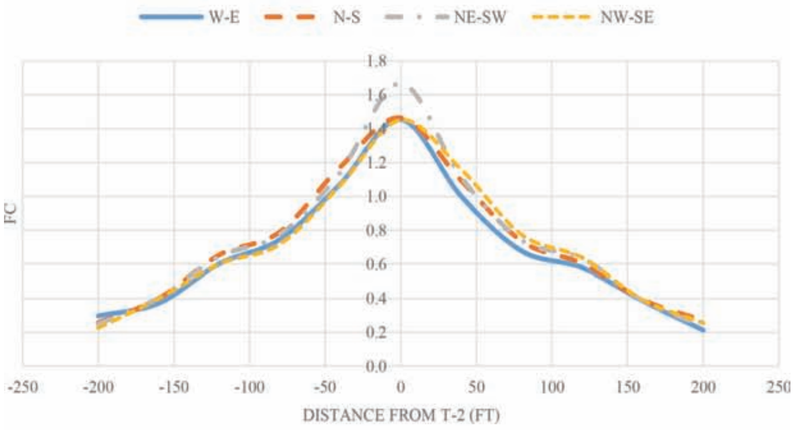


(b) HPS 1000W

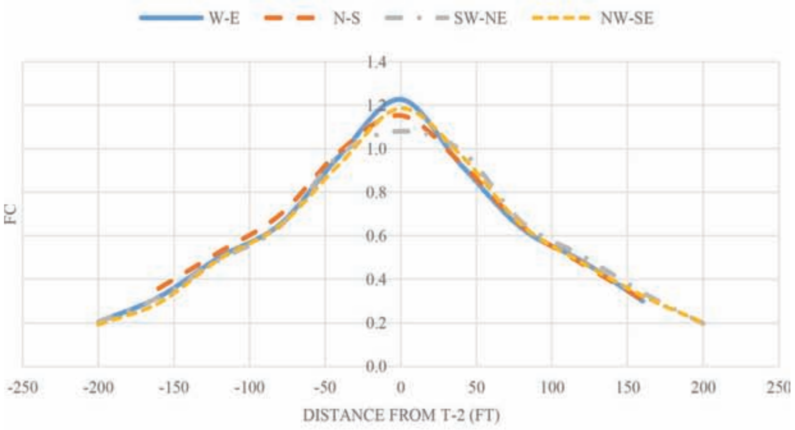
Figure 4.55 Illuminance distributions at Site 14-T1.



(a) 05/08/13

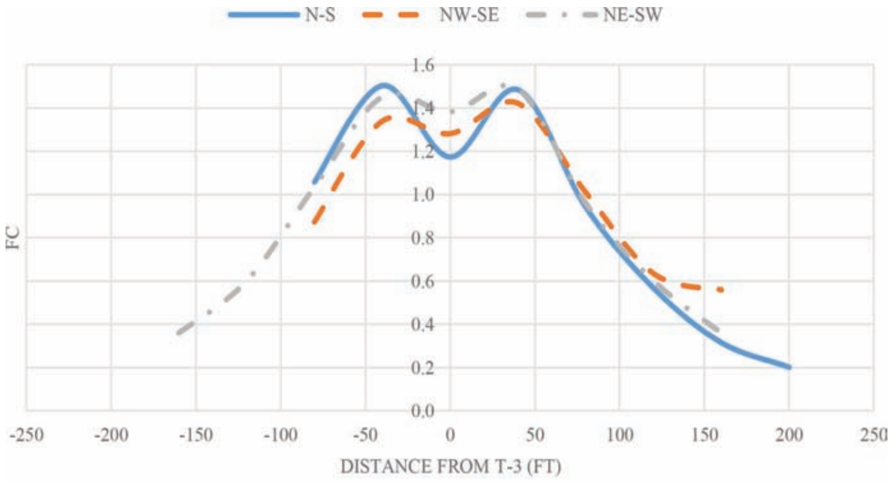


(b) 10/16/14

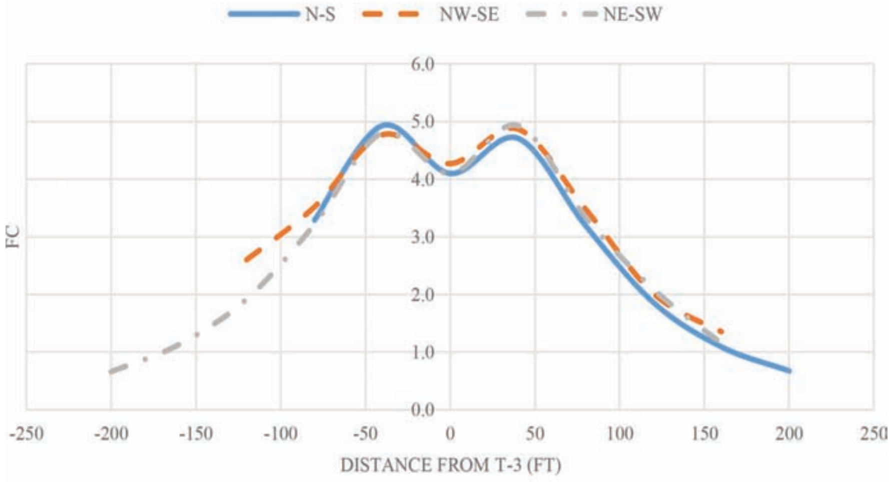


(c) 12/08/15

Figure 4.56 Illuminance distributions at Site 14-T2.



(a) CMH 375W



(b) HPS 1000W

Figure 4.57 Illuminance distributions at Site 14-T3.

4.4 Illuminance Metrics and Implications

Illuminance performances are evaluated by illuminance metrics, including indicators such as minimum illuminance, average maintained illuminance, and uniformity ratio. As discussed in the beginning of this chapter, there are several roadway lighting standards as shown in Tables 4.2 through 4.5. The minimum illuminance is provided in a standard as a threshold value required to ensure traffic safety at night. The uniformity ratio, defined as the ratio of average measured illuminance to the minimum measured illuminance, is recommended to ensure an appropriate lighting condition for drivers. With the minimum illuminance satisfied, a lower uniformity ratio will ensure the evenness of the light on the road surface.

Field measurements of illuminance at intersections are different from those on non-junction roadway sections. Intersection lighting usually involves isolated lighting poles for a limited area, while non-junction roadway lighting provides lighting for a relatively long roadway segments with regularly spaced lighting poles. Therefore, for intersection lighting, it is necessary to determine the measuring lighting area or distance for a given lighting system at the intersection. Based on the Indiana Design Manual, roadway lighting includes short, medium, and long light distributions. A short distribution is capable of providing enough luminous intensity within a range of between 1 and 2.25 mounting heights from the luminaire, a medium distribution between 2.25 and 3.75 mounting heights, and a long distribution between 3.75 and 6 mounting heights. The

TABLE 4.9
Summary of Illuminance Metrics

#	Lamp Type	Measured One Side Distance (ft)	Min (fc)	Max (fc)	Average (fc)	UR (Avg/Min)	Effective Distance (feet when UR ≤ 4.0)	Average by Effective Distance (fc)
1	HPS 400W	188	0.95	6.82	3.51	3.69	188	3.51
2	HPS 250W	104	0.13	5.16	1.47	11.12	48	2.32
	Plasma 270W	104	0.02	4.47	1.07	46.34	N/A*	N/A
3	HPS 250W	104	0.26	2.18	0.80	3.07	104	0.80
4	HPS 250W	104	0.12	2.92	1.33	11.33	64	1.65
	LED 168W	104	0.11	3.10	1.15	10.95	40	1.77
5	LED 109W	80	0.39	9.95	3.16	8.16	32	2.70
6	HPS 250W	120	0.21	4.46	1.31	6.23	80	1.73
	LED 80W	120	0.05	2.32	0.86	17.92	72	1.26
7	HPS 200W	96	0.08	4.13	1.51	18.89	32	2.34
8	HPS 400W	104	0.35	3.37	1.38	3.96	104	1.38
	CMH 210W	104	0.15	2.10	0.77	5.12	80	0.92
9	LED 142W	128	0.06	1.91	0.46	8.00	88	0.59
10	MH 150W	96	0.05	0.37	0.13	2.52	96	0.13
11	LED 80W	112	0.12	2.73	0.61	5.11	48	0.60
12	MH 250W	88	0.15	1.39	0.58	3.79	88	0.58
13	LED 130W	104	0.06	2.63	0.98	16.29	48	1.51
14-T1	HPS 1000W	200	0.64	5.19	2.68	4.19	–	–
	LED 240W	200	0.90	1.70	1.37	1.53	–	–
14-T2	LED 392W in 2013	200	0.24	1.75	0.79	3.28	–	–
	LED 392W in 2014	200	0.21	1.67	0.70	3.30	–	–
	LED 392W in 2015	200	0.19	1.23	0.61	3.18	–	–
14-T3	HPS 1000W	200	0.66	4.93	3.00	4.56	–	–
	CMH 375W	200	0.20	1.50	0.94	4.68	–	–

*Plasma 270W cannot achieve UR ≤ 4 with any measuring distance.

long light distribution is rarely used for intersection lighting, so illuminance should be measured with an area that medium or short light distribution can cover. During the testing, researchers in this study tried to measure the illuminance with a distance from the pole as far as possible. The illuminance metrics for the study sites are presented in Table 4.9. From this table, if a typical mounting height of 30 feet is chosen, it can be shown that measured areas satisfy the requirements of medium light distribution for most of the study sites.

To compare the lighting effects of the conventional HPS and the new luminaires installed at the selected sites, the key measured illuminance values can be found in Table 4.9. The INDOT standard for roadway lighting requires a minimum maintained average illuminance of 0.8 fc. The values in the table indicate that except five luminaire models, all other new and old luminaires satisfy this requirement. It should be mentioned that the minimum maintained average illuminance of 0.77 fc for CMH 210W at Site 8 is fairly close to 0.8 fc. The poor performance for MH 150W at Site 10 is due to the approaching to its end of life cycle as mentioned before. Factors that may cause deficiencies of average illuminance for the other three luminaires: LED 142W at Site 9, LED 80W at Site 11, and MH 250W at Site 12, include measured distance, type of light distribution, and wattage of luminaire.

The maximum uniformity ratio specified in the INDOT standard is 4.0. As shown in the table, most of the ratios are considerably greater than 4.0. This is because the measuring illuminance distances were not specified. Thus, as the measuring distance increases, the minimum illuminance decreases to a small level that would yield a high uniformity ratio. The maximum illuminance measuring distances for the study sites, were calculated that would make the uniformity ratio less than or equal to 4.0 as listed in the 8th column of Table 4.9. These distance values can be considered the effective distances of the intersection lighting. With the effective distances, the average illuminance would generally increase as shown in the last column of Table 4.9.

With the illuminance metrics in Table 4.9, it can be seen that luminaires of LED 168W, Horner LED 80W, and CMH 210W performed satisfactorily with lower power requirements compared to the old HPS lamps. However, the Plasma 270W luminaires at Site 2 produced less satisfactory lighting output with high electricity usage.

5. SURVEYS ON INTERSECTION LIGHTING

5.1 Survey Description

Two surveys were conducted in this study. The first survey was sent to the state highway agencies (SHA) and local cities statewide to collect information on the adoption of new lighting technologies and their applications at intersections. Participants of the survey include traffic engineers, illuminating engineers, and design engineers from SHAs and local cities. The survey contains eight questions as shown in Appendix A. The survey was sent to 48 SHAs and 12 Indiana cities and 15 SHAs and 2 local cities responded to the survey. As shown in Table 5.1, the response rate was 31.3% from SHAs and 16.7% from the local cities. The total response rate was 28.3%.

The second survey was sent to the communities near the five intersections where new types of lamps were installed to replace HPS lamps to gather information on public perceptions toward lighting improvement. As shown in Appendix B, four questions are included in the community survey. The community survey was conducted through post office mailing. The survey was conducted to seek people's opinions and comments on the performance of the five intersections with new luminaire installations. A total of 330 residential and 73 commercial addresses were identified in the neighborhoods within 200 feet to 2000 feet near the five intersections. The survey was sent out on September 19, 2015 with a response deadline of October 31, 2015. The response rates are given in Table 5.2.

5.2 The SHA Survey

Illustrated in Figure 5.1 is the geographical locations of the 15 SHAs responded to the survey. The states in green indicates that new lighting technologies have been used, while the states in yellow refer to those states that currently only use HPS lamps.

Figure 5.2 shows the numbers of agencies that use different technologies for roadway lighting in the past five years among the 17 agencies (15 SHAs and 2 local cities). Figure 5.3 shows a different distribution of lighting technology adoption. As can be seen in the figure, in the past five years, six agencies used HPS only, two agencies used LED only, and eight agencies used HPS and LED. Figure 5.4 shows the applications of various lighting technologies at different types of intersections. The assessment of the lighting performance from the agencies is presented in Figure 5.5. Table 5.3 presents the types of projects in which the agencies applied the new lighting technologies in the past five years. The proportion of agencies that include warrants in their lighting projects is shown in Figure 5.6. The major benefits and risks that were considered in lighting projects are listed in Tables 5.4 and 5.5.

The results of SHA survey indicated that new lighting technologies, especially LED, has been used at intersections by some SHAs and local cities for common

TABLE 5.1
SHA and Local City Survey Response Rates

Organizations	No. of Surveys Sent	No. of Feedbacks Received	Response Rate
SHA	48	15	31.30%
Local City	12	2	16.70%
Total	60	17	28.30%

TABLE 5.2
Community Survey Response Rates

Site #	City	New Lighting Type	No. of Commercial Address	No. of Residential Address	No. of Surveys Sent	No. of Feedbacks Received	Response Rate
2	Lafayette	Plasma	39	42	81	9	11.1%
4	W Lafayette	LED	0	64	64	8	12.5%
6	Brownsburg	LED	0	98	98	12	12.2%
12	W Lafayette	MH	18	61	79	9	11.4%
13	Lafayette	LED	16	65	81	11	13.6%
Total			73	330	403	49	12.2%

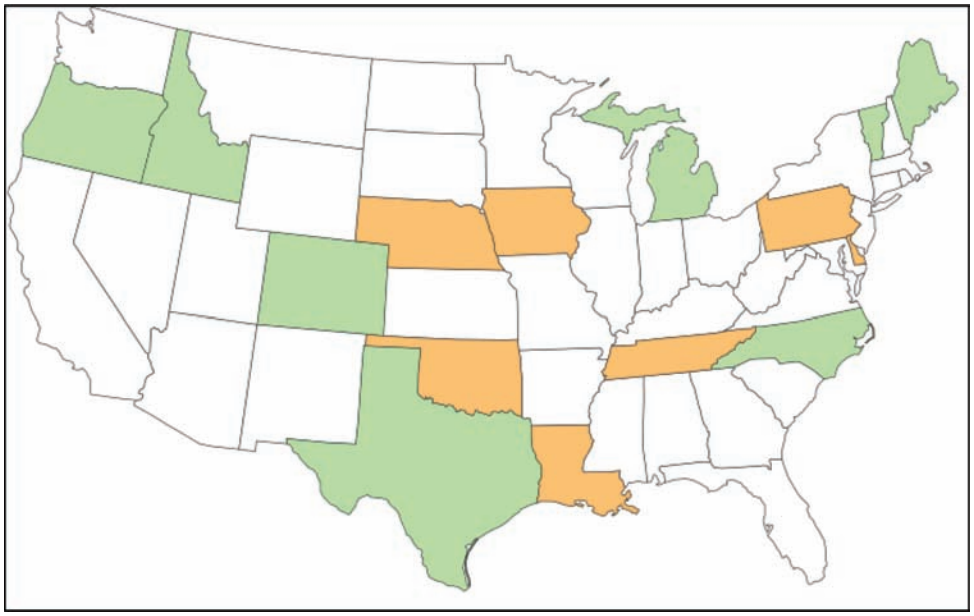


Figure 5.1 Geographical locations of SHAs responded to the survey.

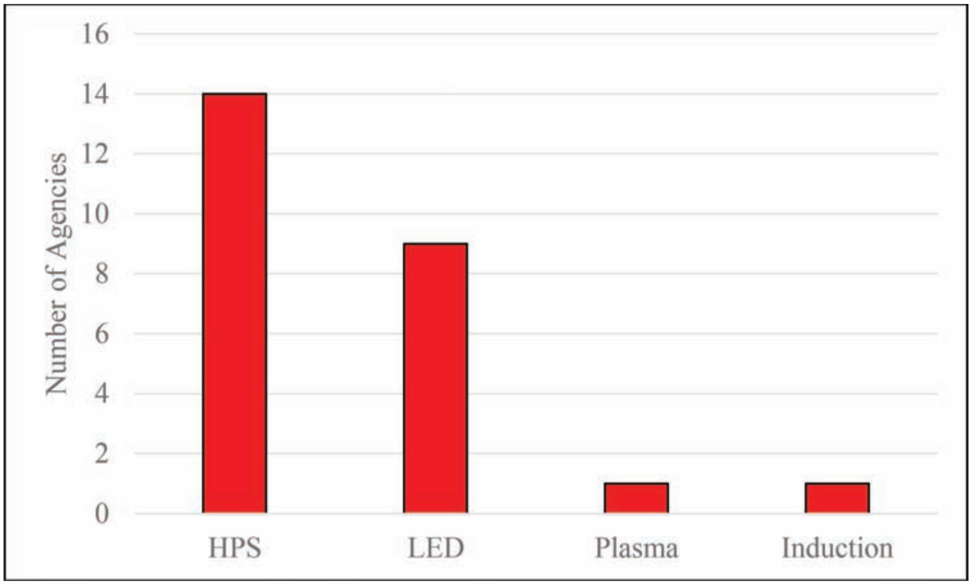


Figure 5.2 Distributions of lighting technologies adopted by agencies.

reasons including safety improvements, energy savings, and visibility improvements. The major barriers for SHAs and local cities to use new technologies are concerns of potential higher initial cost, eye comfort, and new lighting poles as potential roadside hazards. Although the number of agencies that use LED only is small compared with that using HPS only and using both LED and HPS, it can be seen that many agencies are already in the transition period replacing old HPS with new lighting technologies. The going-down price of new lighting technology luminaires could persuade more agencies replacing HPS with LED, Plasma, and other new types.

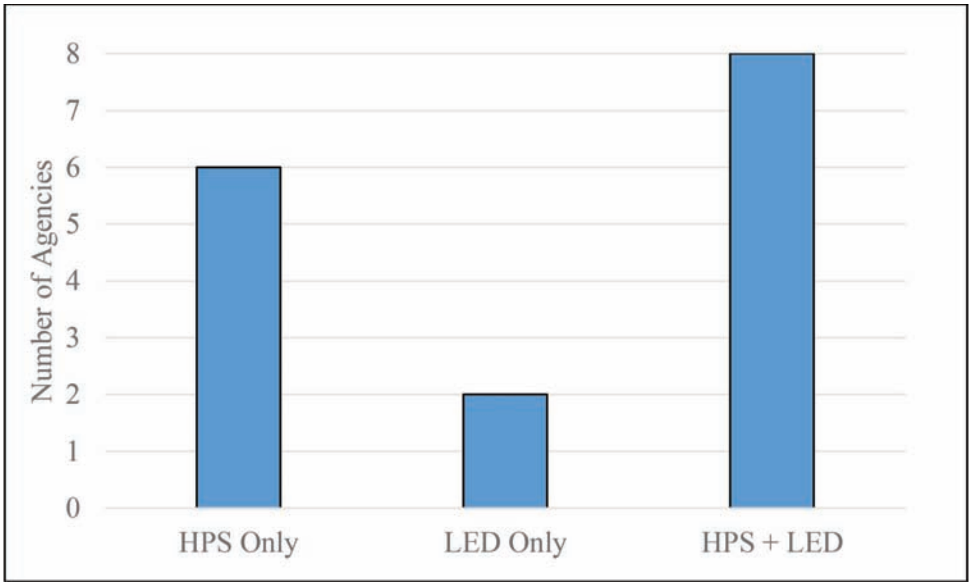


Figure 5.3 Distributions of usage of lighting technologies by agencies.

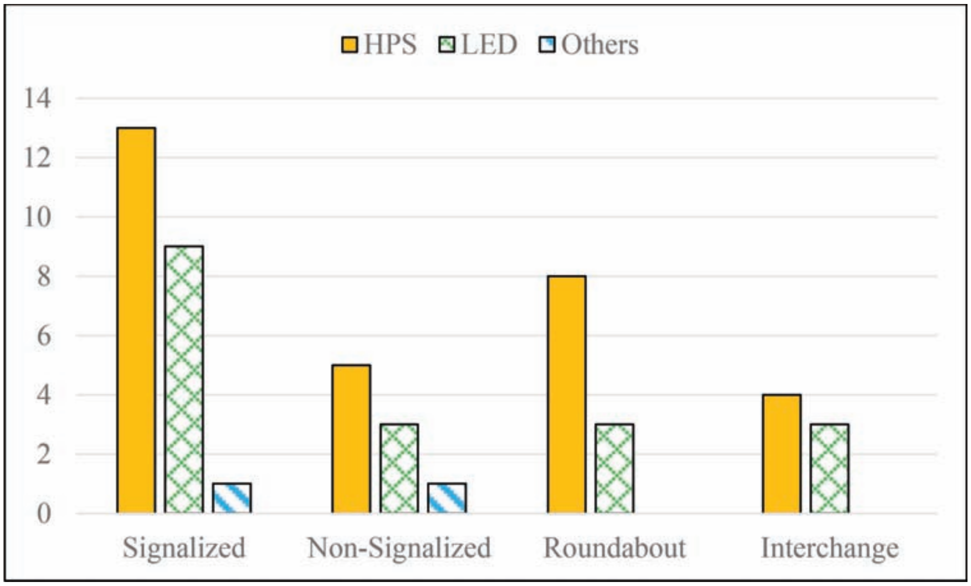


Figure 5.4 Distributions of lighting technologies by types of intersection.

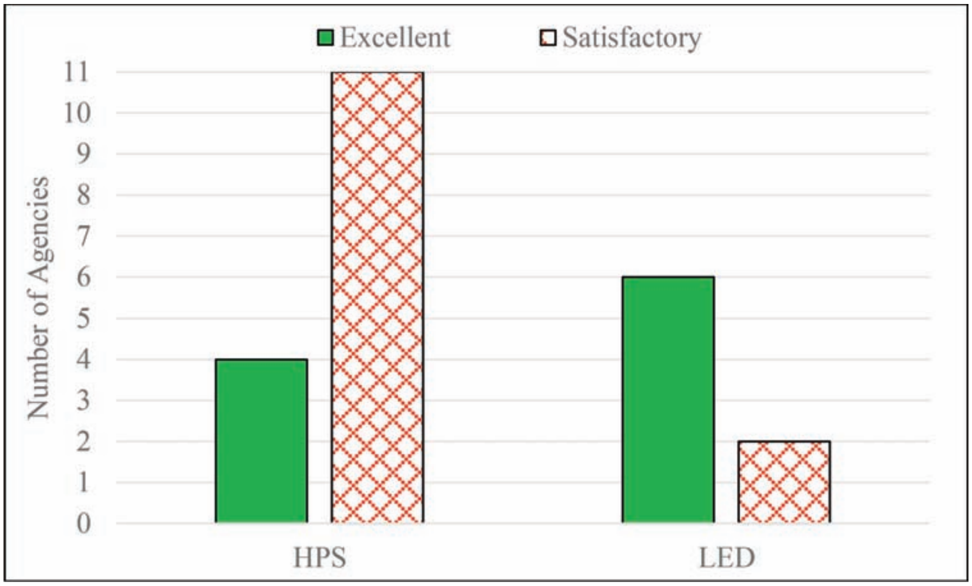


Figure 5.5 Distributions of satisfactions on LED and HPS.

TABLE 5.3
Types of Applications of New Lighting Technologies

Agency	**New Lighting Installation**	**Lighting Modernization**
Colorado DOT		√
Delaware DOT		√
Idaho DOT		√
Maine DOT	√	√
Michigan DOT		√
North Carolina DOT	√	√
Oklahoma DOT	√	
Texas DOT	√	√
Vermont Agency of Transportation	√	
City of Bloomington	√	√
City of Fort Wayne		√

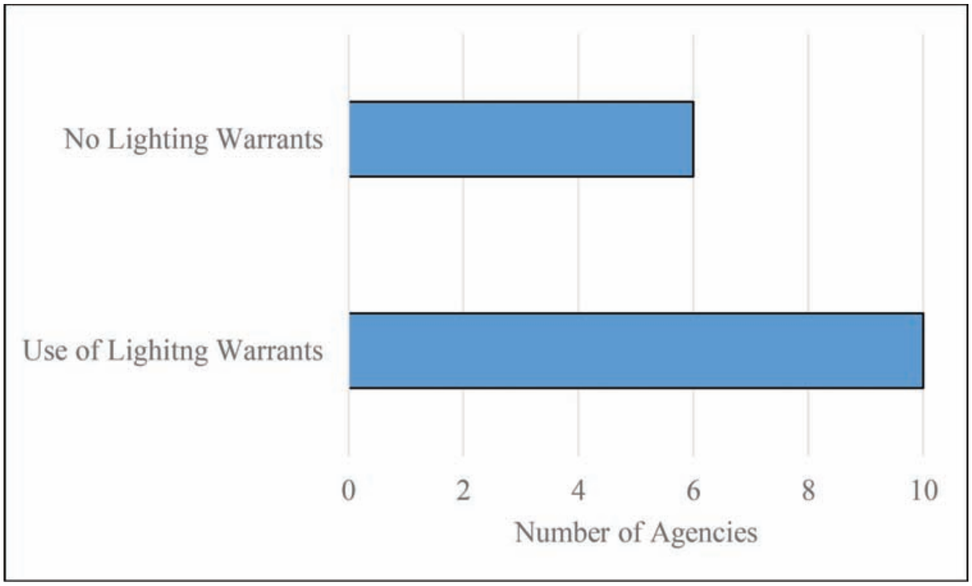


Figure 5.6 Use of warrants in new lighting applications.

TABLE 5.4
Major Benefits by Intersection Lighting Projects

Agency	Safety Improvement	Energy Saving	Visibility Improvement	Public Security	Economic Development
Iowa DOT	√				
Louisiana DOT		√			
Maine DOT	√	√			
Michigan DOT	√		√		
Nebraska Dept. of Road	√				
North Carolina DOT	√			√	√
Oklahoma DOT	√				
Oregon DOT	√	√			
Texas DOT	√				
Vermont Agency of Transportation	√	√			
City of Bloomington	√	√			
City of Fort Wayne	√	√	√		

TABLE 5.5
Major Risks by Intersection Lighting Projects

Agency	Related Cost	Eye Comfort	Roadside Hazard	Traffic Control	Light Pollution
Iowa DOT	√		√		
Louisiana DOT					
Maine DOT	√	√			
Michigan DOT	√				
Nebraska Dept. of Road		√	√		
North Carolina DOT			√	√	
Oklahoma DOT					
Oregon DOT	√				
Texas DOT	√		√		
Vermont Agency of Transportation					√
City of Bloomington					
City of Fort Wayne					

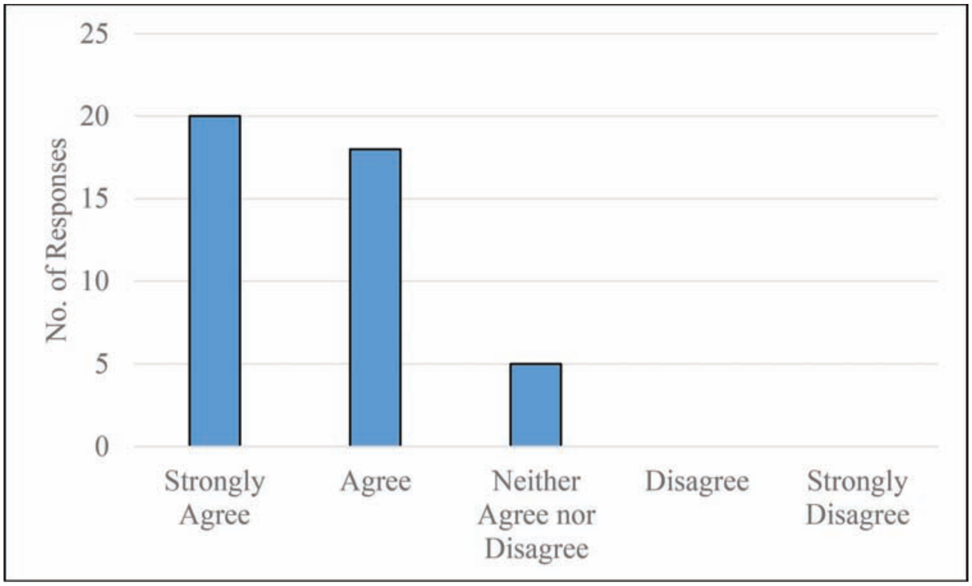


Figure 5.7 Light level improved by new lighting.

5.3 Community Survey

As shown in Table 5.2, a total of 403 questionnaires were mailed to residential and commercial addresses near the five target intersections. Forty-seven valid responses were received. As indicated in Figure 5.7, most of the responses strongly agreed or agreed that the new lighting improved light level at the intersections. Similarly, Figures 5.8 through 5.12 show the positive opinions on various aspects of the new lighting at the intersections, including nighttime visibility, safety, nighttime street use, and overall satisfaction with the intersection lighting.

Some of the survey responders provided comments in the questionnaire, the comments with respect to the five intersections are summarized as follows.

Plasma at Four-leg Intersection (Creasy & SR 38) in Lafayette

- Many right angle vehicle crashes happened at this intersection and it is strongly recommended that the left turn only arrow be added into the traffic signal.
- The performance of lighting has been greatly improved.

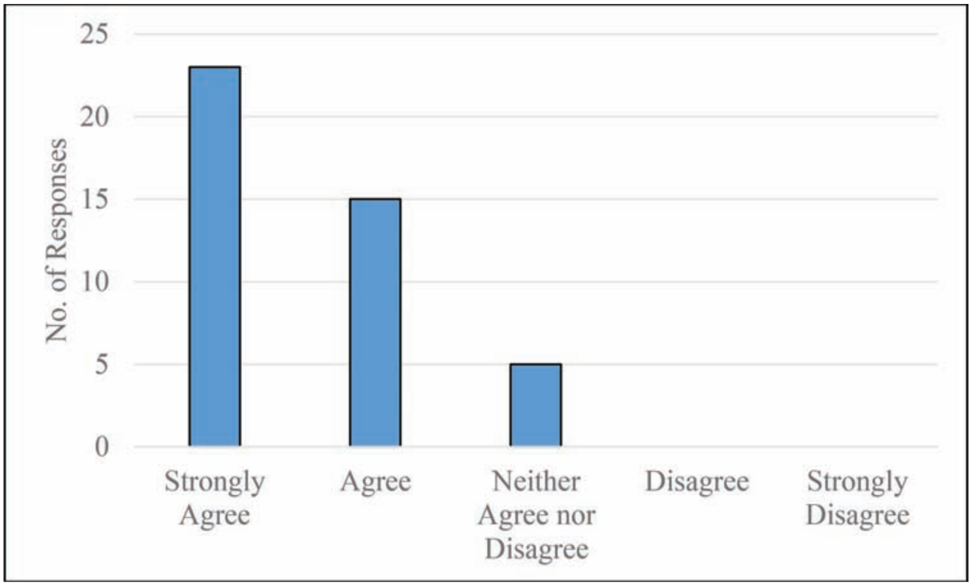


Figure 5.8 Nighttime visibility improved by new lighting.

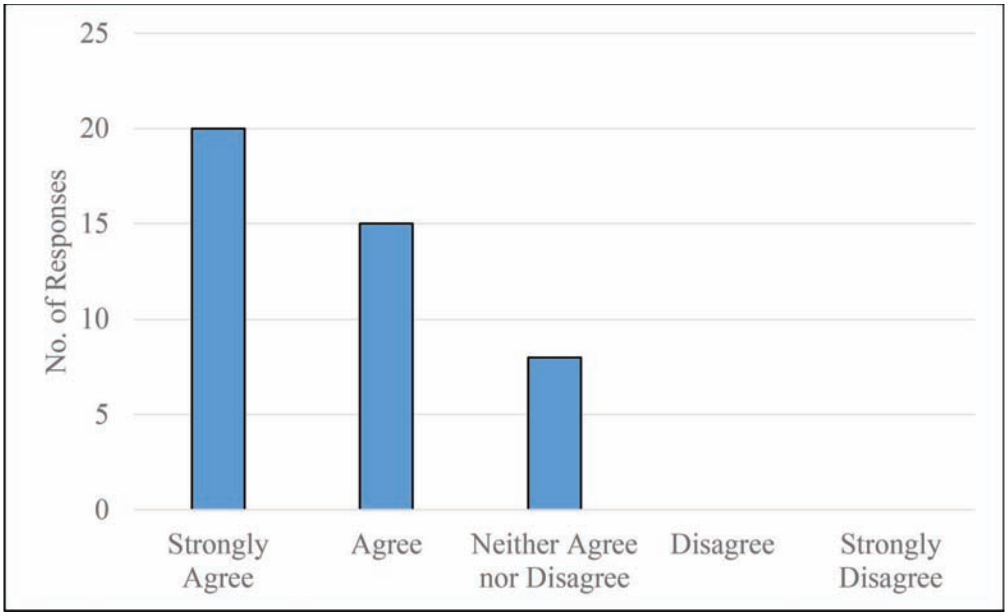


Figure 5.9 Driving safety by new lighting.

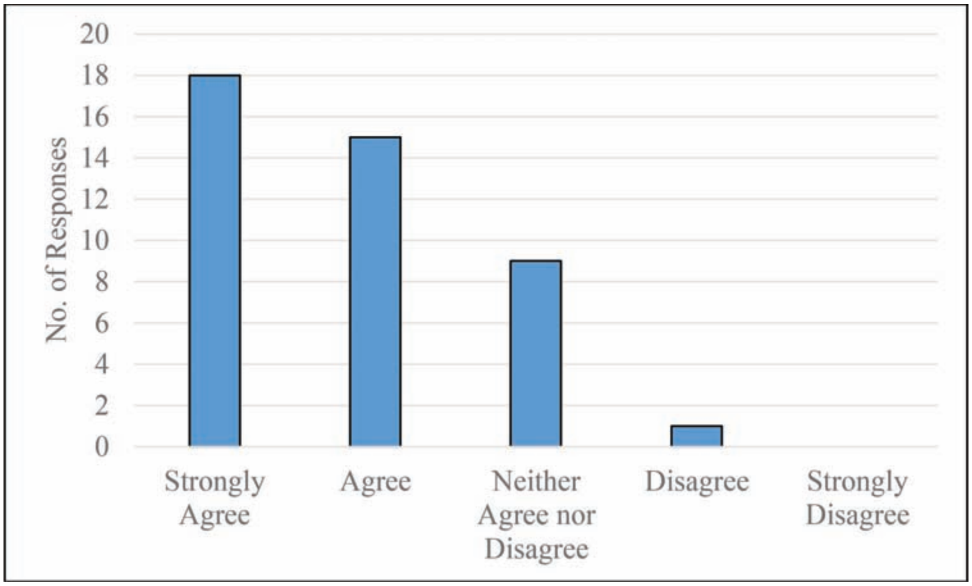


Figure 5.10 Nighttime street use and neighborhood security with new lighting.

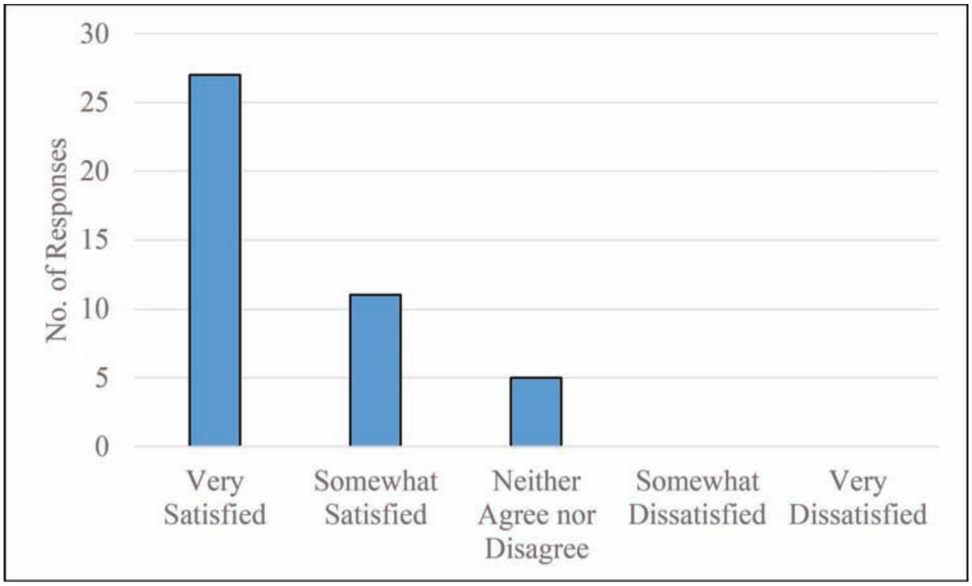


Figure 5.11 Overall satisfactions on the new lighting.

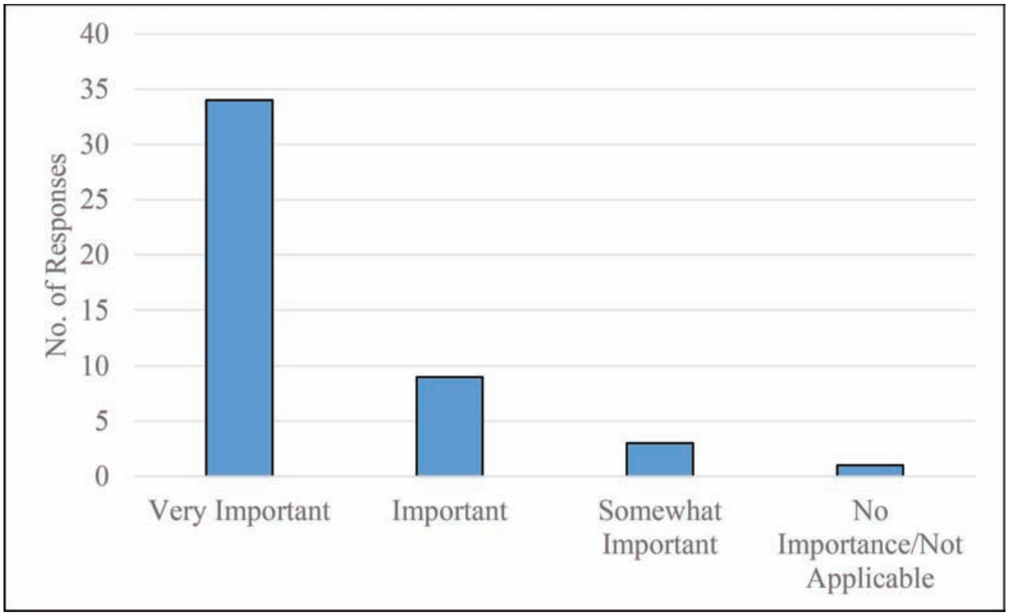


Figure 5.12 Opinions on the importance of intersection lighting.

LED at Four-leg Intersection (US 52 & US 231) in West Lafayette

- This intersection has no traffic lights. When football season approaches, high traffic volumes make traffic on US 231 hard to get on US 52. The school buses can be delayed for quite a long time.

LED at Three-leg Intersection (US 136 & Connector) in Brownsburg

- The LED lighting provides necessary illumination for safe navigation of the intersection.
- Nighttime visibility is improved greatly due to the new lighting.
- Concerns are made on the environmental impact by the new lighting.
- Similar lightings should be considered at the intersection of US 136 and CR 900.

MH at Roundabout (Northwestern Ave & Yeager) in West Lafayette

- Light pollution may be a problem since many apartment buildings are around the roundabout.
- More lighting fixtures should be provided between Montgomery Street and Cumberland Avenue.

LED at Roundabout (Poland Hill & Twyckenham Blvd) in Lafayette

- The lights provided at this roundabout are very important to keep the crime rate down since many apartments bordering around this location.
- Many cars still exceed the speed limit passing through this roundabout.
- The oncoming traffic always blinds drivers at this roundabout.

6. LIGHTING CRASH MODIFICATION FACTORS

Safety effects of countermeasures can be quantified by the Crash Modification Factors (CMFs). As discussed previously, the observational before-and-after analysis and cross-sectional statistical analysis were used to develop the CMF values for Indiana with Indiana crash data. In this Chapter, the methods for developing CMFs are discussed and the CMF values are presented.

6.1 Before-and-After Analysis

6.1.1 Basics of Before-and-After Analysis

When the treatments are identified at specified sites, crash data before and after the treatments can be used to estimate safety changes. The time period within which crash data is collected before the treatment is called before-period. Similarly, after-period refers to the period of time within which crash data is collected after the treatment.

The before-and-after analysis can be conducted through naïve method, Comparison Group (CG) method, and Empirical Bayes (EB) method. All methods share the similar analyzing steps. Figure 6.1 is a flow chart illustrating operations of before-and-after analysis. With the use of before-period and after-period crash data, the two fundamental tasks in the before-and-after analysis are observing what the crash condition was in the after-period, and predicting what would have been the crash condition in the after-period if the treatment had not been applied. The treatment in this study refers to the lighting installation at selected intersections.

Let *i* be the intersection index number, be the estimated after-period crash counts at site *i* had it not been treated, and $\lambda(i)$ be the expected after-period crash counts at site i. In order to measure the treatment effect, let $\delta(i) = \pi(i) - \lambda(i)$ be the expected after-period crash reduction at site i, and $\theta(i) = \lambda(i)/\pi(i)$ be the ratio of crash condition with the treatment to crash condition without the treatment at site i. Therefore, $\theta(i)$ is essentially the index of treatment effectiveness, or the lighting CMF.

The basic before-and-after analysis method, naïve method, assumes that the treatment is the only change happened on sites and all other factors remain the same, so at each site, before-period crash count is deemed as $\pi(i)$ and after-period crash count is treated as $\lambda(i)$. Safety effect estimation due to the treatment are then purely based on crash data. However, the treatment effect estimated by naïve method is not accurate. In addition to the treatment, unwanted factors also influence safety change as time passes. As shown in Figure 6.2, some unwanted factors such as traffic volume can be measured directly, while other factors such as weather condition, road user demography, and economic condition cannot. For the purpose of accounting for the influence of unwanted casual factors, naïve method was revised by past researchers and CG method was proposed (Hauer, 1997). The before-and-after analysis with CG approach picks out a comparison group of sites and assumes unwanted factors are influencing safety in the same manner on both comparison group and study group. Thus, unwanted factor effects can be removed by comparing the two groups. Ensuring maximum similarity between comparison group and study group is essential but often hard to achieve in practice by CG approach. However, the difficulty in selecting appropriate comparison group of sites can be reduced by the following setting. It has been proved that lighting is mainly affecting nighttime safety, so the daytime crash group is set as the comparison group and the nighttime crash group as the study group. Through this setting, the greatest similarity between comparison group and study group can be achieved. Additionally, the influence on safety due to traffic volume changes can be estimated by applying Safety Performance Functions (SPFs). More information is provided in the following sections.

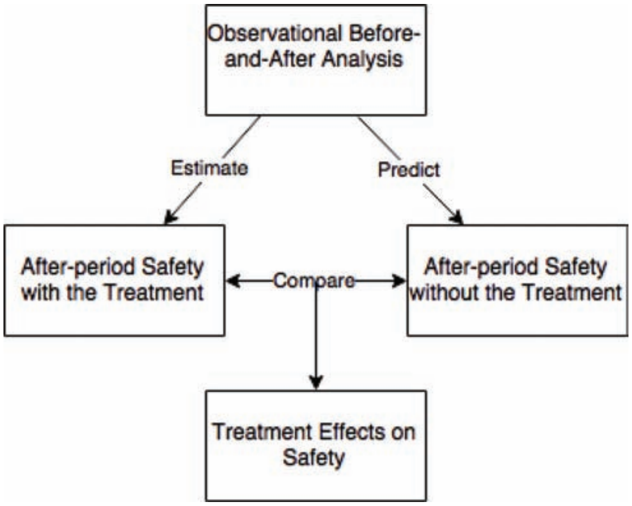


Figure 6.1 Process of before-and-after analysis.

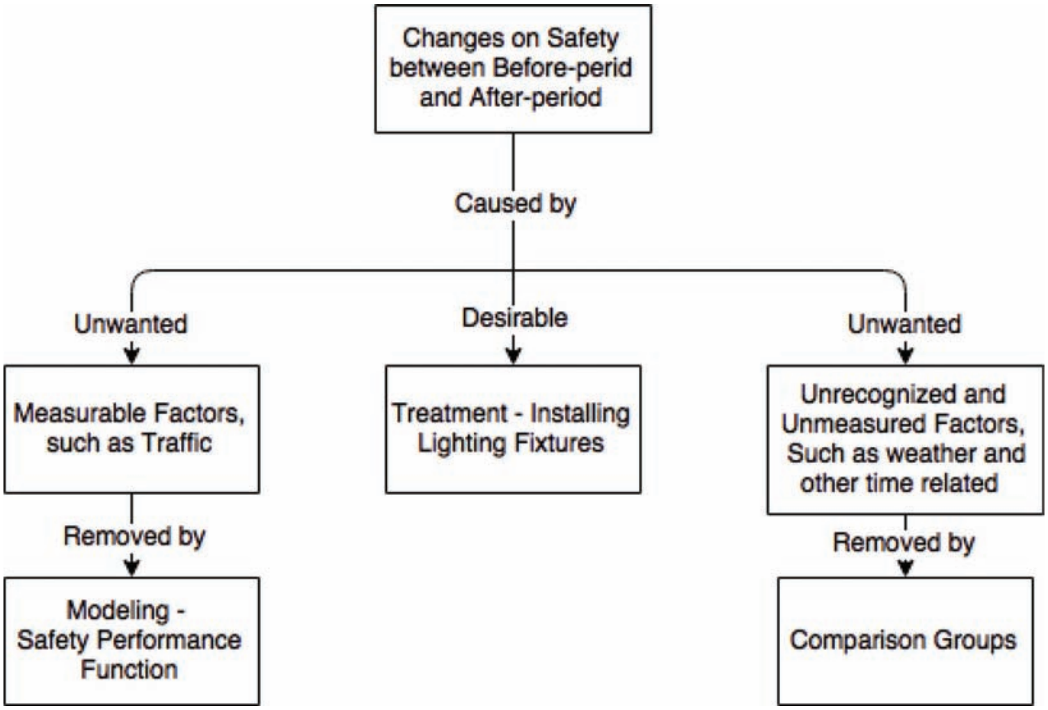


Figure 6.2 Approaches to improving estimation.

TABLE 6.1
Selected Intersections for Before-and-After Analysis

Site #	Location	City	Luminaire	Installation Date
1	Coldwater & Dupont	Fort Wayne	HPS	Feb-03
2	Spring & St Marys	Fort Wayne	HPS	Dec-03
3	Jefferson & Clinton	Fort Wayne	LED	Mar-05
4	Wells & State	Fort Wayne	HPS	Dec-02
5	Stellhorn & Maplecrest	Fort Wayne	HPS	Mar-04
6	Clinton & Main	Fort Wayne	LED	Aug-13
7	Clinton & State	Fort Wayne	HPS	Aug-12
8	St Joe Center & Upper St Joe Center	Fort Wayne	HPS	May-09
9	St Joe & St Joe Center	Fort Wayne	HPS	May-09

TABLE 6.2
Crash Data for Selected Intersections

			Crash Count					
			Total		Daytime		Nighttime	
Site #	# Months Before	# Months After	Before	After	Before	After	Before	After
1	13	142	20	274	14	199	6	75
2	23	132	4	9	3	8	1	1
3	38	117	18	70	8	51	10	19
4	11	144	4	115	3	93	1	22
5	26	129	39	312	30	241	9	71
6	139	16	93	13	75	11	18	2
7	127	28	73	19	55	15	18	4
8	88	67	11	6	7	4	4	2
9	88	67	124	78	90	57	34	21

6.1.2 Site Determination and Data Collection

To conduct before-after analysis, nine intersections in Fort Wayne, Indiana are selected. The first reason for selecting those intersections is that all intersections are located in urban areas with traffic signals and turning lanes installed, so they share similar geographic characteristics. Second, the crash and traffic data is available to conduct before-and-after analysis. Third, lighting installation dates are known. Provided by local transportation agencies, the lighting installation month and year for each intersection is given in Table 6.1.

To conduct the before-and-after analysis, the crash data from 2002 to 2014 at these intersections were obtained from the Indiana ARIES crash database. Table 6.2 provides the crash data used for the before-and-after analysis, including the time lengths before and after lighting installations.

Traffic volumes for selected intersections were retrieved from the Indiana Department of Transportation Interactive Traffic Data Map. This traffic map is a public database for state owned routes. The traffic volume for the most recent available year in 2011was obtained by locating each intersection on the traffic map and then obtain the traffic volumes for all intersecting roads of the intersection. The entering intersection AADT was calculated by summing up AADT from all legs and then dividing the summation by two. The INDOT traffic yearly adjustment factors were used to convert the traffic volume in 2011 to that in different years. Table 6.3 shows the converted AADT values from 2002 to 2014.

6.1.3 Naïve Before-and-After Analysis

Crash Counts. Initial comparisons of average monthly crash counts between before-period and after-period are summarized in Table 6.4. As shown in this table, after-period crash counts for both daytime and nighttime crashes became larger than before-period crash counts at No. 1, No. 4, No. 5, and No. 7 intersections. The rest of intersections experienced a decline in nighttime crash counts after lightings were installed, but daytime after-period crash counts were not always less than daytime before-period crash counts. The largest nighttime crash decrease occurred at the No. 3 intersection from a monthly crash count of 0.263 to 0.162, while the No. 6 intersection had the smallest decrease from 0.129 to 0.125. The inconsistency of crash trends between daytime and nighttime crash indicates more factors other than lighting were affecting safety.

Crash Rates. Another indicator of safety is the crash rate. Crash rates for selected intersections can be calculated with Equation 6.1. The crash rate is in the

TABLE 6.3

Entering Intersection AADT for Selected Intersections and Yearly Traffic Adjustment Factors

Site #	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
1	56840	56063	55390	55446	55838	55110	53372	53203	53540	54549	54493	53708	54276
2	16317	16094	15900	15916	16029	15820	15321	15273	15369	15659	15643	15418	15581
3	38551	38024	37567	37605	37872	37377	36199	36084	36313	36997	36959	36427	36812
4	19990	19716	19480	19499	19637	19381	18770	18711	18829	19184	19164	18888	19088
5	31877	31441	31064	31095	31315	30906	29932	29837	30026	30592	30561	30120	30439
6	27350	26976	26653	26680	26868	26518	25681	25601	25762	26248	26221	25843	26117
7	32078	31639	31260	31291	31513	31101	30121	30026	30215	30785	30753	30310	30631
8	19990	19716	19480	19499	19637	19381	18770	18711	18829	19184	19164	18888	19088
9	19990	19716	19480	19499	19637	19381	18770	18711	18829	19184	19164	18888	19088
Factor	1.042	1.028	1.015	1.016	1.024	1.010	0.978	0.975	0.982	1.000	0.999	0.985	0.995

TABLE 6.4

Crash Counts per Month Before-Period and After-Period

	Crash Count per Month							
	Total		Daytime		Nighttime		Nighttime Crash Count Portion	
Site #	Before	After	Before	After	Before	After	Before	After
1	1.538	1.930	1.077	1.401	0.462	0.528	0.300	0.274
2	0.174	0.068	0.130	0.061	0.043	0.008	0.250	0.111
3	0.474	0.598	0.211	0.436	0.263	0.162	0.556	0.271
4	0.364	0.799	0.273	0.646	0.091	0.153	0.250	0.191
5	1.500	2.419	1.154	1.868	0.346	0.550	0.231	0.228
6	0.669	0.813	0.540	0.688	0.129	0.125	0.194	0.154
7	0.575	0.679	0.433	0.536	0.142	0.143	0.247	0.211
8	0.125	0.090	0.080	0.060	0.045	0.030	0.364	0.333
9	1.409	1.164	1.023	0.851	0.386	0.313	0.274	0.269

TABLE 6.5

Before-Period and After-Period Crash Rates

			Crash Rate					
	Total Traffic (in million vehicles)		Overall		Daytime		Nighttime	
Site #	Before	After	Before	After	Before	After	Before	After
1	22	236	0.922	1.160	0.645	0.842	0.276	0.318
2	11	63	0.360	0.143	0.270	0.127	**0.090**	**0.016**
3	45	137	0.398	0.511	0.177	0.372	**0.221**	**0.139**
4	6	84	0.623	1.365	0.467	1.104	0.156	0.261
5	25	120	1.590	2.600	1.223	2.008	0.367	0.592
6	118	14	0.788	0.956	0.636	0.809	**0.153**	**0.147**
7	120	26	0.609	0.723	0.459	0.571	0.150	0.152
8	26	19	0.425	0.309	0.270	0.206	**0.154**	**0.103**
9	52	39	2.393	2.008	1.737	1.467	**0.656**	**0.540**
Total	425	739	0.909	1.213	0.671	0.919	0.238	0.294

unit of crash counts per million vehicles. Table 6.5 shows the before-period and after-period crash rates.

$$\text{Crash Rate} = \frac{1{,}000{,}000 \times \text{Crash Counts}}{\text{Traffic Volumes}} \qquad (6.1)$$

Changes of nighttime crash rates in Table 6.5 are consistent with changes of nighttime crash counts in Table 6.4. Nighttime after-period crash rates are higher than nighttime before-period crash rates at No. 1, No. 4, No. 5, and No. 7 intersections, but changes of daytime crash rates are not necessarily following the same pattern.

Effects of lighting at selected intersections are hard to interpret by merely looking at crash counts and crash rates. Results from this naïve analysis can be misleading since other factors other than lighting exist and they may distort estimations of the lighting effects. The revised approach, CG approach, therefore is introduced in the next section to increase the accuracy of estimations.

6.1.4 Before-and-After Analysis with CG method

As described previously, π , λ, δ, and θ are expected values, which are never known from the discipline of statistics. However, these values can be estimated from observed crash data. Estimates are generally designated by a caret (^) above each symbol. For example, $\hat{\pi}(i)$ means the estimate of $\pi(i)$. To make estimates unbiased, equations may be adjusted. For example, the index of effectiveness is $\theta(i)=\lambda(i)/\pi(i)$ for intersection i, while the unbiased estimate $\hat{\theta}(i)$ should be calculated by the equation $\hat{\theta}(i)=\dfrac{\hat{\lambda}(i)/\hat{\pi}(i)}{1+\frac{Var(\hat{\pi}(i))}{\hat{\pi}(i)^2}}$.

Step 1: Define Comparison Group and Study Group. In the before-and-after analysis with CG approach, let nighttime crash data be the study group and daytime crash data be the comparison group. Presented in Table 6.6 are the symbols that represent crash counts in the analysis. N denotes nighttime crash counts and D denotes daytime crash counts. The subscript "b" refers to before-period and subscript "a" refers to after-period. Letter "i" is the intersection index number from one to nine.

Step 2: Estimate Adjustment Factors. Crash data in Table 6.2 needs to be adjusted because:

a. The durations of before-period and after-period are not the same for each intersection;
b. The change of traffic volumes affected safety throughout the time period; and
c. Other time changing sundry factors affected safety throughout the time period.

Equation 6.2 is used to calculate average yearly crash counts in daytime before-period (D_b), daytime after-period (D_a), nighttime before-period (N_b), and nighttime after-period (N_a). Results are listed in Table 6.7.

$$\text{Average Yearly Crash Counts} = \frac{12 \times \text{Crash Counts}}{\text{Duration (in Months)}} \quad (6.2)$$

In order to account for effects brought by the change in traffic, SPFs, which were developed in Highway Safety Manual (HSM), were used to calculate the difference of crash counts between before-period and after-period. Since SPF is a function of traffic volume, the total crash counts estimated by SPFs can be denoted as $f(AADT)$.

If numbers of crash are estimated during both before-period and after-period, the traffic adjustment factor can be computed by using Equation 6.3. The traffic adjustment factor is the ratio of after-period estimated crash counts to before-period estimated crash counts.

$$r_{tf}=\frac{f(AADT_{after})}{f(AADT_{before})} \quad (6.37)$$

The SPF coefficients in Table 6.8 were used to determine multiple-vehicle crash counts and single-vehicle crash counts. Then the total estimated crash count was calculated as the summation of multiple-vehicle crash counts and single-vehicle crash counts. The results are listed in Table 6.9 and Table 6.10.

With the total estimated crashes in Table 6.9 and Table 6.10, the traffic adjustment factor for each intersection can be determined using Equation 6.3. The calculated traffic adjustment factors are listed in Table 6.11.

Since time changing factors exert same influences on nighttime crash group (study group) and daytime crash group (comparison group), the effects of these factors can be removed by simply comparing nighttime crash

TABLE 6.6
Notations of Crash Counts in Groups

Period	Study/Nighttime Group	Comparison/Daytime Group
Before	$N_b(i)$	$D_b(i)$
After	$N_a(i)$	$D_a(i)$

TABLE 6.7
Average Yearly Crash Counts

	Daytime		Nighttime	
Site #	Before $D_b(i)$	After $D_a(i)$	Before $N_b(i)$	After $N_a(i)$
1	12.92	16.81	5.54	6.34
2	1.56	0.73	0.52	0.10
3	2.53	5.23	3.16	1.94
4	3.28	7.75	1.09	1.84
5	13.85	22.42	4.15	6.60
6	6.48	8.26	1.55	1.50
7	5.20	6.43	1.70	1.72
8	0.96	0.72	0.54	0.36
9	12.28	10.21	4.63	3.76

TABLE 6.8
Safety Performance Functions for Correction Factors of Traffic

Crash Type	Function	a	b	c
Multiple-Vehicle Crashes	$\exp[a+b\times\ln(AADT_{major})+c\times\ln(AADT_{\min or})]$	-10.99	1.07	0.23
Single-Vehicle Crashes		-10.21	0.68	0.27

TABLE 6.9
Estimated Before-Period Crashes

	AADT		Expected Number of Crash Estimated per Year		
Site #	**Major**	**Minor**	**Multiple-Vehicle Crash**	**Single-Vehicle Crash**	**Total $f(AADT_{after})$**
1	34854.90	21985.16	12.19	0.67	12.86
2	9994.86	6321.81	2.40	0.21	2.61
3	20918.45	17128.84	6.67	0.44	7.11
4	9994.86	9994.86	2.67	0.23	2.90
5	21732.37	9926.52	6.12	0.39	6.52
6	16761.61	9652.82	4.61	0.33	4.94
7	21343.00	9659.89	5.97	0.39	6.35
8	9748.13	9748.13	2.59	0.23	2.81
9	9748.13	9748.13	2.59	0.23	2.81

TABLE 6.10
Estimated After-Period Crashes

	AADT		Expected Number of Crash Estimated per Year		
Site #	**Major**	**Minor**	**Multiple-Vehicle Crash**	**Single-Vehicle Crash**	**Total $f(AADT_{after})$**
1	33387.92	21059.84	11.53	0.64	12.17
2	9574.20	6055.74	2.27	0.20	2.47
3	20222.85	16559.25	6.38	0.43	6.81
4	9597.86	9597.86	2.53	0.22	2.76
5	20924.75	9557.63	5.83	0.38	6.21
6	16572.72	9544.04	4.54	0.32	4.86
7	20976.66	9494.08	5.84	0.38	6.22
8	9515.37	9515.37	2.51	0.22	2.73
9	9515.37	9515.37	2.51	0.22	2.73

TABLE 6.11
Traffic Adjustment Factors

Site #	Value of the Factor
1	0.95
2	0.95
3	0.96
4	0.95
5	0.95
6	0.99
7	0.98
8	0.97
9	0.97

group with daytime crash group. Thus, the adjustment factor of comparison group could be defined as $r_{cg}(i)=\frac{D_a(i)}{D_b(i)}$ for each intersection. With the traffic adjustment factor $r_{tf}(i)$, the unbiased estimate of $r_{cg}(i)$ can be calculated with the following equation. The adjustment factors are shown in Table 6.12.

$$\hat{r}_{cg}(i)=\frac{D_a(i)/[r_{tf}(i)\times D_b(i)]}{1+1/[r_{tf}(i)\times D_b(i)]} \tag{6.4}$$

Step 3: Estimate $\hat{\delta}'(i)$, $\hat{e}(i)$, and Their Variances. Table 6.13 provides the predicted after-period crash counts at intersection i ($\hat{\pi}(i)$) if lighting had not been installed, the variance of $\hat{\pi}(i)$, expected after-period crash counts $\hat{\lambda}(i)$, and the variance of $\hat{\lambda}(i)$. $\hat{\pi}(i)$ is estimated by using before-period nighttime crash counts and the adjustment factor of comparison group as shown in Equation 6.5. The variance of $\hat{\pi}(i)$ has a more complex form as in Equation 6.6.

$$\hat{\pi}(i)=\hat{r}_{cg}(i)\times N_b(i) \tag{6.5}$$

$$Var[\hat{\pi}(i)]=\hat{\pi}(i)^2\{\frac{1}{N_b(i)}+\frac{Var[\hat{r}_{cg}(i)]}{\hat{r}_{cg}(i)^2}\} \tag{6.6}$$

The observed after-period nighttime crash counts are used as the expected numbers of after-period nighttime crashes, as described in Equation 6.7. In the before-and-after analysis, after-period crash counts are commonly assumed following the Poisson distribution. This study adopts this common practice and uses Poisson distribution to estimate the variance of expected after-period crash counts. According to the Poisson distribution, the variance is equal to the mean, so the variance of expected after-period crash counts can be calculated by using Equation 6.8.

$$\hat{\lambda}(i)=N_a(i) \tag{6.7}$$

TABLE 6.12
Adjustment Factors of Comparison Groups

Site #	$r_{tf}(i)$	$r_{tf}(i) \times D_b(i)$	$\hat{r}_{cg}(i)$
1	0.95	12.23	1.27
2	0.95	1.48	0.30
3	0.96	2.42	1.53
4	0.95	3.11	1.89
5	0.95	13.19	1.58
6	0.99	6.39	1.12
7	0.98	5.08	1.06
8	0.97	0.93	0.37
9	0.97	11.90	0.79

TABLE 6.13
Estimated $\hat{\partial}'(i)$ and $\hat{\ddot{e}}(i)$ and Variances

Site #	$\hat{\pi}(i)$	$Var[\hat{\pi}(i)]$	$\hat{\lambda}(i)$	$Var[\hat{\lambda}(i)]$
1	7.04	15.74	6.34	6.34
2	0.15	0.09	0.10	0.10
3	4.82	20.99	1.94	1.94
4	2.06	5.72	1.84	1.84
5	6.56	15.38	6.60	6.60
6	1.73	2.76	1.50	1.50
7	1.80	3.04	1.72	1.72
8	0.20	0.17	0.36	0.36
9	3.67	5.31	3.76	3.76
Total	28.03	69.20	24.14	24.14

$$Var[\hat{\lambda}(i)] = N_a(i) \tag{6.8}$$

Step 4: Estimate $\hat{\ddot{a}}$, $\hat{\grave{e}}$, and the Variance of $\hat{\grave{e}}$. This is the last step of before-and-after analysis with CG approach. As discussed previously, the safety effectiveness of lighting can be measured by $\ddot{a}$, the crash reduction between the expected nighttime after-period crashes and the predicted nighttime after-period crashes if lighting had not been installed. The safety effectiveness of lighting can also be measured by the index of effectiveness $\grave{e}$, the ratio of what crash condition was with lighting installed to what it would have been without lightings. Equations 6.9 through 6.15 can be used to calculate the yearly average crash reduction per intersection, the index of effectiveness, and their variances.

$$\hat{\lambda} = \sum_{i=1}^{9} \hat{\lambda}(i) \tag{6.9}$$

$$\pi = \sum_{i=1}^{9} \hat{\pi}(i) \tag{6.10}$$

$$Var(\hat{\lambda}) = \sum_{i=1}^{9} Var[\hat{\lambda}(i)] \tag{6.11}$$

$$Var(\hat{\pi}) = \sum_{i=1}^{9} Var[\hat{\pi}(i)] \tag{6.12}$$

$$\hat{\delta} = \frac{1}{9}(\hat{\pi} - \hat{\lambda}) \tag{6.13}$$

$$\hat{\theta} = \frac{\hat{\lambda}/\hat{\pi}}{1 + \frac{Var(\hat{\pi})}{\hat{\pi}^2}} \tag{6.14}$$

$$Var(\hat{\theta}) = \frac{\hat{\theta}^2 [\frac{Var(\hat{\lambda})}{\hat{\lambda}^2} + \frac{Var(\hat{\pi})}{\hat{\pi}^2}]}{(1 + \frac{Var(\hat{\pi})}{\hat{\pi}^2})^2} \tag{6.15}$$

Based on the crash data of the selected intersections, the following values were obtained:

- The yearly average crash reduction per intersection = 0.43
- The index of effectiveness of lighting = 0.79
- The variance of the index of effectiveness = 0.05

The index of effectiveness of lighting is actually the crash modification factor (CMF). Therefore, the CMF for the intersection lighting was obtained as 0.79.

6.2 Cross-Sectional Statistical Analysis

The cross-sectional statistical analysis explores the relationship between the presence of lighting and crash frequency by comparing a group of lighted intersections with another group of unlit intersections during the same time period. To account for effects of factors other than lighting, the cross-sectional method was applied to analyze the safety improvement with lighting.

The raw crash data from 2008 to 2014 was retrieved from the Indiana crash database ARIES for the cross-sectional analysis. The crashes at the selected intersections were identified, separated, and processed. Table 6.14 presents the main variables of the processed crash data for the cross-sectional analysis.

In order to illustrate the cross-sectional analysis, the detailed analysis process is outlined below with the intersection crash data from 2008 to 2014. The calculated statistics for the 7-year intersection crashes is shown in Table 6.15.

It is shown that from 2008 to 2014, a total of 182,123 daytime crashes and 70,641 nighttime crashes were recorded. The crash means of daytime and nighttime crashes (6.49 and 2.52) are much lower than their corresponding variances (177.16 and 14.75). The very high variances and low means generally indicate that the crash data is over dispersed. The crash data distributions are shown with the histograms in Figures 6.3 and 6.4.

As can be seen in the two figures, the intersection crash distributions are heavily skewed toward the low numbers of crashes. The two histograms clearly indicate that on average at an intersection in terms of number of crashes it is most likely there would be no crashes during daytime (30% frequency) and there would be one crash during nighttime (64% frequency).

Two distributions, Negative Binomial and Poisson, are commonly used to analyze recorded data. One major assumption of the Poisson model is that the data has equal mean and variance, which is apparently not appropriate for the crash data shown in Table 6.15. Therefore, the Binomial regression was applied to study the lighting effects on intersection crashes. The negative binomial regression is expressed as:

$$E(y_i) = \lambda_i = \exp(\beta X_i + \varepsilon_i) \tag{6.16}$$

Where,

$E(y_i)$=expected crash count at intersection i;

y_i= the observed number of crashes at intersection i;

λ_i= the expected crash counts at intersection i;

X_i= the vector containing variables correlated with;

β= the vector of estimated regression parameters of model variables; and

ε_i= the Gamma-distributed error term.

TABLE 6.14
Variables Used in Cross-Sectional Analysis

#	Variable	Description
1	Number of Daytime Crash	Numerical
2	Number of Nighttime Crash	Numerical
3	Type of Intersection	Including Four-leg Intersection (68.72%), Three-leg Intersection (30.26%), and Roundabout (1.03%)
4	Locality	Including Rural (18.88%) and Urban (81.12%)
5	Lighting Indicator	Including Present (74.34%) and Not Present (25.66%)
6	Roadway Class	Including County (6.55%), Local/City (66.62%), State (15.02%), US (11.31%), and Unknown (0.50%)
7	Road Character	Including Straight and level (81.60%) and Others (18.40%)
8	Type of Roadway Surface	Including Asphalt (92.44%), Concrete (7.26%), and Others (0.31%)
9	Type of Traffic Control	Including Traffic Control Signal (43.18%), Stop Sign (25.27%), Lane Control (12.29%), None (13.99%), and Others (5.27%)

TABLE 6.15
Descriptive Statistics of Crash Data

Variable	Number of Intersection	Crash Mean	Variance	Crash Sum	Minimum	Maximum
Daytime Crash	28,078	6.49	177.16	182,123	0	238
Nighttime Crash	28,078	2.52	14.75	70,641	1	69

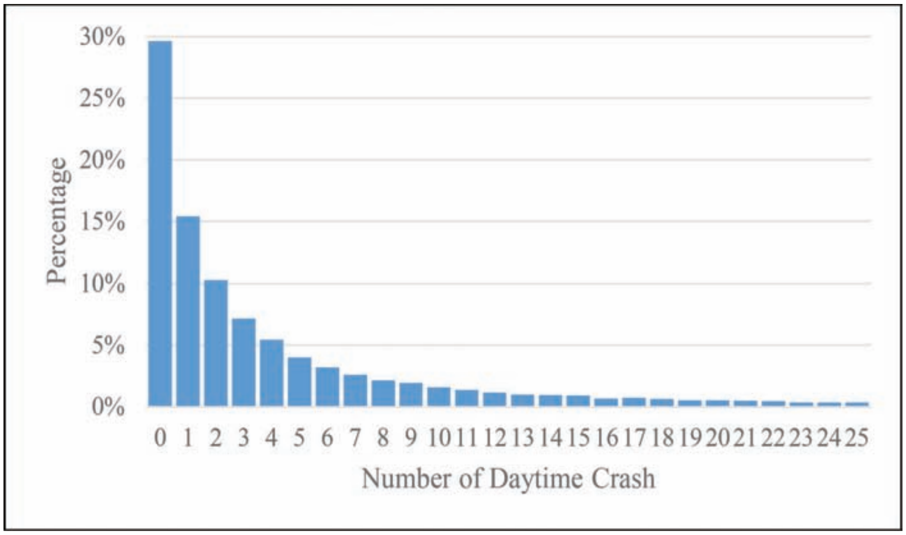


Figure 6.3 Histogram of daytime crash per intersection.

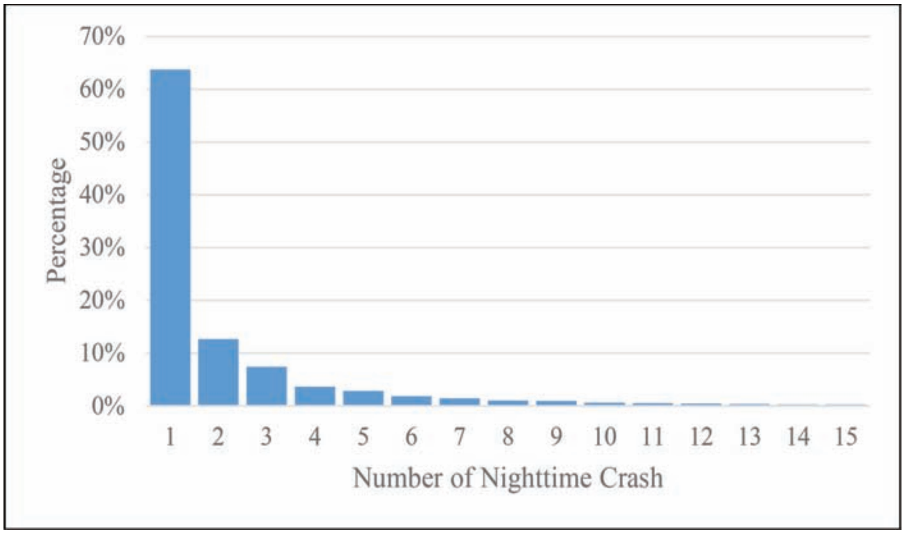


Figure 6.4 Histogram of nighttime crash per intersection.

TABLE 6.16
Over-Dispersion Validation for Initial Analysis

	Estimate	Standard Error	Wald 95% Confidence Limits	
Daytime Crash Model	2.534	0.024	2.487	2.581
Nighttime Crash Model	0.611	0.007	0.597	0.626

To account for data over-dispersion, the relationship between mean and variance of crashes for the negative binomial regression is established as Equation 6.17.

$$Var(y_i) = E(y_i)[1 + \alpha E(y_i)] \tag{6.17}$$

Where,

$Var(y_i)$=variance of the observed crashes y at intersection i;

α=the parameter of over-dispersion.

To test the fitness of the binomial model, the parameter estimates of a negative binomial model with the crash data from Table 4.14 are shown in Table 6.16. As can be seen in the table, the over-dispersion estimates for daytime and nighttime crashes are greater than zero. In addition, both estimates are within their responding 95% confidence levels. Therefore, the intersection crash data fits the negative binomial model well.

The significances of the various variables were statistically tested with a 95% confidence level. The results of the test are given in Table 6.17. The p-values are used to determine the significances of the variables. If the p-value of a variable is less than 0.05, with is corresponding to 95% confidence level, the variable should be judged as significant in terms of its effect on lighting effectiveness. The p-values in the table indicate that lighting, roadway class, and type of traffic control are significant for nighttime crashes. Similarly, locality, lighting, and roadway class are significant for daytime crashes. In order to use the same variables in daytime and nighttime models, it was decided to include locality, lighting, roadway class, and type of traffic control in the analysis. In addition, type of intersection was also included in the analysis model to examine the effects of this important variable.

Summarized in Table 6.18 are the statistical results from the daytime and nighttime negative binomial models. The variable coefficient (β) and elasticity are listed in the table. For each variable, there are more than one levels. The level with the variable coefficient and elasticity of 0 was used as the baseline in the analysis.

Elasticity, or termed pseudo-elasticity (Lee & Mannering, 2003), is used to measure the crash percent change from the baseline level to a non-baseline level. In the negative binomial models, elasticity for a given variable level “k” can be calculated using the following equation.

$$E_k = \exp(\beta_k) - 1 \tag{6.18}$$

By looking at elasticity values in Table 6.18, it is shown that four-leg intersections experienced 2.6% more daytime crashes and 0.6% more nighttime crashes

TABLE 6.17
Significance Test of Model Variables

	Daytime Crash Model			Nighttime Crash Model		
Variable	**DF**	**Chi-Square**	**P-value**	**DF**	**Chi-Square**	**P-value**
Type of Intersection	1	1.29	0.257	1	0.42	0.5179
Locality	1	10.44	0.0012	1	0.1	0.7535
Lighting Indicator	1	170.16	<.0001	1	156.6	<.0001
Roadway Class	4	21.38	0.0003	4	47.83	<.0001
Road Character	1	0.01	0.9095	1	2.54	0.1113
Type of Roadway Surface	2	1.59	0.4522	2	0.69	0.7072
Type of Traffic Control	4	33.55	<.0001	4	27.29	<.0001

TABLE 6.18
Statistics of Negative Binomial Statistical Models

		Daytime Model		Nighttime Model	
Variable	**Variable Level**	**Coef (β)**	**Elasticity**	**Coef (β)**	**Elasticity**
Type of Intersection	Four-leg	0.026	2.6%	0.006	0.6%
	Three-leg	0	0.0%	0	0.0%
Locality	Rural	-0.102	-9.7%	0.008	0.8%
	Urban	0	0.0%	0	0.0%
Lighting Indicator	Present	0.339	40.4%	0.206	22.9%
	Not Present	0	0.0%	0	0.0%
Roadway Classification	County Road	0.058	6.0%	0.047	4.8%
	Local/City Road	-0.089	-8.5%	-0.092	-8.8%
	State Road	-0.008	-0.8%	-0.049	-4.8%
	US Highway	0	0.0%	0	0.0%
Traffic Control	Lane Control	0.063	6.5%	0.034	3.5%
	No Traffic Control	-0.073	-7.0%	-0.037	-3.6%
	Others	-0.058	-5.6%	-0.019	-1.9%
	Stop Sign	0.096	10.1%	0.057	5.9%
	Traffic Control Signal	0	0	0	0

than the three-leg intersections. The rural intersections had 9.7% fewer daytime crashes and 0.8% more nighttime crashes than the urban intersections. The comparisons of other variable levels can also be similarly made with the elasticity values in Table 6.18 to determine the relative impact of the variables.

In addition to using elasticity values, the intersection crashes were further analyzed with variable coefficients so that the effects of some other hidden factors can be eliminated (3). The following equation can be used to find crash reduction due to the presence of lighting.

$$Crash\ Reduction = \frac{\exp(\hat{\beta}_{Night\ time\ Light})}{\exp(\hat{\beta}_{Day\ time\ Light})} - 1 \qquad (6.19)$$

Listed in Table 6.19 are the lighting coefficients for daytime model and nighttime model based on three different databases. The crash reductions and crash modification factors were obtained as shown in the table. The crash modification factors were computed from the crash reductions as shown below:

$$CMF_{overall} = 1 - 12.4\% = 0.88$$

$$CMF_{Four-way} = 1 - 9.7\% = 0.90$$

$$CMF_{Three-way} = 1 - 16.0\% = 0.84$$

The CMFs for roundabout intersections were not included in the cross-sectional models discussed above. This is because the crash data and the number of roundabout intersections were not sufficiently large for the analysis. Therefore, the before-and-after analysis was performed for roundabout intersection lighting. Four roundabout intersections listed in Table 6.20 were included in the crash analysis. The information in the table includes the location, intersecting roads, the type of intersection before converting to roundabout, and the year of the roundabout was built.

The crash data from ARIES was obtained for the period from 2003 to 2014 for the roundabout study. The before and after average annual crashes during daytime and nighttime are shown in Table 6.21. The nighttime crash values were treated as the study group and daytime crashes as control group in the analysis.

In order to eliminate the effects of traffic volumes, SPFs were used to estimate multiple-vehicle crashes and single-vehicle crashes in the before period as well as in the after period. With the multiple-vehicle crashes and single-vehicle crashes in the before period and the after period, the adjustment factor (r_{tf}) for traffic volumes were calculated through Equation 6.3. Also, using Equation 6.4, the adjustment factors for the control group were computed with r_{tf} values and daytime before and after crash counts. The calculation results are shown in Table 6.22.

The predicted after-period nighttime crash counts if lighting had not been installed $\hat{\pi}(i)$ and its variance were calculated through Equations 5.5 and 5.6. Presented in Table 6.23 are the values of $\hat{\pi}(i)$ and $\hat{\lambda}(i)$ with the variances.

By comparing $\hat{\pi}(i)$ and $\hat{\lambda}(i)$ in the table, it can be shown that the overall annual crashes per roundabout were reduced by an average of (7.862-7.533)/4 = 0.082. The effectiveness of roundabout lighting in crash reduction can be measured by the index of effectiveness , the ratio of what crash condition was after roundabout was built to what it would have been without changing to roundabout. By using Equation 6.14 and 6.15,

TABLE 6.19
Model Coefficients of Lighting Indicator for Separate Datasets

Dataset	Daytime Model	Nighttime Model	Crash Reduction	CMF
Overall Dataset	0.339	0.206	-12.4%	0.88
Four-leg Intersection Dataset	0.298	0.196	-9.7%	0.90
Three-leg Intersection Dataset	0.371	0.197	-16.0%	0.84

TABLE 6.20
Roundabout Sites in Before-and-After Analysis

	City	Major Rd	Minor Rd	Type of Intersection Before	Year of Change
1	Carmel	136th/Smokey Row	Range Line	Four-leg signalized	2008
2	Westfield	151th	Carey	Four-leg with Stop Sign	2009
3	Lafayette	Twyckenham	Poland Hill	Four-leg with Stop Sign	2013
4	West Lafayette	Northwestern	Yeager	Three-leg signalized	2012

TABLE 6.21
Average Annual Crash Counts

	Daytime		Nighttime	
Roundabout #	**Before $D_b(i)$**	**After $D_a(i)$**	**Before $N_b(i)$**	**After $N_a(i)$**
1	0.40	1.00	0.60	0.83
2	0.83	1.00	0.67	0.20
3	1.70	10.00	0.90	2.00
4	3.89	11.50	1.56	4.50

TABLE 6.22
Estimated Adjustment Factors for Roundabouts

	Total Crash Counts Estimated by SPF			
Roundabout #	**Before**	**After**	**$r_{tf}(i)$**	**$\hat{r}_{cg}(i)$**
1	3.103	2.987	0.963	0.722
2	1.788	1.753	0.980	0.550
3	1.587	1.574	0.992	3.722
4	2.944	2.892	0.982	2.386

TABLE 6.23
Estimated $\hat{\delta}'(i)$ and $\hat{e}(i)$Values with Variances

Site #	$\hat{\pi}(i)$	$Var[\hat{\pi}(i)]$	$\hat{\lambda}(i)$	$Var[\hat{\lambda}(i)]$
1	0.433	0.969	0.833	0.833
2	0.367	0.498	0.200	0.200
3	3.350	20.194	2.000	2.000
4	3.712	13.598	4.500	4.500
Total	7.862	35.259	7.533	7.533

TABLE 6.24
CMFs for Intersection Lighting

Intersection Location	Type of Intersection	Lighting CMF
Fort Wayne	Four-leg Urban	0.79
Indiana	Overall	0.88
	Four-leg	0.90
	Three-leg	0.84
Carmel, Lafayette, West Lafayette	Roundabout	0.61

the index of effectiveness and its variance were estimated as:

$$\hat{\theta} = \frac{\hat{\lambda}/\hat{\pi}}{1+\frac{Var(\hat{\pi})}{\hat{\pi}^2}} = 0.61 \text{and } Var(\hat{\theta}) = \frac{\hat{\theta}^2\left[\frac{Var(\hat{\lambda})}{\hat{\lambda}^2}+\frac{Var(\hat{\pi})}{\hat{\pi}^2}\right]}{\left(1+\frac{Var(\hat{\pi})}{\hat{\pi}^2}\right)^2} = 0.11$$

Therefore, the CMF for replacing traditional intersections with roundabouts is 0.61 with a variance of 0.11. It should be noted that the CMF value of 0.61 was developed with limited number of roundabout intersections and it may not be representative for wide applications. All the CMF values developed in this study are shown in Table 6.24.

7. LIFE CYCLE COST ANALYSIS

7.1 Methodology

The FHWA publication *Economic Analysis Primer* (USDOT, 2003) is a great source of economic analysis methods for highway projects. The FHWA publication indicates that Life Cycle Cost Analysis (LCCA) is applied when an agency must undertake a project and is seeking to determine the lowest life cycle cost (i.e., most cost-effective) means to accomplish the project's objectives. LCCA enables the analyst to make sure that the selection of a design alternative is not based solely on the lowest initial costs, but also considers all the future costs (appropriately discounted) over the project's usable life. To ensure that the alternatives can be compared fairly, the analyst specifies a multiyear analysis period over which the life cycle costs will be measured.

The values of a certain amount of money are different at different points in time. For example, the value of \$100 at present will not be \$100 in ten years because some values will be added to the money in terms of interest. Through LCCA, the future costs are converted to the present values using an interest rate so that the costs can be compared on a common basis. The values of interest rates used in highway projects range from 3% to 5% historically. The interest rate of 4% is currently used by INDOT in economic analysis of highway projects. Therefore, the interest rate of 4% is applied in this study for the life cycle costs of the lighting systems.

To compare two alternatives with LCCA, it is necessary for the two alternatives to have a service period for the same number of years (USDOT, 2003). The service life of current Indiana highway HPS lighting fixtures is 25 years with a lamp replacement cycle of three years. It is expected that the service life of the lighting fixtures for LED, Induction, and Plasma should also be 25 years. The light emitter replacement cycles for the three new lighting systems are not known. For the purpose of life cycle cost analysis, the warranty periods of the three new lighting systems are used as their replacement cycles.

In this study, the initial investment of a lighting device is the total cost of the installed lighting fixture (including labor cost), the annual cost includes the electricity cost and maintenance cost, and the periodical cost is the lamp or emitter replacement cost at the fixed time interval. For one cycle of the service life, the costs for the HPS lights along the time line are shown in Figure 7.1, where the estimated service life is 25, the initial investment is "I," the lamp replacement cost is "r," the annual maintenance cost is "m," and the annual electricity cost is "e."

To calculate life cycle cost, the following symbols are used in the formulas that convert monetary values at different points in time:

- represents an interest rate per year.
- n represents a number of years in the interest period.
- P represents a present value of money, i.e., the value of money at Year 0.
- F represents the value of money at the end of the n^{th} year from the present time (Year 0) that is equivalent to P with interest rate i.
- A represents the end-of-year payment in a uniform series continuing for the coming n years, the entire series equivalent to P at interest rate i.

In this study, the following three formulas that express the relationship between P, F, and A in terms of i and n

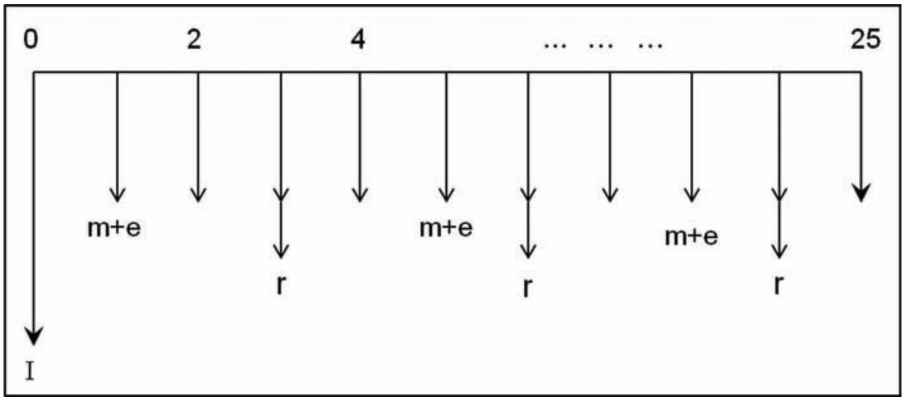


Figure 7.1 Cost flow along service life.

are used to convert the lighting costs to the equivalent present values (Jiang, Li, Guan, & Zhao, 2015):

Given F, to find P:

$$P=F\left[\frac{1}{(1+i)^n}\right] \tag{7.1}$$

Given A, to find P:

$$P=A\left[\frac{(1+i)^n-1}{i(1+i)^n}\right] \tag{7.2}$$

Given P, to find A:

$$A=P\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \tag{7.3}$$

7.2 Life Cycle Benefit and Cost Analysis on New Lighting Project

To show the procedures for life cycle cost analysis on new lighting project, it is assumed that a new light fixture of 168W is to be installed at a four-leg intersection. The cost data for the new lighting project is presented in Table 7.1. According to cost records of past new lighting projects provided by the SAC members, the average construction cost per lighting pole (foundation and other materials included) is \$15,101.63. Since four poles were installed at the intersection, the total cost for each cost item is calculated as four times of the unit cost. Therefore, the total pole and foundation related cost for the project is estimated as \$60,406.54, the total cost of new luminaires is \$3,200.00, the total cost of lamp or emitter replacement is \$780.00, and the total cost for maintenance is \$200.00. The annual electricity cost is calculated by assuming an annual operating time of 4380 hours estimated by INDOT Traffic Administration Section. The Indiana electricity price is \$0.1/kWh, so the annual electricity cost at this intersection is calculated as $\$0.10/\text{kWh}\times 168\text{W}4380\times \text{hours}\div 10004\times \text{Poles}=\$294.34$. The warranty period for the new lighting fixtures is 5 years. Thus, this warranty period is used as the lamp or emitter replacement cycle. In addition, since the service life of luminaires is 25 years estimated by the manufacturer, a 25-year analysis period is used in the following life cycle analysis.

TABLE 7.1
Data Pertinent to Life Cycle Cost Analysis on New Lighting Project

Item	Cost
Pole and Foundation Related Cost	\$60,406.54
Installed New Luminaire Cost	\$3,200.00
Lamp or Emitter Replacement Cost	\$780.00
Annual Electricity Cost	\$294.34
Annual Maintenance Cost	\$200.00

In summary, the Life Cycle Benefit and Cost Analysis (LCBCA) used on the new lighting project applies the following assumptions.

1. Service life: 25 years;
2. Discount Rate: 4%;
3. Lamp replacement cycle: 5 years.

To illustrate the analysis process, the detailed life cycle cost calculations are presented as follows:

Present Worth of Initial Cost.

$$P_{Initial}=P_{Pole\&Foundation}+P_{Luminaire}=\$60{,}406.54$$

$$+\$3200.00=\$63{,}606.54$$

Present Worth of Annual Cost.

$$A=A_{Electricity}+A_{Maintenance}=\$294.34+\$200.00=\$494.34$$

$$P_{Annual}=A\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]$$

$$=\$494.34\times\left[\frac{(1+0.04)^{25}-1}{0.04(1+0.04)^{25}}\right]=\$7{,}722.56$$

Present Worth of Lamp Replacement (Every 5 Years) Cost.

$$P_{Replacement} = F\left[\frac{1}{(1+i)^n}\right] = \$780.00 \times \left\{\left[\frac{1}{(1+0.04)^5}\right] + \left[\frac{1}{(1+0.04)^{10}}\right] + \ldots + \left[\frac{1}{(1+0.04)^{20}}\right]\right\} = \$1957.13$$

Total Present Worth.

$$P = P_{Initial} + P_{Annual} + P_{Replacement} = \$73{,}286.22$$

Equivalent Uniform Annual Cost (EUAC).

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$96{,}746.48 \times \left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$4{,}691.19$$

Safety Benefits. As discussed before, the safety performance function, expressed as $SPF = \exp[a + b \times \ln(AADT_{major}) + c \times \ln(AADT_{minor})]$, can be used to estimate the basic yearly crash counts occurred at the intersection. With a=-8.56, b=0.60, and c=0.61 as coefficients for rural four-leg intersections, the SPF can produce the base crash counts. The yearly crash reductions after installing lighting fixtures at the intersection can then be calculated by using the formula: $SPF * CMF_{lighting} * C$. The lighting CMF for four-leg intersection used here is 0.90, which comes from the last chapter. The coefficient C refers to local calibration factor and it is commonly assumed with the value of one. In order to determine the numbers of fatal crash, injury crash, and PDO crash, results from Chapter 3 are used. From Chapter 3, the proportions of fatal crash, injury crash, and PDO crash in Indiana are estimated as 0.40%, 21.40%, and 78.10%, so yearly crash reductions of fatal crash, injury crash, and PDO crash can be calculated. Listed in Table 7.2 is the summary of crash reductions for the new lighting project in this study.

According to Road Hazard Analysis Tool developed by INDOT, crash can be monetized by using the crash costs for each type of intersection as shown in Table 7.3. For the new lighting project at rural state-state four-leg intersection in this study, the crash costs for fatal crash, injury crash, and PDO crash are selected as \$445,900.00, \$38,600.00, and \$6,800.00. Therefore, the safety benefits due to installing lighting fixtures at the intersections can be estimated as Crash Reduction × Unit Crash Cost.

Presented in Table 7.4 is the yearly safety benefits due to crash reductions in the analysis period. In order to get total project benefits in present value, yearly future safety benefit is converted into present value by using Equation 7.1. Finally, the total project benefit in present value is calculated by summing up all yearly benefit in present value, which produce a total benefit of \$128,338.40.

With a total cost of \$73,286.22 and a total benefit of \$128,338.40 in the analysis period of 25 years, the Net Present Value (NPV) can be calculated as \$55,052.19 and the Benefit Cost Ratio (BCR) can be calculated as 1.75, so this new lighting project can be well justified from the economic perspective. In addition, the return

TABLE 7.2
Crash Reductions in the Analysis Period

Year	Overall	Fatal	Injury	PDO
1	0.362	0.001	0.078	0.283
2	0.375	0.002	0.080	0.293
3	0.389	0.002	0.083	0.304
4	0.403	0.002	0.086	0.315
5	0.418	0.002	0.089	0.326
6	0.433	0.002	0.093	0.338
7	0.449	0.002	0.096	0.351
8	0.465	0.002	0.100	0.363
9	0.482	0.002	0.103	0.377
10	0.500	0.002	0.107	0.390
11	0.518	0.002	0.111	0.405
12	0.537	0.002	0.115	0.419
13	0.557	0.002	0.119	0.435
14	0.577	0.002	0.123	0.450
15	0.598	0.002	0.128	0.467
16	0.620	0.002	0.133	0.484
17	0.642	0.003	0.137	0.501
18	0.665	0.003	0.142	0.520
19	0.690	0.003	0.148	0.539
20	0.715	0.003	0.153	0.558
21	0.741	0.003	0.159	0.579
22	0.768	0.003	0.164	0.600
23	0.796	0.003	0.170	0.622
24	0.825	0.003	0.177	0.644
25	0.855	0.003	0.183	0.668

TABLE 7.3
Unit Crash Cost Used in LCBCA

Type of Intersection	Fatal Crashes	Injury Crashes	PDO Crashes
Rural Local-Local	$281,200.00	$34,500.00	$6,800.00
Rural State-State	***$445,900.00***	***$38,600.00***	***$6,800.00***
Rural State-Local	$377,600.00	$37,300.00	$5,900.00
Urban Local-Local	$281,200.00	$34,500.00	$6,800.00
Urban State-State	$398,900.00	$37,800.00	$7,700.00
Urban State-Local	$285,000.00	$36,400.00	$7,200.00

TABLE 7.4
Life Cycle Benefits for New Lighting Project

Year	Fatal Crash Cost	Injury Crash Cost	PDO Crash Cost	Overall Crash Cost	Present Value
1	$646.21	$2,992.79	$1,924.13	$5,563.12	$5,349.16
2	$669.74	$3,101.76	$1,994.19	$5,765.70	$5,330.71
3	$694.13	$3,214.71	$2,066.81	$5,975.65	$5,312.33
4	$719.40	$3,331.77	$2,142.07	$6,193.24	$5,294.01
5	$745.60	$3,453.09	$2,220.07	$6,418.76	$5,275.75
6	$772.75	$3,578.83	$2,300.91	$6,652.49	$5,257.56
7	$800.89	$3,709.15	$2,384.69	$6,894.73	$5,239.43
8	$830.05	$3,844.21	$2,471.53	$7,145.79	$5,221.36
9	$860.27	$3,984.19	$2,561.53	$7,405.99	$5,203.35
10	$891.60	$4,129.27	$2,654.80	$7,675.67	$5,185.41
11	$924.06	$4,279.63	$2,751.47	$7,955.16	$5,167.52
12	$957.71	$4,435.46	$2,851.66	$8,244.84	$5,149.70
13	$992.59	$4,596.98	$2,955.50	$8,545.06	$5,131.94
14	$1,028.73	$4,764.37	$3,063.12	$8,856.22	$5,114.25
15	$1,066.19	$4,937.85	$3,174.66	$9,178.70	$5,096.61
16	$1,105.01	$5,117.66	$3,290.26	$9,512.93	$5,079.03
17	$1,145.25	$5,304.01	$3,410.07	$9,859.33	$5,061.52
18	$1,186.95	$5,497.15	$3,534.24	$10,218.34	$5,044.06
19	$1,230.17	$5,697.32	$3,662.94	$10,590.43	$5,026.67
20	$1,274.97	$5,904.78	$3,796.32	$10,976.06	$5,009.33
21	$1,321.40	$6,119.79	$3,934.55	$11,375.74	$4,992.06
22	$1,369.51	$6,342.63	$4,077.82	$11,789.97	$4,974.84
23	$1,419.38	$6,573.59	$4,226.31	$12,219.28	$4,957.68
24	$1,471.07	$6,812.96	$4,380.21	$12,664.23	$4,940.59
25	$1,524.63	$7,061.04	$4,539.70	$13,125.38	$4,923.55
Total					$128,338.40

period can be found by listing yearly cumulative cost and benefit as shown in Table 7.5. In the economic analysis, cost items are commonly expressed as negative values. In this table, negative cost items are marked with parenthesis and benefit items are positive values without any special marking. The NPV at each year is the difference between the cumulative cost and cumulative benefit, so it can be seen that at the year of 14, NPV becomes positive value indicating the return period for this project is 14 years.

7.3 Life Cycle Cost Analysis on Lighting Retrofit Project

Lighting retrofit project is different from new lighting project. Lighting CMFs at intersections developed by past researches do not differentiate different types of luminaires, so safety benefits are equal among all luminaire alternatives. To simplify the analysis procedure, benefits are not included in the evaluation of lighting retrofit projects. Therefore, when INDOT replaces the original HPS luminaires with new types of luminaires, LCCA instead of LCBCA is used to find the most cost effective luminaire candidate.

In this section, LCCA are conducted on the project that is going to replace HPS 250W with three new lighting alternatives at the four-leg intersections in Lafayette. The lighting performances of three new lighting alternatives all satisfy what HPS 250W can provide. The cost data and the replacement cycle for each type of luminaire pertinent to LCCA is summarized in Table 7.6. Cost data is provided by either SAC members or the manufacturers. The annual electricity cost is estimated by using similar method mentioned in the previous section. The annual operating time of luminaires is 4380 hours and the Indiana electricity price is $0.10/kWh, so annual electricity cost is calculated by $0.10/kWh × Wattage ÷ of Luminaire × 4380 hours1000. From Table 7.6, it is shown that the

TABLE 7.5
Cumulative Cost, Cumulative Benefits, and Net Present Value

Year	Cumulative Cost	Cumulative Benefits	Net Present Value
Current	$(63,606.52)		$(63,606.52)
1	$(64,081.84)	$5,349.16	$(58,732.69)
2	$(64,538.88)	$10,679.87	$(53,859.02)
3	$(64,978.35)	$15,992.20	$(48,986.15)
4	$(65,400.91)	$21,286.20	$(44,114.70)
5	$(66,448.32)	$26,561.95	$(39,886.37)
6	$(66,839.00)	$31,819.51	$(35,019.49)
7	$(67,214.65)	$37,058.94	$(30,155.72)
8	$(67,575.86)	$42,280.29	$(25,295.57)
9	$(67,923.18)	$47,483.64	$(20,439.53)
10	$(68,784.07)	$52,669.05	$(16,115.02)
11	$(69,105.18)	$57,836.57	$(11,268.61)
12	$(69,413.94)	$62,986.27	$(6,427.67)
13	$(69,710.83)	$68,118.22	$(1,592.61)
14	$(69,996.30)	$73,232.46	$3,236.17
15	$(70,703.89)	$78,329.07	$7,625.18
16	$(70,967.82)	$83,408.10	$12,440.28
17	$(71,221.60)	$88,469.62	$17,248.02
18	$(71,465.62)	$93,513.68	$22,048.06
19	$(71,700.25)	$98,540.35	$26,840.10
20	$(72,281.84)	$103,549.68	$31,267.84
21	$(72,498.77)	$108,541.73	$36,042.96
22	$(72,707.36)	$113,516.58	$40,809.22
23	$(72,907.92)	$118,474.26	$45,566.34
24	$(73,100.77)	$123,414.85	$50,314.07
25	$(73,286.21)	$128,338.40	$55,052.19

TABLE 7.6
Cost Data for Lighting Retrofit Project

	Original HPS-250W	New Lighting Alt.1-250W	New Lighting Alt.2-80W	New Lighting Alt.3-168W
Pole & Foundation Retrofit Cost	$2,140.00	$2,140.00	$2,140.00	$2,140.00
Luminaire Cost	$195.00	$1,100.00	$385.00	$800.00
Lamp/Emitter Replacement Cycle	3 Years	5 Years	5 Years	5 Years
Lamp/Emitter Replacement Cost	$40.00	$195.00	$195.00	$195.00
Annual Electricity Cost	$132.28	$118.26	$35.04	$73.58
Annual Maintenance Cost	$60.00	$50.00	$50.00	$50.00
Total Annual Cost	$192.28	$168.26	$85.04	$123.58

annual electricity cost for three alternatives is all lower than that of HPS 250W. This finding is consistent with the fact that new lighting technologies are more energy friendly than conventional HPS lightings. Specifically, the energy cost of Alternative 2 is $35.04 which is the lowest among all four types of luminaires and is almost only a quarter of energy cost of HPS 250W.

In summary, the LCCA used on the lighting retrofit project applies the following assumptions.

1. Service life: 25 years;
2. Discount Rate: 4%;
3. The lamps are replaced every 3 years for HPS and every 5 years for all three new lighting alternatives, which are their warranty periods.

To illustrate the LCCA process, the detailed calculation procedures of the four luminaires are presented as follows. The analysis of four luminaires follows same procedures but different cost values listed in Table 7.6 are used for each type of luminaire.

Original HPS 250W

Present Worth of Initial Cost

$$P_{Initial} = P_{Pole\&Foundation} + P_{Luminaire} = \$2,140.00 + \$195.00 = \$2,335.00$$

Present Worth of Annual Cost

$$A = A_{Electricity} + A_{Maintenance} = \$132.28 + \$60.00 = \$192.28$$

$$P_{Annual} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] = \$192.28$$

$$\times \left[\frac{(1+0.04)^{25} - 1}{0.04(1+0.04)^{25}}\right] = \$3,003.75$$

Present Worth of Lamp Replacement (Every 5 Years) Cost

$$P_{Replacement} = F\left[\frac{1}{(1+i)^n}\right] = \$40.00 \times \left\{ \left[\frac{1}{(1+0.04)^3}\right]\right.$$

$$\left. + \left[\frac{1}{(1+0.04)^6}\right] + \ldots + \left[\frac{1}{(1+0.04)^{24}}\right] \right\} = \$195.37$$

Total Present Worth

$$P = P_{Initial} + P_{Annual} + P_{Replacement} = \$5,534.12$$

EUAC

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$5,534.12 \times \left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$354.25$$

New Lighting Alt.1 270W

Present Worth of Initial Cost

$$P_{Initial} = P_{Pole\&Foundation} + P_{Luminaire} = \$3,240.00$$

Present Worth of Annual Cost

$$A = A_{Electricity} + A_{Maintenance} = \$168.26$$

$$P_{Annual} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] = \$192.28$$

$$\times \left[\frac{(1+0.04)^{25} - 1}{0.04(1+0.04)^{25}}\right] = \$2,628.57$$

Present Worth of Lamp Replacement (Every 5 Years) Cost

$$P_{Replacement} = F\left[\frac{1}{(1+i)^n}\right] = \$195.00 \times \left\{ \left[\frac{1}{(1+0.04)^5}\right]\right.$$

$$\left. + \left[\frac{1}{(1+0.04)^5}\right] + \ldots + \left[\frac{1}{(1+0.04)^{20}}\right] \right\} = \$489.28$$

Total Present Worth:eplacement (Every 5 Years) Cost

$$P = P_{Initial} + P_{Annual} + P_{Replacement} = \$6357.85$$

EUAC

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$6,357.85 \times \left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$406.98$$

New Lighting Alt.2 80W

Present Worth of Initial Cost

$$P_{Initial} = P_{Pole\&Foundation} + P_{Luminaire} = \$2,525.00$$

Present Worth of Annual Cost

$$A = A_{Electricity} + A_{Maintenance} = \$85.04$$

$$P_{Annual} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] = \$85.04 \times \left[\frac{(1+0.04)^{25} - 1}{0.04(1+0.04)^{25}}\right] = \$1328.50$$

Present Worth of Lamp Replacement (Every 5 Years) Cost

$$P_{Replacement} = F\left[\frac{1}{(1+i)^n}\right] = \$195.00$$

$$\times \{ \left[\frac{1}{(1+0.04)^5}\right] + \left[\frac{1}{(1+0.04)^{10}}\right] + \ldots$$

$$+ \left[\frac{1}{(1+0.04)^{20}}\right] \} = \$489.28$$

Total Present Worth

$$P = P_{Initial} + P_{Annual} + P_{Replacement} = \$4,342.78$$

EUAC

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$4,342.78 \times \left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$277.99$$

New Lighting Alt.3 168W

Present Worth of Initial Cost

$$P_{Initial} = P_{Pole\&Foundation} + P_{Luminaire} = \$2,940.00$$

Present Worth of Annual Cost

$$A = A_{Electricity} + A_{Maintenance} = \$123.58$$

$$P_{Annual} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] = \$123.58$$

$$\times \left[\frac{(1+0.04)^{25} - 1}{0.04(1+0.04)^{25}}\right] = \$1{,}930.64$$

Present Worth of Lamp Replacement (Every 5 Years) Cost

$$P_{Replacement} = F\left[\frac{1}{(1+i)^n}\right] = \$195.00 \times \left\{\left[\frac{1}{(1+0.04)^3}\right]\right.$$

$$\left. + \left[\frac{1}{(1+0.04)^6}\right] + \ldots + \left[\frac{1}{(1+0.04)^{24}}\right]\right\} = \$489.28$$

Total Present Worth

$$P = P_{Initial} + P_{Annual} + P_{Replacement} = \$5{,}359.92$$

EUAC

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$5{,}359.92 \times \left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$343.10$$

Summarized in Table 7.7 are the above calculation results. HPS 250W has the smallest initial costs and overall replacement costs compared with other three new lighting alternatives. However, the overall annual cost of HPS is the highest, which eventually compensate its relatively lower initial costs.

The life cycle costs of the luminaire alternatives are compared with that of HPS 250W as presented in Table 7.8. The differences between the life cycle cost of HPS 250W and alternatives are listed in the second column and the differences of EUAC between HPS 250W and alternatives are listed in the last column as the equivalent uniform annual savings. The positive value of life cycle cost difference and EUAC difference mean the alternative is more cost effective than the HPS. Otherwise, the negative values, marked in parenthesis, mean the alternative is not as cost effective as HPS. As indicated in Table 7.8, Alt.2-80W and Alt.3-168W are more cost effective, but Alt.-1 270W is less cost effective compared with the HPS due to its higher luminaire wattage. This is also clearly illustrated in Figure 7.2.

In addition to the life cycle cost comparisons, the return period provides information on the time needed for luminaire alternatives to have a break-even life cycle cost as compared to the original HPS. The return period of a luminaire alternative is useful to identify how soon the new type of luminaire can become cost effective within its service life so that the minimum warranty time period can be determined.

Figure 7.3 shows how to identify the return periods of new lighting Alt.1-270W, Alt.2-80W, and Alt.3-168W compared to the HPS 250W. Original HPS, Alt.1, Alt.2, and Alt.3 are represented by red line, blue dash line, yellow dash-dot-dot line, and green dash-dot line, correspondingly. Because Alt.1-270W never crosses original HPS 250W, no return period exists for Alt.1. As can be seen from the figure, HPS intersects Alt.2-80W at the second year and HPS intersects Alt.3-168W at the year of 17, so the return periods for Alt.2 and Alt.3 are 2 year and 17 years respectively.

In summary, with a discount rate of 4% and warranty periods as lamp or emitter replacement cycles, the LCCA for this lighting retrofit project indicates that Alternative 2 and 3 are more cost effective than the original HPS 250W. The life cycle cost of Alternative 1 is higher than HPS by $823.73 so it is not cost effective. Major reason leading to unfavorable Alternative 1 in this project is the luminaire wattage. With higher wattage and thus higher energy consumption and higher initial and replacement cost, Alternative 1 is not as competitive as the other two alternatives. Because Alternative 2 has a wattage of only 80W, its energy savings are greater than the Alternative 3 by around 600 dollars in the analysis period.

TABLE 7.7
Comparisons of Life Cycle Costs in Lighting Retrofit Project ($ in Present Value)

	Original HPS-250W	New Lighting Alt.1-250W	New Lighting Alt.2-80W	New Lighting Alt.3-168W
Initial Cost	$2,335.00	$3,240.00	$2,525.00	$2,940.00
Overall Annual Cost	$3,003.75	$2,628.57	$1,328.50	$1,930.64
Overall Replacement Cost	$195.37	$489.28	$489.28	$489.28
Total Cost	$5,534.12	$6,357.85	$4,342.78	$5,359.92
EUAC	$354.25	$406.98	$277.99	$343.10

TABLE 7.8
Comparisons of Life Cycle Costs with HPS 250W

Luminaire Type	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,534.12-LCC)	EUAC	Equivalent Uniform Annual Savings ($354.25-EUAC)
Original HPS 250W	$5,534.12	–	$354.25	–
New Alt.1 270W	$6,357.85	$(823.73)	$406.98	$(52.73)
New Alt.2 80W	$4,342.78	$1,191.34	$277.99	$76.26
New Alt.3 168W	$5,359.92	$174.20	$343.10	$11.15

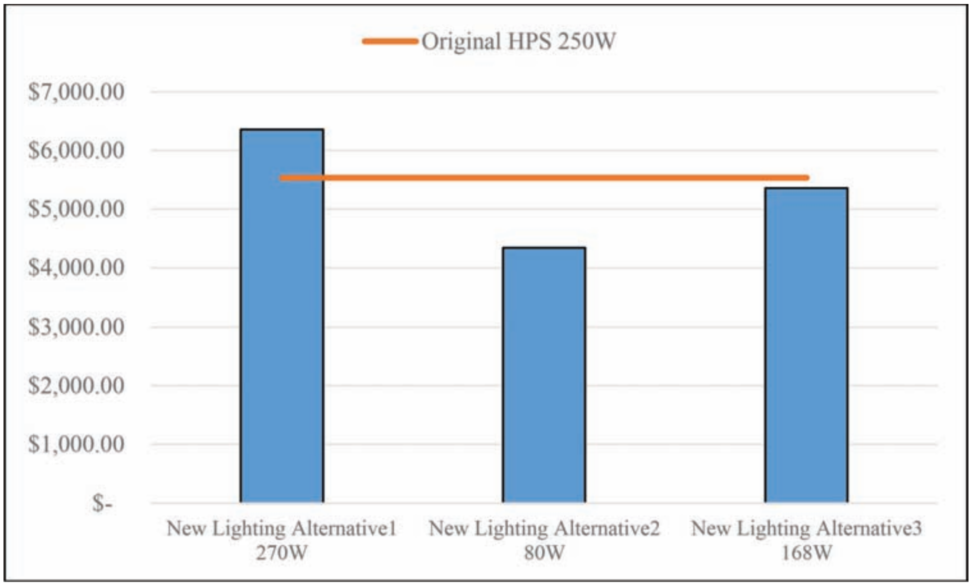


Figure 7.2 Comparison of life cycle costs with 250W HPS.

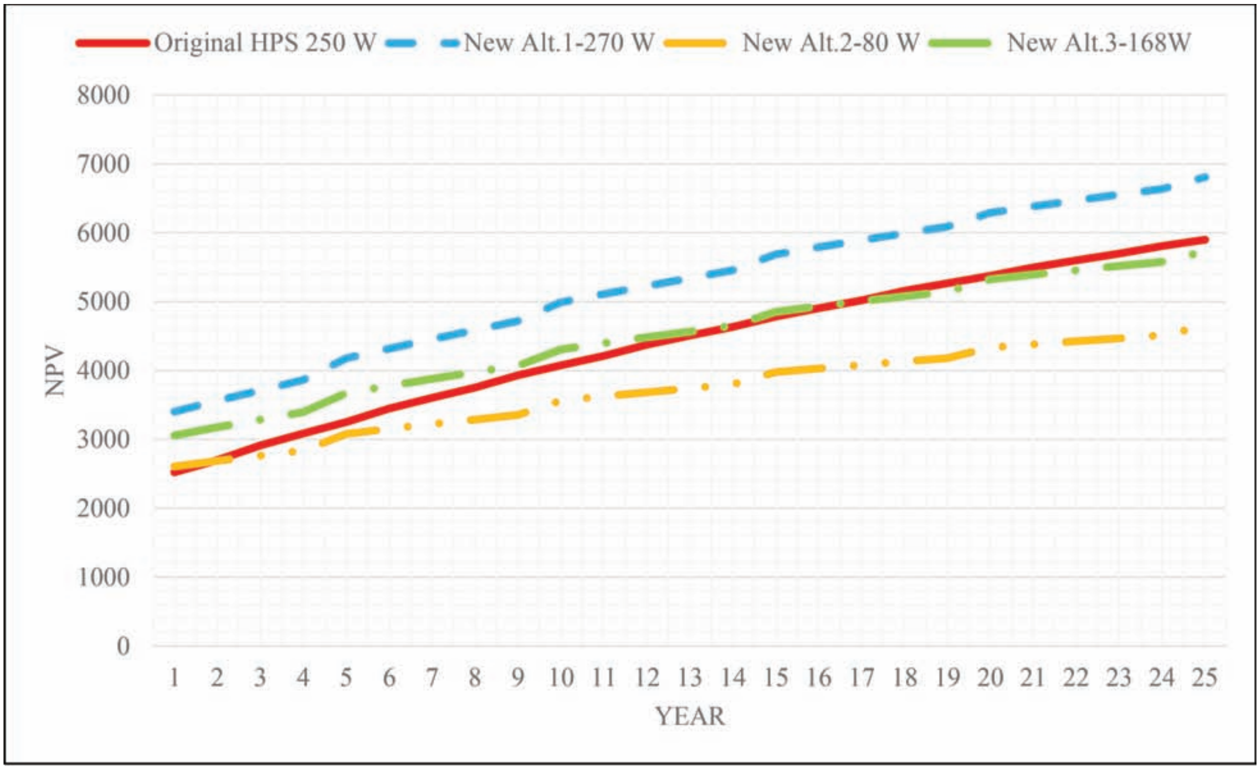


Figure 7.3 Return period identifications.

8. FINDINGS AND CONCLUSIONS

It is believed that the results of this study will be very useful for safety enhancement at roadway intersections. The major findings from this study are summarized below.

8.1 Crash Data Analysis

From crash data retrieved from database of FARS, GES, and ARIES, it was shown that from 2004 to 2013 the percentage of intersection fatal crash was 30.6% in Indiana, which was higher than the US level, 28.6%. Among the neighboring states, including Indiana, Illinois, Kentucky, Michigan, Ohio, and Wisconsin, Indiana had the second highest intersection fatality rate and the highest the percentage of crashes at unlit intersections. From the distribution of nighttime fatal intersection crashes, it was shown that in Indiana 73% of crashes occurred at unlit intersections, which was much higher than the US level of 34% and the neighboring states of 38%. In Indiana, on average, 0.4% of crashes were fatal, 21.4% involved injuries, and 78.1% resulted in property damages only. Top five primary factors that led to crashes at intersections were failure to yield right of way, following too closely, disregard signal, ran off road right, and speed too high for weather conditions. Top five manners of collision for intersection crashes in Indiana were rear end, right angle, ran off road, head on of two vehicles, and same direction sideswipe.

8.2 Illuminance Measurements

Illuminance measurements were conducted at 14 intersections, including five four-leg intersections, three three-leg intersections, five roundabouts, and one interchange. Among the 14 intersections, new lighting luminaires were installed at six intersections to replace the existing HPS lamps. Therefore, the measurements were made before and after the new lighting installations at these six intersections. It was found that the installation of Stray Light Plasma 270W was quite easy at the intersection of Creasy Lane and SR 38 in Lafayette. When replacing HPS with Philips CMH 210W at the intersection of SR 43 and I-65 north exit ramp, installation of CMH ballast was time consuming because the electrical connections needed some extra efforts.

To compare the lighting effects of the conventional HPS and the new luminaires installed at the selected sites, the key measured illuminance values and illuminance distributions were provided. The maximum uniformity ratio specified in the INDOT standard is 4.0. As the measuring distance increases, the minimum illuminance decreases to a small level that would yield a high uniformity ratio. The maximum illuminance measuring distances for the study sites were calculated that would make the uniformity ratio less than or equal to 4.0. These distance values can be considered the effective distances of the intersection lighting. With the effective distances, the average illuminance would generally increase. An effective distance can be used as a basis for future intersection lighting design and illuminance measurements.

8.3 Survey Results

The SHA and local city survey indicated that LED is the most attractive new lighting technologies used by highway agencies. LED was used more frequently at signalized intersections than non-signalized intersections, roundabouts, and interchanges in the past five years. With respect to the performance, the performance of LED received more “Excellent” evaluations than that of HPS. The major benefits of LED mentioned by surveyed highway agencies included safety improvement and energy savings, and the major concerns included higher initial and maintenance cost, lighting pole as potential roadside hazard, and eye adjustment to the new lighting technologies. The community survey investigated public perceptions toward the installations of new lightings at five intersections. It showed 88% of respondents were quite pleased with the performance of new lightings. Some people suggested new lighting lamps be used at more intersections.

8.4 Lighting CMFs

The crash modification factors for intersection lighting were developed with the Indiana crash data. The resulted CMF values for Indiana intersection lighting include, 0.88 for overall intersection lighting, 0.90 for a four-leg intersection lighting, and 0.84 for three-leg intersection lighting.

8.5 Life Cycle Analysis

The life cycle cost analysis was performed for the luminaires under evaluation in this study. It was shown that all of the new luminaires, except the Alt.2-270W, installed at the selected intersections are cost effective compared to the replaced HPS lamps. In addition, the return period, or the break-even time, of each cost effective luminaire was determined. To facilitate the life cycle analysis on new lighting projects and lighting retrofit projects, an MS excel based worksheet has been developed in this study. It is recommended this worksheet be used as a standard tool for life cycle benefit and cost analysis of roadway lighting projects.

8.6 Lighting Test Method

Based on the results of this study, the INDOT Lighting Test Method was developed as shown in Appendix C. The Lighting Test Method has been adopted by the Indiana Test Methods (ITM) Committee. Appendix C is the current version of the adopted Lighting Test Method. It includes the general requirements and procedures for new lighting device’s sampling, submittal, evaluation, warranty, and approval list.

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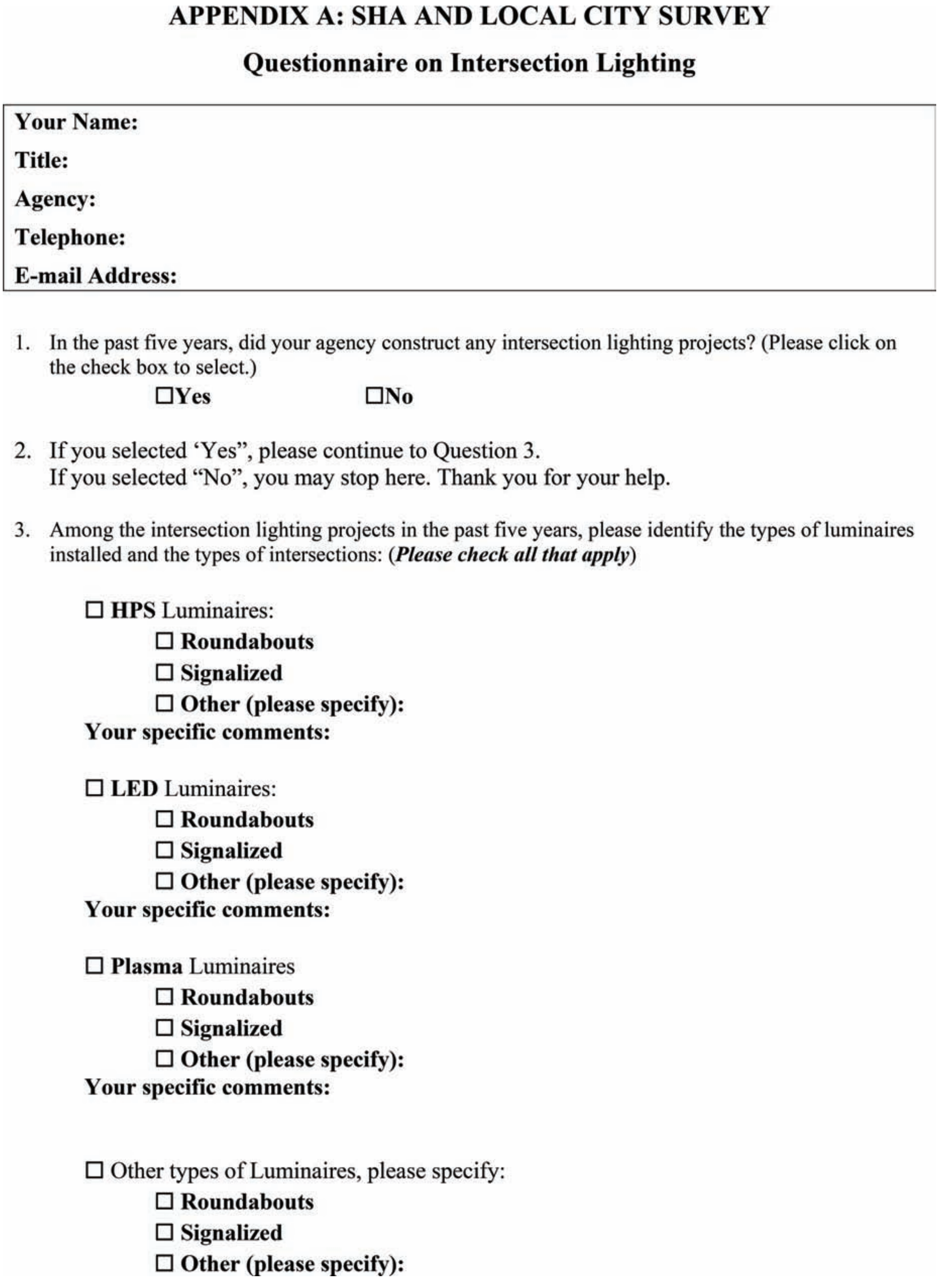


APPENDIX A: SHA AND LOCAL CITY SURVEY

Questionnaire on Intersection Lighting

Your Name:
Title:
Agency:
Telephone:
E-mail Address:

1. In the past five years, did your agency construct any intersection lighting projects? (Please click on the check box to select.)

   ☐**Yes** ☐**No**

2. If you selected 'Yes", please continue to Question 3.
   If you selected "No", you may stop here. Thank you for your help.

3. Among the intersection lighting projects in the past five years, please identify the types of luminaires installed and the types of intersections: (***Please check all that apply***)

☐ **HPS** Luminaires:
  ☐ **Roundabouts**
  ☐ **Signalized**
  ☐ **Other (please specify):**
Your specific comments:

☐ **LED** Luminaires:
  ☐ **Roundabouts**
  ☐ **Signalized**
  ☐ **Other (please specify):**
Your specific comments:

☐ **Plasma** Luminaires
  ☐ **Roundabouts**
  ☐ **Signalized**
  ☐ **Other (please specify):**
Your specific comments:

☐ Other types of Luminaires, please specify:
  ☐ **Roundabouts**
  ☐ **Signalized**
  ☐ **Other (please specify):**

4. Please indicate the performance of your intersection lighting systems:

LED lighting:
☐**Excellent**
☐**Satisfactory**
☐**Unsatisfactory**
☐**N/A**
Your specific comments:

Plasma lighting:
☐**Excellent**
☐**Satisfactory**
☐**Unsatisfactory**
☐**N/A**
Your specific comments:

HPS lighting:
☐**Excellent**
☐**Satisfactory**
☐**Unsatisfactory**
☐**N/A**
Your specific comments:

5. Among the intersection lighting projects in the past five years, please provide the justifications or main reasons for the lighting projects:

☐ **New lighting installations** (such as installing lighting at a new intersection, changing an existing intersection from non-lighted to lighted, safety improvements, etc.):
Your specific comments:

☐ **Lighting modernizations** (such as replacing HPS lighting with LED, improving existing lighting design, safety improvements, etc.)
Your specific comments:

☐ **Other:**
Your specific comments:

6. With respect to safety improvements, please identify and list the major benefits and risks that you considered for intersection lighting projects.

   Benefits (such as crash reduction, energy savings, low life cycle cost, pedestrian safety, public security, etc.):

   Risks (such as lighting pole as potential roadside obstacle, high construction cost, glare effects, etc.):

7. For the intersection lighting projects in the past five years, are there any warrants considered for intersection lighting?

   ☐**Yes**
   Please provide a copy of the warrants, thank you.

   ☐**No**

8. Would you like to share your experience with us?

   Also, do you have something to suggest to us?

Thank you very much for your help.

APPENDIX B: COMMUNITY SURVEY

The survey questions for other four intersections are the same.
***New LED (light-emitting diode)** lighting devices were installed on July 15, 2015 to replace the **old HPS (high pressure sodium)** lighting lamps at the **intersection of Creasy Lane and State Road 38 in Lafayette near you neighborhood**. The purpose of using the new lighting technology at this intersection is to improve safety as well as to significantly reduce electricity usage. As part of the evaluation effort, we would like to receive input from you about your feelings and opinions on the performance of the new lighting devices in comparison with the old lighting devices.*

Note:

1. ***The survey is approved by Purdue Human Research Protection Program.***
2. ***The survey is 100% voluntary and all respondents must be above 18 years old.***
3. ***Your responses will be anonymous and confidential and only project researchers will use the data you provide.***
4. ***It takes at most 5 minutes to complete this questionnaire and please use the included stamped envelope to mail your response back within 30 days. The address is already on the envelope.***
5. ***You could also complete the same survey online:*** ***https://purdue.qualtrics.com/SE/?SID=SV_0D3pguQo9uXBmJf***

Thank you in advance for your input.

1. Compared with the previous intersection lighting, please indicate whether you agree or disagree with the following statements:

The light level is improved at night by the new lighting.

☐ Strongly Agree
☐ Agree
☐ Neither Agree nor Disagree
☐ Disagree
☐ Strongly Disagree

The nighttime visibility is improved by the new lighting.

☐ Strongly Agree
☐ Agree
☐ Neither Agree nor Disagree
☐ Disagree
☐ Strongly Disagree

Driving is safer at night under the new lighting.

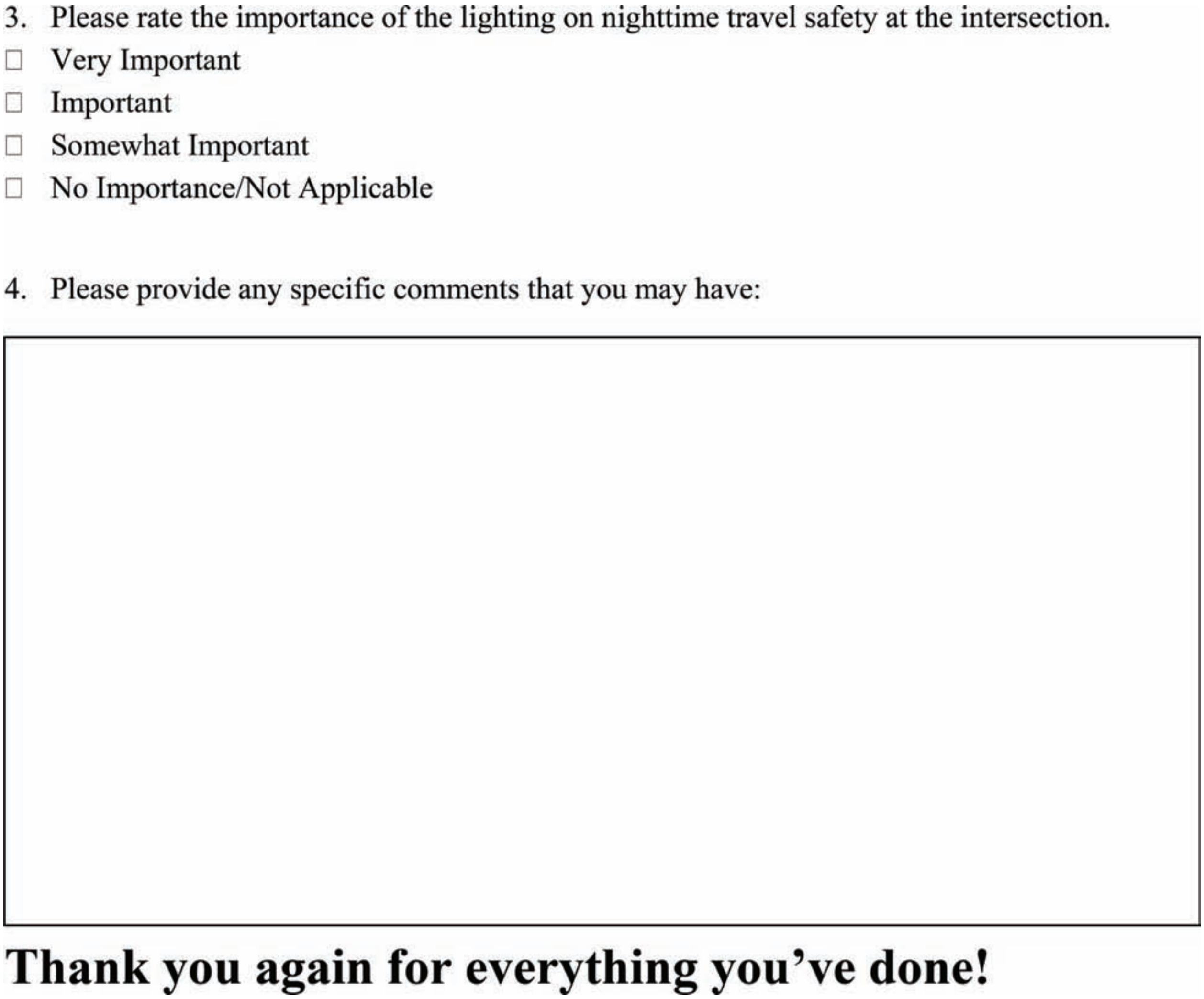
☐ Strongly Agree
☐ Agree
☐ Neither Agree nor Disagree
☐ Disagree
☐ Strongly Disagree

The new lighting improves nighttime street use and neighborhood security.

☐ Strongly Agree
☐ Agree
☐ Neither Agree nor Disagree
☐ Disagree
☐ Strongly Disagree

2. Please indicate your level of overall satisfaction with the new intersection lighting.

☐ Very Satisfied
☐ Somewhat Satisfied
☐ Neither Agree nor Disagree
☐ Somewhat Dissatisfied
☐ Very Dissatisfied



3. Please rate the importance of the lighting on nighttime travel safety at the intersection.

☐ Very Important
☐ Important
☐ Somewhat Important
☐ No Importance/Not Applicable

4. Please provide any specific comments that you may have:

Thank you again for everything you've done!

APPENDIX C: LIGHTING TEST METHOD

INDIANA DEPARTMENT OF TRANSPORTATION
OFFICE OF TRAFFIC ADMINISTRATION
PROCEDURE FOR EVALUATION AND APPROVAL LIST REQUIREMENTS FOR SOLID STATE LUMINAIRES

1.0 SCOPE

1.1 This procedure establishes the method that a luminaire utilizing solid state technology is evaluated and is placed, maintained, or removed from the approval list.

1.2 Luminaires submitted for evaluation will be considered for approval under one or more of the following sublists:

1.2.1 High Mast

Models placed on this list must be a suitable and cost effective alternative to a 1000 watt High Pressure Sodium luminaire. To be approved the model shall provide adequate light output so that INDOT design light levels are met in a system consisting of towers with mounting heights as great as 200 ft (typically 125 ft to 150 ft) while operating at no more than 550 watts of power. Models should be capable of both symmetric and asymmetric light distributions, but those that are limited to symmetric distribution patterns may be considered for approval with that limitation.

1.2.2 High Lumen Roadway

Models placed on this list must be a suitable and cost effective alternative to a 400 watt High Pressure Sodium luminaire. To be approved the model shall provide adequate light output so that INDOT design light levels are met in a system utilizing 40 ft mounting heights while operating at no more than 250 watts of power. Models shall be capable of IESNA Type II and Type III light distributions.

1.2.3 Low Lumen Roadway

Models placed on this list must be a suitable and cost effective alternative to a 250 watt High Pressure Sodium luminaire. To be approved the model shall provide adequate light output so that INDOT design light levels are met in a system utilizing 35 or 40 ft mounting heights while operating at no more than 150 watts of power. Models shall be capable of IESNA Type II and Type III light distributions.

1.2.4 Low Lumen- Low Mounting Height Roadway

Models placed on this list must be a suitable and cost effective alternative to a 250 watt High Pressure Sodium luminaire. To be approved the model shall provide adequate light output so that INDOT design light levels are met in a system utilizing 25 or 30 ft mounting heights while operating at no more than 150 watts of power. Models shall be capable of IESNA Type II and Type III light distributions.

1.2.5 Underpass

Models placed on this list must be a suitable and cost effective alternative to a 150 watt High Pressure Sodium luminaire. To be approved the model shall provide adequate light output so that AASHTO recommended light levels are met at the same or lower operating power.

1.3 This ITM may involve hazardous materials, operations, and equipment and may not address all of the safety problems associated with the use of the test method. The user of the ITM is responsible for establishing appropriate safety and health practices and determining the applicability of regulatory limitations prior to use.

2.0 REFERENCES

2.1 ANSI Standards

C136 Series	Standards for Roadway and Area Lighting Equipment
C62.41.2	Practice on Characterization of Surges in Low-voltage (1000 V and Less) AC Power Circuits

C78.377	Specifications for the Chromaticity of Solid-state Lighting Products
C82.77	Harmonic Emission Limits-Related Power Quality Requirements for Lighting Equipment
1449	Safety, Transient Voltage Surge Suppressors, Third Edition (ANSI/UL)
1598	Luminaires (ANSI/UL)
8750	Light Emitting Diode (LED) Equipment for Use in Lighting Products (ANSI/UL)
60529	Degrees of Protection Provided by Enclosures (IP Code)

2.2 IES Standards

RP-8-14	Recommended Practice for Roadway Lighting
LM-16	Correlated Color Temperature
LM-79-08	Electrical and Photometric Measurements of Solid State Lighting Products
LM-80-08	Measuring Lumen Maintenance of LED Light Sources
TM-15-11	Luminaire Classification System for Outdoor Luminaires
TM-21 -11	Projecting Long-Term Lumen Maintenance of LED Light Sources

2.3 INDOT Standards

INDOT Standard Specifications, Sections 807 & 920
Indiana Design Manual, Chapter 502-4

3.0 TERMINOLOGY. Definitions for terms and abbreviations shall be in accordance with Indiana Design Manual as well as ANSI/IESNA RP-8-14, American National Standard Practice for Roadway Lighting.

4.0 SIGNIFICANCE AND USE. This ITM is used to evaluate, approve, maintain approval, and remove luminaires which are placed on the Department List of Luminaires. Each luminaire model will be evaluated separately.

5.0 SAMPLING.

5.1 High Mast Luminaires. The manufacturer shall furnish, at no cost to the Department, 6 randomly selected production-run luminaires of each model to be evaluated for a test period of at least 3 months. The manufacturer shall deliver the luminaires to the location determined by the Department.

5.2 Roadway and Underpass Luminaires. The manufacturer shall furnish, at no cost to the Department, 3 randomly selected production-run luminaires of each model to be evaluated for a test period of at least 3 months. The manufacturer shall deliver the luminaires to the location determined by the Department.

6.0 SUBMITTAL

6.1 The manufacturer shall submit the Preliminary Product Evaluation Form for each model of luminaire to be considered for the approved list.

6.2 The following documentation regarding the proposed luminaire shall be submitted with the Evaluation Form. Certifications and test reports shall be provided by a laboratory that is either listed as a National Recognized Testing Laboratory or accredited by the National Voluntary Laboratory Accreditation Program (NVLAP).

6.2.1 Luminaire specifications and data sheets;
6.2.2 Test report verifying UL 1598 compliance;
6.2.3 Test report indicating compliance with ANSI C 136.31 2G or 3G requirements;
6.2.4 Test reports in accordance with ANSI/IEC 60529 indicating the IP ratings for the optical assembly, power drivers, and surge protection devices;
6.2.5 Test reports in accordance with ANSI C82.77 for electronic power drivers indicating the total harmonic distortion and power factor
6.2.6 IESNA LM-79 test report;
6.2.7 Test report indicating surge protection device survival in accordance with ANSI/IEEE C62.41.2;
6.2.8 UL 1449 certification;
6.2.9 Test report indicating Title 47 CFR Part 15, Class A compliance;
6.2.10 Mean time to failure prediction for the power driver in accordance with Telcordia SR 332, issue 3 or MIL-HDBK-217F;
6.2.11 Power driver lifetime report;
6.2.12 IESNA LM-80 test report if the proposed light source is LED;
6.2.13 IESNA TM-21 test report indicating the maximum LED junction temperature if the proposed light source is LED.
6.2.14 IESNA photometric distribution file in either Visual, developed by Acuity Brands Lighting, or AGi32 from Lighting Analysis, Inc for the applicable distribution types (see section 7.2).
6.2.15 Salt spray test report in accordance with ASTM B117
6.2.16 Warranty documents.

The requestor is encouraged to submit any supporting documents and references as to the manufacturer's experience and performance history. This documentation should indicate experience in providing luminaires for public agency projects, show ability to honor warranties, and attest to long term stability of the manufacturer.

7.0 EVALUATION. The evaluation will consist of three steps- review of the required documentation, physical check, and a field test of the model.

7.1 Submittal Documentation Review. The documentation provided with the Evaluation Form will be reviewed for completeness and to determine that the required reports and certifications demonstrate the model meets or exceeds the requirements set forth in INDOTs Standard Specifications. This review will include a theoretical check of the photometric adequacy of the luminaire by applying the photometric file to a typical system. The photometric analysis must show that the applicable INDOT design levels for average illumination and uniformity (ratio of average to minimum illumination levels) are met. The manufacturer's warranty will also be reviewed for compliance with section 8.0 and the standard specifications. The manufacturer's long term stability and ability to meet warranty requirements will also be considered.

7.2 Physical Review. Once all the required documentation is reviewed and found to be acceptable the following will be verified prior to field testing:

7.2.1 A slip-fitter is provided that is capable of mounting to a 2 inch mounting bracket with adjustments $\pm 5^{\circ}$ from level.

7.2.2 Housing is painted in light gray.

7.2.3 The weight of luminaire is no more than 53 lb.

7.2.4 The effective projected area is no more than 2.4 sq. ft.

7.2.5 External and internal labels in accordance with ANSI C136.15 and ANSI C136.22 respectively are provided.

7.2.6 Fans or other mechanical cooling systems are not used for thermal management.

7.2.7 Access (door) to optical and electrical components is provided. Hinges and latches are made of corrosion resistant materials and remain closed during the operation.

7.2.8 Power supply drivers, surge protection devices, LED arrays, and plasma emitters are replaceable without replacing the entire luminaire.

7.2.9 The luminaire has a five or seven wire photo-control receptacle in accordance with ANSI C136.41 with shorting cap for adaptive lighting control.

7.3 **Field Test**. Unless waived by the Department, a field test will be conducted on existing lighting poles/high mast towers in order to verify:

- Light Output
- Chromaticity
- Power Consumption
- Ease of Installation
- Reliability

The testing period shall last at least 3 months or as determined by INDOT. The method for in-service illuminance performance will conform to the procedure below:

7.3.1 Light Output Measurement Procedure:

7.3.1.1 An illuminance or chroma meter will be used to obtain readings two times- the first proximate to the time of activation and the second towards the end of the test period.

7.3.1.2 Measurement Locations:

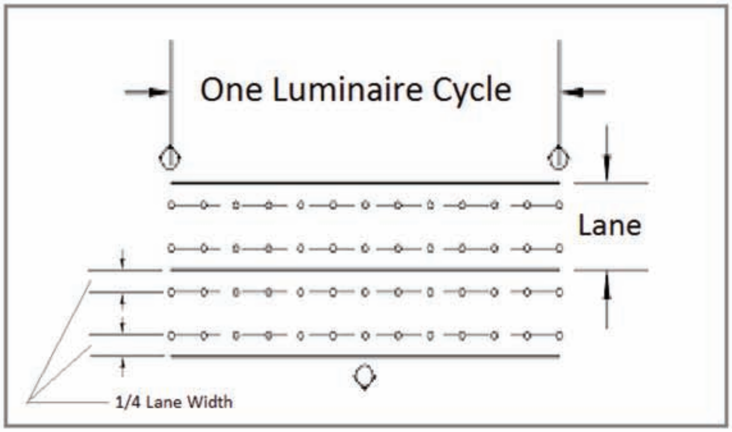
a. Roadway and Underpass Luminaires:

i. For staggered pole placements one luminaire cycle (3 Light Poles) will be tested and cover the distance of two adjacent poles.

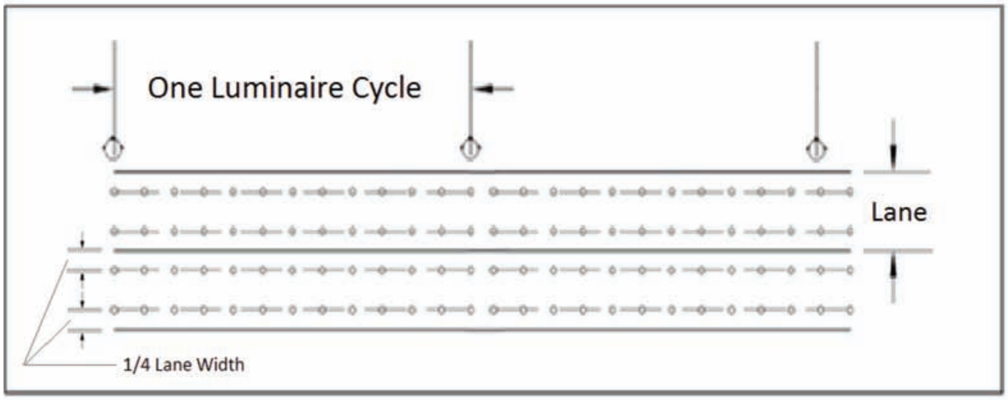
ii. For one sided pole placements two luminaire cycles (2 poles) will be tested and cover the distance between the two poles.

iii. If the distance between two adjacent luminaires is large, the luminaire cycle will begin from the selected pole to its two sides at a distance where rapid changing illuminance readings are found.

iv. Test points on straight roadway areas shall be determined as in the figure below. Test points shall be at the quarter-lane lines. From the selected pole, test points shall be marked and measured at a space no more than 16 ft.



Staggered Pole Placement



One -Sided Pole Placement

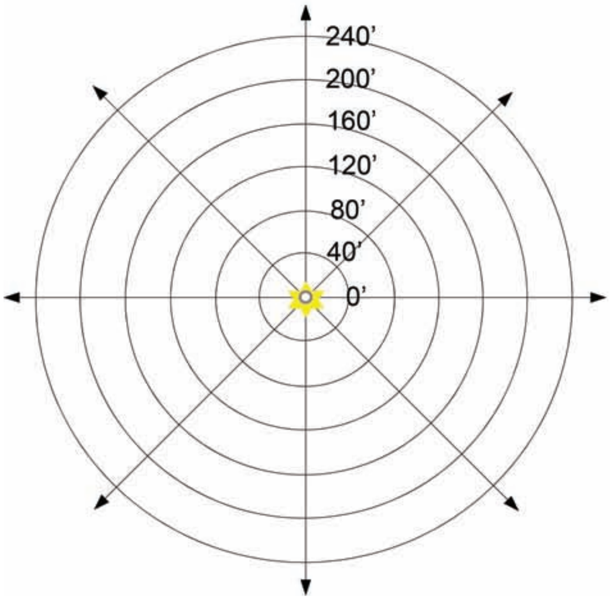
v. Determination of test points on junctions shall meet the criteria on straight roadway areas.

    vi. Once the illuminance data is collected for the test area, the maximum illuminance, average illuminance, minimum illuminance, and uniformity ratio will be determined and compared to the illuminance design criteria provided in Figure 502-4E of the Indiana Design Manual.

b. High Mast Luminaires:

    i. For high mast luminaires one tower (100’ or 125’) with 4 or 6 luminaires will be tested for both symmetric and asymmetric patterns unless the requestor indicates that the model is for symmetric use only. Luminaire aiming capabilities at 360 degree angles.

    ii. Test points along 6 lines at 60 angles radiating from the tower will be determined as in the figure below. Test points shall be marked and measured at a space of 40 ft or as site conditions allow.



iii. Determination of test points on junctions shall meet the criteria at an interchanges.

iv. Once the illuminance data is collected for the test area, the maximum illuminance, average illuminance, minimum illuminance, and uniformity ratio will be determined and compared to the illuminance design criteria provided in Figure 502-4E of the Indiana Design Manual.

7.3.2 Chromaticity Verification

7.3.2.1 A chroma meter will be used to obtain Color Temperature readings two times- the first proximate to the time of activation and the second towards the end of the test period.

7.3.2.2 Correlated Color Temperature readings will be taken at one location which will be noted. For roadway and underpass, the reading will be taken proximate to the midpoint of the cycle. The reading towards the end of the test period will be taken at the same location.

7.3.2.3 All values taken must be within the range allowed by the Standards Specifications.

7.3.3 Power Consumption Check

7.3.3.1 An amp meter will be used to measure current draw of each luminaire Provided two times- the first proximate to the time of activation and the second towards the end of the test period.

7.3.3.2 Measured current will be converted to power by the following relationship: Power (wattage) = Current Drawn (amps) x Electric Potential (voltage)

7.3.3.3 This calculated power will be compared to the documentation submitted. A value greater than the limit indicated in Section 1.2 will be grounds for rejection. A value that is significantly greater than that indicated by the submittal documentation may also be cause for rejection.

7.3.4 Ease of Installation. District personal that install will be asked if they had any problems with the installation and how the process compared to installing a traditional HPS luminaire.

7.3.5 Reliability. During the test period any performance issues will be noted. Luminaire failure, light source flickering, loss of light output, or color degradation will be cause for rejection

8.0 WARRANTY

In accordance with INDOT Specifications a non-prorated manufacturer's written warranty against loss of performance and defects in materials and workmanship for a period not less than five years after installation shall be provided covering all components of the luminaire including ballast, driver, and light source.

The criteria defining the loss of performance includes more than 10% of the total number of original individual LEDs fail, the luminaire is operating below the lumen maintenance curve, and the color temperature shifts more than 500K outside of the specified color temperature range.

Warranty documents shall provide the manufacturer's name, contact person, telephone phone number, and email address. Warranty documents shall provide the estimated life cycle of the lamps, LEDs, or Plasma emitter, and power driver.

9.0 APPROVAL LIST

9.1 The luminaire unit(s) may be placed on the approval list when the following conditions are met:

a) A potential net benefit to the Department is realized by inclusion of the item on the list.
b) The physical review and field testing are completed with satisfactory results.
c) The required documentation is submitted.
d) Only minimal maintenance operations were necessary during the field testing.

9.2 The Indiana Department of Transportation reserves the right to perform random sample testing on all shipments at its own cost. Random sample testing will be completed as soon as possible after delivery. INDOT shall determine the sampling parameters to be used for random testing. If the units tested fail random testing the units will be removed from the INDOT product list for LED luminaires.

9.3 The Department reserves the right to remove models from the approved list as better performing models are submitted as determined by the procedure detailed in Section 7.0.

The Department may choose to limit the number of models on any of the sub lists to facilitate maintenance.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

About This Report

An open access version of this publication is available online. This can be most easily located using the Digital Object Identifier (doi) listed below. Pre-2011 publications that include color illustrations are available online in color but are printed only in grayscale.

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