To the University Council:

The Thesis Committee for Najmeh Jami certifies that this is the final approved version of the following electronic thesis: "LED Traffic Signal Retrofits: Implications for Intersection Safety."

Stephanie S. Ivey, Ph.D.
Major Professor

We have read this thesis and recommend its acceptance:

Martin E. Lipinski, Ph.D.

Michail Gkolias, Ph.D.

Accepted for the Graduate Council:

Karen D. Weddle-West, Ph.D.
Vice Provost for Graduate Programs

LED TRAFFIC SIGNAL RETROFITS: IMPLICATIONS FOR INTERSECTION SAFETY

by

Najmeh Jami

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ABSTRACT

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The recent advancements in light emitting diode (LED) technology and the comparative energy savings over traditional incandescent bulbs have led to many municipalities retrofitting traffic signals with new LED bulbs. Although a significant amount of literature exists regarding benefits of LED installations in terms of energy and economic savings, less attention has been given to the potential safety impacts of these massive retrofit projects. This thesis will evaluate the safety implications of the change to LED technology in traffic signals in Memphis, Tennessee, where 56 full LED conversions and 712 partial conversions (red and green only) of signalized intersections have occurred since 2000 and present findings from analysis of before and after crash data to determine the intersection safety impact, if any, of LED traffic signals.

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CHAPTER 1

INTRODUCTION

In August, 2005, the Highway Safety Improvement Program (HSIP) was legislated as a core of the Federal-aid program conducted by The Federal Highway Administration (FHWA) Office of Safety, with the main purpose of "achieving a significant reduction in traffic fatalities and serious injuries on all public roads through the implementation of infrastructure-related highway safety improvements." (FHWA Safety n.d.) In addition to HSIP, the FHWA Office of Safety has developed other safety programs in different transportation areas including Intersection Safety, Local and Rural Road Safety, Pedestrian and Bicycle Safety, Roadway Departure Safety, and additional safety programs and initiatives. This wide range of programs indicates the importance of conducting research and studies regarding safety evaluation.

In 2009, 33,808 fatalities occurred on U.S roadways, with 20.8% of them occurring at an intersection or being intersection-related. One-third of intersection-related fatalities happen at or near signalized intersections while only 10% of the Nation's intersections are signalized (FHWA Safety n.d.). According to the Institute of Transportation Engineers (ITE) Policy Recommendation, the main goal in transportation safety is to "Establish national safety standards to cut surface transportation fatalities in half from current levels by 2025." (Institute of Transportation Engineers n.d.). Based on these facts regarding the number of crashes and fatalities, studies conducted on intersection safety are extremely important. As a result, a comprehensive report was published by the National Cooperative Highway Research Program (NCHRP) as a guide to investigate different factors regarding signalized intersection safety improvements. In general, reduction of crashes at signalized intersections is addressed through various strategies (traffic control and operational improvements, geometric improvements, sight distance improvements, driver awareness of intersections and signal control improvements, driver compliance with traffic control devices improvements, access management near signalized intersections improvements, and other infrastructure treatments.)

Considering signalized intersections, it is obvious that traffic signals play an important role in safety considerations, as the Manual on Uniform Traffic Control Devices (MUTCD) states the reduction of the frequency and severity of certain types of crashes as one advantage of traffic control signals which are designed, located, operated and maintained appropriately (U.S. Department of Transportation n.d.). With regard to the safety aspect of signals, two factors can be evaluated: the physical characteristics of the signals and the methods of operation. Therefore, any treatment regarding the traffic signal should include consideration of any corresponding change to either factor.

The purpose of this project is to evaluate the safety impact of the widespread replacement of incandescent traffic signals with Light Emitting Diode (LED) types due to their physical characteristics. It has been more than two decades that a large number of traffic signals have been replaced by LED lights due to incredible energy efficiency; however, the possible effect of this change on intersection safety has not been thoroughly evaluated.

The City of Memphis has also engaged in a city-wide replacement initiative, and has replaced almost all signalized intersection bulbs with LEDs. This research evaluates the effect of this treatment on safety for selected intersections in the City of Memphis by conducting a before-after crash analysis. To develop this safety analysis, available information and tools regarding intersection safety analysis on the FHWA Safety website have been considered. The most recent resource that was used to guide this thesis is the Highway Safety Manual (HSM), which includes a comprehensive approach to deal with crash prediction methodology. Moreover, at the time of conducting this research, only one other study has evaluated the safety effect of LED usage in signals; therefore the current research applies a similar approach in order to make comparisons between the results of the two studies more transparent.

CHAPTER 2

LITERATURE REVIEW

There are two main areas of literature relating to this research. The first part of this literature review will review the research conducted to date considering various aspects of LED traffic signals, due to the wide-spread usage of them in the nation since the 1990s. The second part of this review examines literature pertaining to existing before-after studies as a methodology of safety measurement.

2.1 LED Traffic Signal Studies

Based on the research of the U.S Department of Energy (DOE), LED surpassed incandescent usage in traffic signals with 52% market share, equaling more than 8.5 million traffic signals (all types of signals including three-colored ball, arrow, bi-modal arrow, walking person, hand and countdown) converted to LEDs (Navigant Consulting Inc. September 2008). This conversion initially started by only replacement of red signal bulbs since yellow and green LED bulbs were not financially feasible. Recently, this replacement has been widely applied for green and red, while there are still some economic problems for yellow LED bulbs.

This tremendous number of retrofit projects has led to many studies estimating the pros and cons of LED conversion.

2.1.1 Generalized Benefits of LED

The majority of studies on LED traffic signals have been conducted regarding the significant energy savings they provide. One of the earliest studies about LED usage is the review of related articles and information in 1999 and 2000 conducted by the Lighting Research Center. It reviewed case studies of LED traffic signal installation and evaluated them based upon their economic, technical and visibility characteristics. Data was collected throughout the United States, Europe, Australia and New Zealand, and indicated 78% of red signals, 56% of green signals and 11% of yellow signals were replaced with LED, resulting in 80% energy savings and 90% maintenance savings for municipalities (Lighting Research center and Rensselaer Polytechnic Institute July 2000). The City of Portland released a report regarding the process of replacing traffic signal bulbs with LED lamps (The City of Portland, Oregon 2001). The city started considering this conversion in 1995, and by 2001 the energy crisis in that area led to the replacement of almost all red and green traffic signal bulbs with LEDs. The project accomplished 6,900 red, 6,400 green, 140 flashing amber beacons, and several light rail transit signals retrofits, which led to 4% liability, 8% maintenance, 18% relamping, and 70% energy savings. This result again proved the significant advantages of LEDs compared to incandescent signal bulbs in terms of cost and energy savings (The City of Portland, Oregon 2001).

A similar study was conducted in 2003 by Iwasaki to investigate the process of LED traffic signal module installation in the State of California (Iwasaki 2003). The California Department of Transportation (Caltrans) is known internationally as one of the largest users of LEDs, as they first began considering LED usage to reduce energy consumption in the late 1980s. The first significant electricity consumption reduction led to $10 million in savings per year for just the California state highway system by conversion of only 10 percent of red lamps in traffic signals to an LED modulus. This prompted consideration of a new rule by the California Energy Commission that prohibited the use of incandescent lamps for traffic signal indications on future traffic signal installations. Caltrans received awards from the California Energy Commission (CEC) and the U.S Department of Energy (National Energy Award) for this field test project and for low power solution demonstrations for traffic signals. California also obtained incredible benefits through LED replacement. They saw energy consumption reduction of 85%, with reduced maintenance activities and, a 90% increase in reliability (Iwasaki 2003). Moreover, the ability of LEDs to operate by battery backup system made them more efficient economically. The results led to other states using red LED modules. Caltrans also considered other aspects of LED performance. They found that more tests were required for LEDs according to the fact that the light output of LEDs changed in different temperatures.

Another report released in 2004 by the U.S. Department of Energy addressed high usage of LEDs in traffic signals in California through a comprehensive overview of this replacement's benefits (The National Renewable Energy Laboratory 2004). It was found that LED replacement in traffic signals has been one of the successful solutions for California's Peak Load Reduction Program (PLRP), which is a program designed to reduce energy consumption throughout the state. The report mentioned the high cost of installing LEDs compared to incandescent bulbs, but it emphasized the greater longevity, energy saving and maintenance cost reduction and the safety benefits. Similar to most other studies, energy consumption reduction was addressed as the most significant advantage compared to traditional bulbs with an estimated 94% reduction in energy costs. The longevity of LEDs was determined to be 10 years compared to 2 years for incandescent bulbs (The National Renewable Energy Laboratory 2004). Because of all the mentioned benefits, by the time the report was released, approximately 87 cities, counties, and public agencies had secured state or federal grants or loans to pay for installing LED traffic signals.

Another report, released by the National Cooperative Highway Research Program (NCHRP) in 2008, reviewed the history of LED traffic signal modulus and general differences between LEDs and incandescent bulbs. The report documented that the increased energy efficiency is due to the fact that LEDs produce much less heat compared to incandescent lamps and they rarely need color filters, which is a requirement for the incandescent bulbs based on their incapability of producing light with colors other than white. Also underscored was the fact that LEDs do not have the catastrophic bulb failure compare to incandescent ones (NCHRP 387 2008).

Ted Schoenecker from the Washington County Public Works Department released a presentation about energy cost reduction in Washington County in the 2009 Local Government Conference. He calculated the power usage of LED and incandescent bulbs and determined that LEDs consume 1/10 of the wattage energy of incandescent usage (Schoenecker 2009). He also compared the cost difference of LED operation between 1998 and 2008, which showed a $45 difference per red light and a $158 per green light, leading to energy saving estimates for the monthly cost of LED operation of $50 per signal. He also mentioned other advantages of LEDs including wire size reduction, longer life, the ability to operate with battery back up and more visibility (Schoenecker 2009).

Another practical study was conducted by The Arkansas Department of Economic Development in Feb 2002 to investigate the advantages and disadvantages of LED traffic signals (Traffic Engineering Division 2003). As with previous reports, it also indicated a significant energy savings compared to incandescent bulbs. Six intersections, with three of them having LED modulus and 3 incandescent bulbs, were compared during the same period of 4 months of operation. This again proved a 90% energy saving for LEDs.

2.1.2 Safety Implications

With regard to the safety aspects of signals, two factors can be evaluated: the physical characteristics of the signals and the methods of operation. Since the method of operation does not depend upon the type of signal lamps (LED or incandescent) the objective of this review is to evaluate strengths and weakness of LED physical characteristics based upon current literature, and to draw conclusions regarding the potential safety implications.

Because of the wide-spread conversion to LED, studies have been conducted to evaluate other aspects of LEDs beside the energy saving issue, particularly focusing on safety implications. In terms of safety, LEDs expire gradually pixel-by-pixel instead of total bulb failure. This was identified as a safety benefit due to reduced instance of signal failure (The National Renewable Energy Laboratory 2004).

Other safety aspects have also been considered. Caltrans started a laboratory research program to evaluate the safety aspects of LED use. This research program was undertaken by the University of California-Berkeley, and the focus was to evaluate the light perception of red LEDs compared to the incandescent lights for the Fresno area

(Iwasaki 2003). The results indicated the same performance and visibility of red LEDs as compared to incandescent traffic lights for the human eye.

The Maryland State Highway Administration (SHA) approved an appropriate field test to evaluate other aspects of LED performance. John P. Young and Thomas Hicks prepared the results of the test which investigated performance of LEDs in different highway devices such as overhead dynamic message signs (DMS), hazard identification beacons (HIB), traffic signals, “Red Signal Ahead” signs and pedestrian signals (Young and Hicks April 2003). In fall 2001, a full LED signal of all red, green and yellow units was installed in an intersection to compare cost versus longevity, cone of vision, and the ability to function with the conflict monitoring system in traffic signal controllers with that of an incandescent signal installed in another similar intersection. The results indicated the failure of several LED units after a few months of installation and 15 degree cone of vision for LEDs compared to 40 degrees for incandescent bulbs. This led SHA to recommend installing LED signals only by mast-arm. It also showed that many LED units were not capable of working with conflict monitors, a device that changes the signal status to a flashing light in abnormal conditions. This lack of functionality was based on some electrical characteristics of LEDs; however some manufactures started to solve this problem at that time (Young and Hicks April 2003).

Considering the limited cone of vision for LEDs, in 2007, a study was conducted by the school of optics at the University Complutense of Madrid, Spain (Va´zquez-Molinı´, et al. 2007). The researchers analyzed the factors related to the louvers used for LEDs in traffic controls which have better performance. The study was based on analyzing far and medium vision of LEDs as a function of the observation distance, which is also related to the sun position during the day and the year. The geographical location was Madrid, Spain with system orientation facing south. Researchers used two types of parameters, including intrinsic parameters (geometry configuration of the LED board, geometry and arrangement of the louvers, geometry arrangement of the display and optical properties), and extrinsic parameters (geometry parameters for the observation of the display, hours of operation weighted with some parameters describing the importance of the displayed message, environmental conditions parameterized in external radiation, background luminance and, technical and economic restriction (Va´zquez-Molinı´, et al. 2007). For far distance vision, evaluation of shaded and non-shaded areas in a display-louver system was used to calculate the minimum distance of appropriate observation (luminance) which resulted in different contrast in various times of the year. When the observer approaches the display-louver system, the vision takes medium distance into account, which is modeled with a different method, showing that the contrast increases by getting the observer closer to the display-louvers system. The researcher recommended that using this function for designing display-louver systems could make it possible to use the best design for the most appropriate vision for different geographical locations, orientations and observer positioning (Va´zquez-Molinı´, et al. 2007).

In one of the most specific issues studied for LEDs, Ray A. Starr, Mayne H. Sandberg and Yuzh Guan estimated the difference of LED traffic signal performance for color-blind and non-color-blind people (Starr, Sandberg and Guan August 2004). It was performed due to a complaint of a color blind person to the Minnesota Department of Transportation (Mn/DOT) stating that the traffic signal appears on in direct sunlight when it is not (where LED signals were installed in Mn by Mn/DOT). To consider this problem, seven intersections were selected as field test areas with 8 persons including 4 color-blind and 4 non-color-blind to evaluate the performance according to their responses. They also tried to determine the impacts of other factors on this property. A test was designed to evaluate the indication of six different designs of green LED lights, which differed in green tinted versus clear lens, old technology with high LED count versus new lens designs, and two brands (brand A and B), as compared to a green incandescent. These were installed at the right or left side of travel lanes for investigation of the impact of angle viewing. The test occurred on April 8 to April 10, 2003 in the early mornings with direct sunlight on the signals to exactly achieve the purpose of the test. 112 observations for each participant were recorded over all of the seven intersections, with researchers asking whether the green traffic signals on the left and right sides of the intersection were lit or not. Less than 4% of non-color-blind people stated the green lights were on while they were not. On the other hand, 25% of color-blind participants indicated they were on when they were not. The researchers also indicated that 5% of participants were red-green color-blind. Data were also analyzed which showed that the clear lens, old technology and brand A of LEDs had more performance difficulties for color-blind participants while the tinted lens, new technology and brand B LEDs had the same effects as on non-color-blind participants. Moreover, angle of viewing was seen to have no significant impact on the test objective (Starr, Sandberg and Guan August 2004).

The most recent study concerning safety implications of LED retrofits was published in the ITE journal (April 2010) and was focused specifically on the effects of

LED traffic signals on urban intersection safety (Eustace, Griffin and Hovey April 2010). Based on the fact that LED traffic signals were described to be brighter than conventional signals, the researchers investigated the number of crashes at 10 urban signalized intersections in the city of Middletown, Ohio before and after the conversion to LED to consider if it enhanced intersection safety. Eight intersections were converted to LEDs between 2003 and 2005 and the other two were considered for comparison (standard incandescent signals). Several variables were chosen for analysis including road classification, number of lanes, lane width, total entering average daily traffic (ADT), entering ADT of the major and minor roads, the number of police officers patrolling each year. The negative binomial distribution was used for the crash estimation model. The Empirical Bayes method (EB) was used for this study, as it is the most accepted method for crash estimation. This approach was also used for the expected number of crashes without any conversion. The predicted values were compared to the actual number of crashes after the conversion and the results showed that the number of crashes increased by about 71% after that change. The researchers concluded that although there was an apparently significant reduction in safety after installation of LEDs, several other factors might have affected the results, and should be considered in future studies. Limitations of the study include very small sample size of both converted and comparison sites, the lack of available data for the years before the conversion, using different specifications for older fixtures, traffic growth in some sites, etc. The researchers recommended more studies be conducted considering all these factors (Eustace, Griffin and Hovey April 2010).

In 2010, the Associated Press indicated a critical safety issue with the LED bulbs (Dinesh 2010). Many complaints were reported in cold weather, including in Illinois, Iowa and Minnesota, about the inability of LED lights to melt the snow, resulting in completely obscured signals. This problem resulted in a fatal crash in Illinois during a storm in April 2010. As a result, some states have started testing the impact of installing weather shields and adding heating elements or coating the lights with water-repellent substances to prevent this problem.

In addition to the generalized benefits of LEDs that were documented in NCHRP 387 as mentioned in the previous section, the technical issues that were addressed in the 2005 ITE specification for LEDs compared to the old version were reviewed. In the new specification the problem regarding the traffic signal safety monitors has been corrected, however the correction for conflicting monitors has not been addressed clearly. In the new specification it is mentioned that incandescent lights are more consistent in the light output compared to the LEDs but LEDs do not have catastrophic failure, which can be considered as an improvement in safety. On the other hand, this gradual loss of light combined with the high cost of LED replacement might lead to LED lights with a low performance in terms of light output remaining in service. Texas still has some problems with the LED signal heads with lightning strikes although a protected voltage has been recommended by the new specification. No correction has been mentioned for the inability of LED lights to melt snow, however some agencies have started their own solutions. "The new specification changes the ratio of red:yellow:green from 1:4.6:2 based on circa 1933 standards developed based on glass lens to 1:2.5:1.3, which was based on human factor issues" (NCHRP 387 2008). The report also presents the result of an Institute of Transportation Engineers (ITE) survey in 2006 among various public agencies and vendors/manufactures of LEDs. The purpose of the survey was to evaluate issues regarding LED usage and maintenance and it proved the widespread usage of LEDs among agencies (59% of respondents have LEDs in more than 50% of their traffic signals while 82% use or plan to use ITE LED specifications.)

In one of the most recent studies regarding LED traffic signals, another NCHRP report (NCHRP 146) was provided to investigate problems related to LEDs and to consider problems that have been solved in the new ITE LED specification (Bullough, et al. n.d.). According to this report, by increasing the LEDs illumines in the new specification, problems related to people with color deficiencies have been corrected. Moreover, new correction has been conducted to solve the inability of LEDs to operate appropriately with conflict monitors. Another problem that was mentioned in this report is the gradual loss of brightness of LEDs. This was seen to cause issues related to discomfort due to glare at night and also through sunlight direction. The new criteria for LED illumination in the ITE specification are intended to address this problem. The inability of LEDs to melt snow was not addressed (Bullough, et al. n.d.).

Even with the apparent hazards resulting in some cases from using LED bulbs in traffic signals, (although some of these have been corrected due to the new ITE specification, there are still some remaining problems and also there are cost limitations for replacing LEDs with ones that fit the new criteria (Bullough, et al. n.d.)) the extremely high energy efficiency resulted in large-scale replacement of incandescent lights by LEDs across the nation. Additionally, new requirements for LEDs became effective via the Energy Policy Act of 2005 Title I, Subtitle C, Section 135 (z). It states that:

> "(c) STANDARD SETTING AUTHORITY—
>
> (z) TRAFFIC SIGNAL MODULES AND PEDESTRIAN MODULES—
>
> Any traffic signal module or pedestrian module manufactured on or after January 1, 2006, shall—
>
> (1) meet the performance requirements used under the Energy Star program of the Environmental Protection Agency for traffic signals, as in effect on the date of enactment of this subsection; and
>
> (2) Be installed with compatible, electrically connected signal control interface devices and conflict monitoring systems."

These criteria prohibit the new installation of incandescent traffic signal and pedestrian modules on or after January 1, 2006 (Department of Energy October 18, 2005). The only signal head not required to be replaced with LED is the yellow, primarily due to the high cost. Thus, with the massive nationwide replacement of incandescent bulbs with LEDs, it is critical that additional studies evaluating safety implications be conducted.

2.2 Before-After Crash Analysis

The number of crashes is the major factor to measure the safety effect of a traffic treatment. In observational before-after studies, one may consider a simple approach of comparing the number of crashes before the treatment with the number of crashes after the treatment and conclude a positive effect for the treatment if the number of crashes decreases after the treatment. This view can be practical only when there is no change in other factors affecting the safety. In fact, the number of crashes after the treatment includes the effect of other possible changes on crash count. Since the assumption of no change in other factors besides the target treatment rarely is accurate, other methods are more applicable to estimate the safety effect of a treatment based on before-after studies. To achieve more reasonable estimation of safety, the number of crashes after the treatment has to be compared to the expected number of crashes that would have been observed after the treatment if the treatment had not been applied. Developing a method to predict this number has been an area of researchers' interest for many years. In general, this procedure is based on creating a function that relates the possible factors that affect the safety to the number of crashes. Therefore, it is critical to recognize these factors and to implement a method to provide the most accurate function, which is known as a Safety Performance Function (SPF) among traffic engineers. Moreover, researchers have also considered possible biases in creating SPFs and have tried to apply some methods for correction of the biases.

Although regression analyses and application of statistical packages have been widely used for studies seeking to create SPFs specifically at intersections over the past several years, earlier research applied a simpler approach. Thrope, Smith and Worsey (Smith 1970)(Worsey December 1985) were the earliest researchers focused on creating SPFs. They related the number of crashes to the summation of all traffic flows entering the intersection (Thorpe 1963). One obvious limitation is that traffic flows in both major and minor approaches are considered to have the same impact on crash counts. This does not lead to an accurate prediction. In a similar way, Breunning, Surti, and Hakkert provided a model which related the number of crashes to the product of the approaching traffic flows (Breunning and Surti 1959)(Surti 1965)(Hakkert and Mahalel 1978). It was first proved by Webb(1955) and McDonald(1966). While this model has some limitations it demonstrated an improved model relating crash counts to the product of traffic flows to the power of parameters with values less than one, referred to as “product-of-flows-to-power” (McDonald 1966; Webb 1955).

There are two main approaches to regression to create SPF: a normal distribution error structure assumption and a nonnormal error structure assumption. Linear regression was commonly used to relate traffic volumes to crash incidence for many years (Ceder and Livneh 1982) (Ceder 1982). Javanis and Chang (1986) were the first to discuss the limitations of using linear regression, based on the required assumptions for this procedure (normal error structure). Homoscedasticity is one such assumption of applying linear regression to data, which means that all predictor variables have the same variance. However, as traffic flow increases, the variance of the number of crashes (dependent variable) increases as well, which is in conflict with the homoscedasticity assumption. Because the hypothesis test for linear regression on crash count data is based on this assumption, this conflict leads to incorrect confidence interval estimation for estimated parameters. Considering these limitations, along with the non-negativity property of crash counts, the second approach is now widely used in estimating parameters to create SPFs. In addition, since the entities with abnormal numbers of crash counts (very large or very small) are usually selected for safety studies because of being more critical for any improvement, there is a biased selection known as “regression-to-mean” bias. To overcome this problem, the Empirical Bayes (EB) approach has been applied to increase the precision of estimation and corrects for this bias. The EB estimation procedure can be abridged or full. The full approach for EB estimation is applicable for crash counts in long time periods, while abridged EB is appropriate for crash counts of 2-3 years.

In the rest of this section, applications of different nonnormal error structure methods and empirical bayes procedures in selected studies will be reviewed.

Regression models that are based on nonnormal error structure are known as generalized linear models (GLM). Based on the fact that the dependent variable in an SPF (crash count) is a nonnegative integer, Poisson regression was first proposed by Jovanis and Chang to overcome the limitation of conventional linear regression to model the relationship of crashes to miles traveled along the Indiana Toll road (Jovanis and Chang 1986). One major disadvantage of the Poisson model for crash count modeling is due to an important characteristic of the distribution of having an equal value for mean and variance. It is realistic to expect crash counts to have a variance greater than the mean (overdispersion) and since the Poisson distribution requires the variance to be equal to the mean, building a model for such data creates a significant bias in the analysis. In addition, although rare, it is possible for crash counts, to be underdispered (having a mean greater than the variance) which also leads to incorrect analysis when applying the Poisson model.

To overcome this issue, Hauer et. al conducted one of the earliest studies to estimate safety at 145 four-legged signalized intersections in metropolitan Toronto using the Negative Binomial (NB) regression model (Hauer, NG and Lovel 1988). The only factors they used to create the SPF were major and minor roads traffic flow as shown below (they applied separate functions for each pattern of crashes; the following is the function for one of those crash patterns):

$$E\{m_6\} = b_0 \times F_1 \times {F_2}^{b_2} \qquad (1)$$

Where, $E\{m_6\}$ is the number of pattern6 crashes, b_0 and b_2 are the model parameters, and F_1 and $F_2$are independent variables (major and minor road traffic flow). A Negative Binomial error structure was specified to estimate the parameters.

Bonneson and Mccoy conducted a study to predict the SPF due to crash data for 125 two-way stop-controlled intersections in Minnesota (Bonneson and McCoy 1993). They also applied a nonlinear relationship between crashes counts and traffic data which is the product of flows to power as shown below:

$$E(m) = b_0 T_m^{b_1} T_c^{b_2} \qquad (2)$$

Where, $E(m)$ is expected crash frequency, b_i shows regression constants, $T_m$is major road traffic demand, and T_c is minor road traffic demand. They developed the model using both Poisson and NB distributions as error structure separately. The Pearson X^2statistic was applied to determine the significance of each model to fit the predicted value. The result showed that NB error structure was able to fit the data with greater significance than Poisson error structure.

Another study was conducted by Sayed and Rodriguez to predict crashes related to 419 unsignalized intersections in urban areas of the Greater Vancouver Regional District and Vancouver Island, British Colombia by applying the GLIM approach based on the assumption of negative binomial distribution as the point probability function (Sayed and Rodriguez 1999). The model structure is shown as:

$$E(\Lambda) = a_0 {V_1}^{a_1} {V_2}^{a_2} \tag{3}$$

Where, $E(\Lambda)$ is expected crash frequency, V_1 is major road traffic volume (annual average daily traffic (AADT)), V_2 is minor traffic volume (AADT), anda_0, $a_1$and a_2 are model parameters. The EB procedure was then applied to reduce the regression-to-mean bias and achieve a more accurate result.

A negative binomial regression was also applied by Poch and Mannering to estimate the crash frequency at intersections in Seattle suburban areas (Poch and Mannering 1996). Traffic volume, geometric characteristics and signalization characteristics were considered as variables.

Miaou and Lord applied Poisson and NB before-after analysis to 4-legged signalized intersection crash data in Toronto, Canada (Miaou and Lord 2003). Both empirical Bayes and full Bayes were conducted to estimate the best model. They also proved the previous mentioned models as proper functions to predict crashes, however; part of the study was based on considering the effect of using different functional forms of the SPF and specifically the impact of this for safety analysis of a transportation network.

Other methodological alternatives have also been used due to their benefits. Lord and Mannering recently conducted a comprehensive review of various methods that have been applied to before-after studies of crash analysis over the years (Lord and Mannering 2010). They evaluated the advantages and disadvantage of each methodology to create an SPF, and reviewed almost all of the existing studies applying these methods as of the time of publication. Their evaluation of the various methods is based on the ability of each model to handle different properties of crash data and consequently create a result with the least possible errors. As mentioned before, dispersion is one major aspect of crash data that may cause significant bias in the result based on the type of model being applied. They mentioned that besides overdispersion phenomena in crash data, sometimes data can be under dispersed which means that the mean of crash counts are larger than the variance. Another aspect related to crash data that they considered is the existence of "time-varying explanatory variables". This means that some explanatory variables that contribute to the number of crashes change by time over the period of the study and not considering this fact may yield a significant bias in the results. Temporal and spatial correlation models were also evaluated based on the capability of formulating a relationship for data with small size and small mean. Another issue of interest is to fit a model to data based on the type of crash and the severity. Table 1 (Lord and Mannering 2010) presents the comparison of various models based on their ability to handle mentioned aspects of crash data. They also identify studies that applied each methodology, as shown in Table 2 (Lord and Mannering 2010). More details on each approach can be found in (Lord and Mannering 2010).

Considering other studies being applied after the comprehensive review of Lord and Mannering, a recent study by Pei, Wong and Sze can be added to the list of studies related to Markov switching model types. They applied Markov switching with full Bayesian analysis to predict the number of crashes and the severity with an application of a proposed joint probability model that can be considered as a new approach to crash safety analysis (Pei, Wong and Sze 2011).

Table 1: Summary of existing models for analyzing crash-frequency data (Reproduced with permission from (Lord and Mannering 2010).

Model type	Advantages	Disadvantages
Poisson	Most basic model; easy to estimate	Cannot handle over- and under-dispersion; negatively influenced by the low sample-mean and small sample size bias
Negative binomial/ Poisson-gamma	Easy to estimate can account for over-dispersion	Cannot handle under-dispersion; can be adversely influenced by the low sample-mean and small sample size bias
Poisson-lognormal	More flexible than the Poisson-gamma to handle overdispersion	Cannot handle under-dispersion; can be adversely influenced by the low sample-mean and small sample size bias (less than the Poisson-gamma), cannot estimate a varying dispersion parameter
Zero-inflated Poisson and negative binomial	Handles datasets that have a large number of zero-crash observations	Can create theoretical inconsistencies; zero-inflated negative binomial can be adversely influenced by the low sample-mean and small sample size bias
Conway-Maxwell-Poisson	Can handle under- and over-dispersion or combination of both using a variable dispersion (scaling) parameter	Could be negatively influenced by the low sample-mean and small sample size bias; no multivariate extension available to date
Gamma	Can handle under-dispersed data	Dual-state model with one state having a long-term mean equal to zero
Generalized estimating equation	Can handle temporal correlation	May need to determine or evaluate the type of temporal correlation a priori; results sensitive to missing values
Generalized additive	More flexible than the traditional generalized estimating equation models; allows non-linear variables interactions	Relatively complex to implement; may not be easily transferable to other datasets
Random-effects	Handles temporal and spatial correlation	May not be easily transferable to other datasets
Negative multinomial	Can account for over-dispersion and serial correlation; panel count data	Cannot handle under-dispersion; can be adversely influenced by the low sample-mean and small sample size bias

Table 1-continued: Summary of existing models for analyzing crash-frequency data (Reproduced with permission from (Lord and Mannering 2010).

Model Type	Advantages	Disadvantages
Random-parameters	More flexible than the traditional fixed parameter models in accounting for unobserved heterogeneity	Complex estimation process; may not be easily transferable to other datasets
Bivariate/multivariate	Can model different crash types simultaneously; more flexible functional form than the generalized estimation equation models (can use non-linear functions)	Complex estimation process; requires formulation of correlation matrix
Finite mixture/Markov switching	Can be used for analyzing sources of dispersion in the data	Complex estimation process; may not be easily transferable to other datasets
Duration	By considering the time between crashes (as opposed to crash frequency directly), allows for a very in-depth analysis of data and duration effects	Requires more detailed data than traditional crash-frequency model; time-varying explanatory variables are difficult to handle
Hierarchical/multilevel	Can handle temporal, spatial and other correlations among groups of observations	May not be easily transferable to other datasets; correlation results can be difficult to interprets;
Neural network, Bayesian neural network, and support vector machine	Non-parametric approach does not require an assumption about distribution of data; flexible functional form; usually provides better statistical fit than traditional parametric models	Complex estimation process; may not be transferable to other datasets; work as black-boxes; may not have interpretable parameters

Table 2: Summary of previous research analyzing crash-frequency data (Reproduced with permission from (Lord and Mannering 2010).

Model Type	Previous Research
Poisson	Jovanis and Chang (1986), Joshua and Garber (1990), Jones et al. (1991), Miaou and Lum (1993), and Miaou (1994)
Negative Binomial	Maycock and Hall 1984, Hauer et al. (1988); Brüde and Larsson (1993); Bonneson and McCoy (1993); Miaou (1994); Persaud (1994); Kumala (1995); Shankar et al. (1995); Poch and Mannering (1996); Maher and Summersgill (1996); Mountain et al. (1996); Milton and Mannering (1998); Brüde et al. (1998); Mountain et al. (1998); Karlaftis and Tarko (1998); Persaud and Nguyen, 1998; Turner and Nicholson (1998); Heydecker and Wu (2001); Carson and Mannering (2001); Miaou and Lord (2003); Amoros et al. (2003); Hirst et al. (2004); Abbas (2004); Lord et al. (2005a); El-Basyouny and Sayed (2006); Lord (2006); Kim and Washington (2006); Lord and Bonneson (2007); Lord et al. (2009); Malyshkina and Mannering (2010b); Daniels et al. (2010); Cafiso et al. (2010a)
Poisson-lognormal	Miaou et al. (2005), Lord and Miranda-Moreno (2008), and Aguero-Valverde and Jovanis (2008)
Zero-inflated Poisson and negative binomial	Miaou (1994), Shankar et al. (1997), Carson and Mannering (2001), Lee and Mannering (2002), Kumara and Chin (2003), Shankar et al. (2003), Qin et al., 2004, Lord et al. (2005b), Lord et al. (2007), and Malyshkina and Mannering (2010a)
Conway-Maxwell-Poisson	Lord et al. (2008), Sellers and Shmueli (in press) and Lord et al. (2010)
Gamma	Oh et al. (2006) and Daniels et al. (2010)
Generalized estimation equation	Lord and Persaud (2000), Lord et al. (2005a), Halekoh et al. (2006), Wang and Abdel-Aty (2006), and Lord and Mahlawat (2009)
Generalized additive	Xie and Zhang (2008) and Li et al. (2009)
Random-effects	Johansson (1996), Shankar et al. (1998), Miaou and Lord (2003), Flahaut et al. (2003), MacNab (2004), Noland and Quddus (2004), Miaou et al. (2003), Miaou et al. (2005), Aguero-Valverde and Jovanis (2009), Li et al. (2008), Quddus (2008), Sittikariya and Shankar (2009), Wang et al. (2009) and Guo et al. (2010)
Negative multinomial	Ulfarsson and Shankar (2003), Hauer (2004), and Caliendo et al. (2007)
Random-parameters	Anastasopoulos and Mannering (2009) and El-Basyouny and Sayed (2009b)

.

Table 2-continued: Summary of previous research analyzing crash-frequency data (Reproduced with permission from (Lord and Mannering 2010)

Model Type	Previous Research
Bivariate/multivariate	Miaou and Lord (2003), Miaou and Song (2005), N'Guessan and Langrand (2005a), N'Guessan and Langrand (2005b), Bijleveld (2005), Song et al. (2006), Ma and Kockelman (2006), Park and Lord (2007), N'Guessan et al. (2006), Bonneson and Pratt (2008), Geedipally and Lord (in press), Ma et al. (2008), Depaire et al. (2008), Ye et al. (2009), Aguero-Valverde and Jovanis (2009), El-Basyouny and Sayed (2009a), N'Guessan (2010), and Park et al. (in press)
Finite mixture/Markov switching	Malyshkina et al. (2009), Park and Lord (2009), Malyshkina and Mannering (2010a), and Park et al. (in press)
Duration	Jovanis and Chang (1989), Chang and Jovanis (1990), Mannering (1993), and Chung (2010)
Hierarchical/multilevel	Jones and Jørgensen (2003) and Kim et al. (2007)
Neural network, Bayesian neural network, and support vector machine	Abdelwahab and Abdel-Aty (2002), Chang (2005), Riviere et al. (2006), Xie et al. (2007), and Li et al. (2008)

Currently, the NB regression model is the most widely used (due to relative ease of application) and applicable to crash count data due to the capability of handling overdispersed data. As mentioned previously, the most related literature to this project was conducted by Eustace et al., which also used NB regression for the SPF. The current research will use the same methodology as this previous study to determine impact of LED conversion for selected intersections in Memphis, TN. Results will then be compared to those obtained by Eustace et al.

CHAPTER 3

METHODOLOGY

In order to assess the safety implications of the LED conversion in Memphis, TN, it was necessary to develop a model to predict the number of crashes that would be expected at sites that have undergone LED conversion if no treatment had been applied. This predicted number can then be compared to the observed number of crashes after the treatment had been applied and the result could be expressed using either of the following evaluation factors (Hauer 1997).

(1) $\delta = B - A$ (4)

(2) $\theta = A/B$ (5)

Where B is the predicted (expected) number of crashes if no treatment had been applied, and A is the actual observed number of crashes after the treatment. A value of $\delta < 0$ or $\theta < 1$ indicates that the treatment resulted in an improvement in the safety.

As mentioned in the previous section, various regression methods have been applied to create a mathematical relationship (Safety Performance Function or SPF) between the number of crashes and other potential factors that have an influence on safety. In other words, the after measurement (number of crashes) doesn't show the effect of the treatment of interest separately. It represents the combined effect of all factors on safety, and to measure the safety effect of the target factor (treatment), the effect of other factors needs to be measured. Consequently, the first step in developing an SPF is to identify other contributing factors.

3.1 Factors (Variables)

Factors that are involved in a before-after study are classified in two general groups. The first group consists of those factors that are recognizable, measurable, and well understood. The second group consists of factors that are difficult to identify, measure, or understand (Hauer 1997). To improve the estimate obtained from an SPF, factors of the first group are applied as the function variables. An approach to deal with the second group of factors will be discussed later in Section 3.4. There are various variables that can be considered for an analysis, such as number of lanes, lane width, weather, type of intersections, traffic flow, etc. However, not all of these variables will produce significant correlation with the number of crashes. Guo et.al recommend three major properties for variables selected in creating an SPF “(1) the variable should have a sound engineering interpretation; (2) the variable should represent different aspects of properties of an intersection; and (3) there should be a weak/moderate correlation among the selected variables.”(Guo, Wang and Abdel-Aty 2010). As pointed out in the literature review in the previous chapter, traffic flow has been recognized as the most appropriate variable related to safety in before-after studies and can be presented as either average daily traffic (ADT) or annual average daily traffic (AADT). The Highway Safety Manual (HSM) recommends the usage of AADT over ADT unless no data is available for AADT (AASHTO 2010). For intersections, the total entering traffic volume may be applied as the only variable of the SPF or two variables may be assumed separately for the traffic volume of the minor and major approaches. The second approach using two variables is more common among researchers since it has been recognized to create a better goodness of fit in improving the SPF. For the current study, the variables considered initially include AADT for both the major and minor approaches, number of lanes and lane width. However, as it was expected, only AADT for both major and minor approaches were found significantly acceptable as explanatory variables to improve the SPF and the two other variables didn't have significant effects on the model.

3.2 SPF Improvement

3.2.1 SPF Structure

According to current literature, the most common structure being used by researchers to relate traffic flows to the number of crashes at an intersection is formulated as;

$$E(\Lambda) = e^{a_0} {V_1}^{a_1} {V_2}^{a_2} \tag{6}$$

Where, $E(\Lambda)$ is expected crash frequency, V_1 is the major road traffic volume (annual average daily traffic (AADT)), V_2 is the minor road traffic volume (AADT), anda_0, $a_1$and a_2 are model parameters (Tarek Sayed 1999). This function has been also suggested by The Federal Highway administration (FHWA) in development of state-of-the-art software tools (Safety Analyst) as the most appropriate model to estimate intersection safety (SafetyAnalyst n.d.), however; it has been recommended that individual states develop SPFs based on their own crash and AADT data (Harwood, et al.

December 2000). For the current research the same functional form was applied as in Equation 6.

3.2.2 Regression Procedure

After selecting the variables and model structure, the next step is to estimate the unknown parameters of the SPF by assuming a probabilistic structure for crash counts. Various methods were discussed in Section 2.2. In this project, negative binomial (NB) error structure is applied, as it best represents crash data. Reasons for selecting NB as the most appropriate error structure distribution for crash counts will be explained in Section 3.2.5.

3.2.3 Crash Counts in Theory

In general, a crash as a random experiment is recognized as a Bernoulli trial, in which the occurrence of a crash is considered as a success and no occurrence of crashes as a failure. The probability distribution of the number of successes in Bernoulli trials is modeled as a binomial distribution which is formulated as follows (Lord, Washington and Ivan n.d.):

$$P(Z = n) = \binom{N}{n} p^n (1 - p)^{N-n}, \qquad (7)$$

Where N is the number of trials (number of vehicles entering the intersection), p is the probability of success (occurrence of a crash), and $Z = 0,1, \ldots, n$ is the random variable that records the number of successes. The mean and variance of the distribution are computed as (Lord, Washington and Ivan n.d.):

$$E(Z) = Np \qquad (8)$$

$$VAR(Z) = Np(1-p) \qquad (9)$$

The Poisson distribution can be used to approximate binomial probabilities when there are a large number of trials and the probability of success is small. These assumptions are true while dealing with crash counts since the probability of crash occurrence is very small compared to the large number of vehicles entering an intersection. In mathematical terms, this occurs when $N \rightarrow \infty$ and $p \rightarrow 0$, where Np is represented by λ and the formulation is changed to the following, which is known as the Poisson distribution (Lord, Washington and Ivan n.d.).

$$P(Z=n) = \binom{N}{n}(\frac{\lambda}{N})^n(1-\frac{\lambda}{N})^{N-n} \cong \frac{\lambda^n}{n!}e^{-\lambda} \qquad (10)$$

Where λ is the mean of the Poisson distribution or the Poisson parameter and is a function of variables, X_i , and estimated parameters, β. The expected value of a random variable that follows a Poisson distribution is equal to λ and is determined as follows:

$$E(y_i) = \lambda_i = EXP(\beta X_i) \qquad (11)$$

3.2.4 Dispersion Parameter

A very important characteristic of the Poisson distribution is that the mean and the variance are equal to λ (functional form of expected number of crashes). Since it is not always the case that crash data have an equal value for the mean and variance, this property is recognized as a limitation of this method. In fact, crash data typically has a variance larger than the mean (overdispersion). As a result, if a Poisson regression model is applied to crash counts, the result would be biased. To overcome this limitation, researchers have found the NB regression procedure is more appropriate for the purpose of crash analysis.

3.2.5 Negative Binomial (NB) Procedure

Since the NB approach is applied due to the limitation of the Poisson method, (the equality of the mean and the variance) one may expect a new parameter in this model to represent the overdispersion of data. This parameter is shown by α which is known as the dispersion or overdispersion parameter. The Poisson method is a special case of the NB procedure where α is equal to zero. The general form of the probability of occurrence of y_i crashes at segment i during a time period, $P(y_i)$, in a NB regression model is represented as (Lord, Washington and Ivan n.d.):

$$P(y_i) = \frac{\Gamma(\left(\frac{1}{\alpha}\right)+y_i)}{\Gamma\left(\frac{1}{\alpha}\right)y_i!}\left[\frac{\frac{1}{\alpha}}{\left(\frac{1}{\alpha}\right)+\lambda_i}\right]^{1/\alpha}\left[\frac{\lambda_i}{\left(\frac{1}{\alpha}\right)+\lambda_i}\right]^{y_i} \quad (12)$$

Where, $\Gamma(.)$ is a gamma function, λ_i is the Poisson parameter, and α is the NB overdispersion parameter. The NB variance is formulated as (Lord, Washington and Ivan n.d.):

$$v(y_i) = E(y_i) + \alpha(E(y_i))^2 \quad (13)$$

So far, the variance for the expected number of crashes has been defined only for a single entity. In this project, similar to other before-after analysis, safety is measured with respect to the number of entities considered. The estimation of the mean and the variance of the total entities are then determined by the summation of these values for all entities.

Once variables, SPF structure, and the regression procedure are defined, data for each entity including crash counts, major road AADT, and minor road AADT are applied to estimate the unknown parameters. This step is implemented by using a statistical package that allows the application of the previously mentioned procedures.

3.3 Calibration Factor

The previously described procedure estimating the number of crashes using an SPF is based on the assumption that the difference between the number of crashes at each entity across different years has the same manner of changing as the difference between the number of crashes across various entities. In other words, no calibration was considered to account for within-period variation for each single intersection. To deal with this in the methodology, a calibration factor is multiplied by the SPF to normalize the number of crashes for each site to a single base year. For each individual site the base year is selected as the first year that before treatment data is available, and all other years are normalized to this year as follows: (Hauer 1997)

$$C_{iy} = \frac{Expected\ \ number\ \ of\ accident\ \ from\ SPF\ of\ intersection\ \ i\ for\ year\ \ y}{Expected\ \ number\ \ of accident\ \ from\ SPF\ of\ intersection\ \ i\ for\ year\ \ 1} \qquad (14)$$

3.4 Comparison Group and Empirical Bayes Approach

The methodology for developing an SPF was conducted based on the measurable variables (traffic volume), however; as mentioned in Section 3.1, other factors may exist that are not easily identified and therefore cannot be measured to estimate the effect of them on the number of crashes. Moreover, there is a high chance that the treated sites under study have been selected because of the high crash frequency which means that the crash count before the treatment cannot be an accurate representation of crash counts due to normal conditions. This phenomenon is known as "regression-to-the-mean" or selection bias. The most common approach to deal with this problem is the use of a comparison group in conjunction with the Empirical Bayes (EB) approach. A comparison group includes sites with no treatment being applied during the study period. The EB method of using a comparison group is based on two assumptions.

"**Assumption a.** That the sundry factors that affect safety have changed from the "before" to the "after" period in the same manner on both the treatment and the comparison group, and

Assumption b. That this change in the sundry factors influences the safety of the treatment and the comparison group in the same way" (Hauer 1997).

In fact, the comparison group is applied to the SPF from the previous step to account for other unmeasured factors as well. One critical part in this procedure is to select the comparison group in such a way that they are as similar as possible to the sites under study by fitting the above assumptions. One criterion to evaluate this similarity is the odds-ratio which is computed as follows:

$$odds - ratio = \frac{R_t/R_{t-1}}{C_t/C_{t-1}} \quad (15)$$

Where, R_t is the number of crashes in year t of study sites before the treatment, and C_t is the number of crashes in year t for the comparison group (Brabander and Vereeck 2007) . It is expected that the closer this ratio is to one, the more reliable the comparison group. After considering the degree of reliability for the selected comparison group, the EB approach is then applied to correct the regression-to-the-mean bias. Before considering the EB procedure, it is noteworthy to understand that a comparison group differs from a control group. A control group is used for experiments that are conducted randomly and therefore the immeasurable factors are changed in the same manner for both the group under study and the control group. It is unlikely that the comparison group and study group in our case have the same manner of changing in factors during time.

The main concept in EB methodology is based on taking into account a weight between the observed and predicted number of crashes of each site as follows: (FHWA 2010)

$$Expectednumberofaccidentsforanintersection(EB) =$$

$$Weight \times PredictednumberofaccidentsfromSPF +$$

$$(1 - Weight) \times Observed\ numberofaccidents\ for\ the\ intersection \quad (16)$$

Where,

$$Weight = \frac{1}{1+\alpha \times P} \tag{17}$$

P= Total expected number of crash due to SPF

α=Overdispersion parameter from SPF

The weight factor is a function of model overdispersion. This means that when data are largely overdispered, less weight is devoted to the predicted number of crashes from the SPF and the expected number of crashes is determined more based on the observed data. The expected number of crashes receives a larger weight from the predicted value of the SPF when the data has smaller overdispersion.

The expected number of crashes in this step is due to the period before treatment. Then, these values are used to predict the after treatment number of crashes .

The predicted number of crashes for the after treatment period, B, can then be determined as: (Eustace, Griffin and Hovey April 2010)

$$B = C_{iy} \times PC_b \tag{18}$$

Where C_{iy} is the normalized number of crash after the treatment as in Equation 14, and PC_b is formulated as:

$$PC_b = \frac{\sum_{before} EB}{\sum_{before} C_{iy}} \tag{19}$$

Once the unbiased predicted number of crashes is estimated, the safety is evaluated by determining δ or θ , as defined in Section 3.

3.5 Model Development

3.5.1 Data Collection:

From the total 768 signalized intersections in the City of Memphis, 56 full LED conversions and 712 partial conversions (red and green only) of signalized intersections have occurred since 2000. To select intersections for this research, several factors were considered to reduce possible occurrence of various types of errors caused by dissimilarity of conditions among sites. Consequently, intersections were selected from those that had full LED replacement where installation occurred at approximately the same time. As a result, 8 intersections were selected for the case study sample, while 2 others were selected as comparison sites in which no LED replacement occurred during the study period. General characteristics of these selected intersections are presented in Table 3.

Table 3. General characteristics of selected intersections.

Treated Sites														
Intersection/ Approach	Number of Lanes				Lane Width (ft)		Left Turn Lane				Right Turn Lane			
	Major		Minor		Major	Minor	Major		Minor		Major		Minor	
E Raines Rd and S Mendenhall Rd	2	3	3	2	12	12	1	1	1	1	1	0	0	1
N Germantown Pkwy and Cordova Rd	3	3	2	2	12	12	1	1	1	1	0	1	1	1
N Germantown Pkwy and Trinity Rd	3	3	2	2	12	12	2	1	2	1	1	1	0	1
Poplar Ave and S Goodlett St	3	3	2	2	9	12	1	1	1	1	0	0	0	0
Winchester Rd and Riverdale Rd	3	3	3	3	12	12	1	2	1	1	0	1	0	0
N Highland St and Poplar Ave	3	3	2	3	9	12	1	1	1	1	0	0	0	0
Winchester Rd and Hickoryhill Rd	3	3	3	3	12	12	2	2	1	1	0	0	0	0
New Getwell Rd and E Shelby Dr	3	3	2	2	12	12	1	1	1	1	0	0	0	1
Comparison Sites														
Intersection/ Approach	Number of Lanes				Lane Width		Left Turn Lane				Right Turn Lane			
	Major		Minor		Major	Minor	Major		Minor		Major		Minor	
Cromwell Ave and S Perkins Rd	3	2	1	1	12	12	1	1	1	1	0	0	0	1
Knight Arnold Rd and Castleman St	2	2	1	1	12	12	1	1	1	1	0	0	0	0

Data was gathered for each site for a time period containing the year of conversion itself, three years before the treatment and three years after the conversion took place. This time period for the study includes seven years between 2000 to 2008, varying slightly for each site based on the year of installation. Crash reports were obtained from the City of Memphis Engineering Department police crash reports archive and reviewed individually to gather the most related crash data for the purpose of this research, which were those that occurred at or near the intersection and specific crash types likely to be related to signal visibility. Abdel et. al state that a default range distance from 50 feet to upwards of 500 feet is used by many state agencies to identify intersection related crashes (Abdel-Aty, Xuesong and Santos Dec 2009). The City of Memphis Engineering Department uses 50 feet as a distance from the location of crash to the intersection to investigate required safety improvements for intersections. However, in this study, crashes that occurred 100 feet away from the intersection or closer are included in the case sample. In addition to the distance of the crashes from the intersections, crashes which took place at entrances of driveways were excluded as these are not likely due to a traffic signal's visibility. Other data that was collected for this study include the AADT of the major and minor roads for each approach at all selected intersections. These data were gathered from the Tennessee Department of Transportation (TDOT) traffic history website (Tennesse Department of Transportation n.d.). Table 6 shows the summary of data collected for this project. The highlighted columns for treated intersections show year of LED replacement at each intersection, with two values reported for the number of crashes; the first one shows the number of crashes that occurred before the month of LED installation and the second number shows that number of crashes occurring after the month of replacement. There is no year of conversion for the last two intersections which are comparison sites. Some AADT are also shown in red. The red indicates data that were not available on the TDOT website. To estimate these missing values, the rule from the HSM was applied. The HSM rule states, "The AADT's for years before the first year for which data are available are assumed to be equal to the AADT for that first year" (AASHTO 2010). Table 4 and Table 5 show summary data for treated and comparison sites separately.

Table 4: Statistical summary of data (treated intersections)

	Mean	Maximum	Minimum
Number of Crashes	43	79	9
AADT Major	36150	68433	14681
AADT Minor	21326	37178	9819

Table 5: Statistical summary of data (comparison intersections)

	Mean	Maximum	Minimum
Number of Crashes	11	20	4
AADT Major	22896	27162	18748
AADT Minor	4369	5754	2843

The sites were also selected to match as closely as possible in terms of land usage. An example of this can be seen in figure1 and figure 2. A list of the intersections selected for study and comparison groups is shown in Table 6.

Table 6: Crash and AADT data for intersectios (treated and comparison), For each intersection, the first row indicates number of crashes, the second row shows AADT for the major approach and the third row presents AADT for the minor approch.

Intersection\Year	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*
E Raines Rd & S Mendenhall Rd			10	10	9	4&12	11	10	13
E Raines Rd			19331	17215	18539	19095	16964	14813	14681
Mendenhall Rd			18358	17051	17562	18536	18344	16295	16303
N Germantown Pkwy &Cordova Rd		38	46	44	39&8	42	47	48	
N Germantown Pkwy		42890	43187	44136	45460	44122	44751	45596	
Cordova Rd		14820	14820	14820	14820	14820	13878	14897	
N Germantown Pkwy & Trinity Rd	41	49	40	20&33	53	56	48		
N Germantown Pkwy	60903	59018	65205	68433	63839	64329	61727		
Trinity Rd	9819	10547	11292	12060	12292	12589	12843		
Poplar Ave & S Goodlett St		40	31	45	38 &12	57	37	28	
Poplar Ave		31969	31808	28179	30190	29615	30349	28379	
S Goodlett St		21677	23356	19647	24060	21661	20705	18346	
Winchester Rd & Riverdale Rd			78	64	54	27&4 7	58	79	48
Winchester Rd			29188	29188	29188	29188	29188	32217	29723
Riverdale Rd			38400	38408	39560	41779	34760	34670	32976
S Highland St & Poplar Ave		57	51	49	14&36	45	37	34	
Poplar Ave		31969	31808	28179	30190	29615	30349	28379	
S Highland St		25190	25481	25092	26059	25432	22502	21954	
Winchester Rd &Hickory Hill Rd		56	41	50	21&31	46	48	55	
Winchester Rd		32172	33412	32068	32809	28005	29024	26155	
Hickory Hill Rd		34898	35950	33307	38317	34146	33994	32968	
E Shelby Dr &Getwell Rd		41	31	33	9&25	40	34	51	
E Shelby Dr		30217	30581	32458	33349	30883	32902	34687	
New Getwell Rd		15094	16782	16560	19080	18420	17967	19676	
S Perkins Rd & Cromwell Ave	20	4	14	15	8	11	12	6	6
Cromwell Ave	5720	5292	4718	4971	5485	5484	5456	4743	5754
S Perkins Rd	26981	24432	27162	22351	24140	23556	24844	22744	23086
Knigh Arnold Rd and Castleman St	13	9	12	10	12	16	14	13	11
Knight Arnold Rd	20582	20849	22835	23329	24802	22251	20297	19141	18748
Castleman St	2843	3118	3408	3411	3513	3448	3688	3873	3712

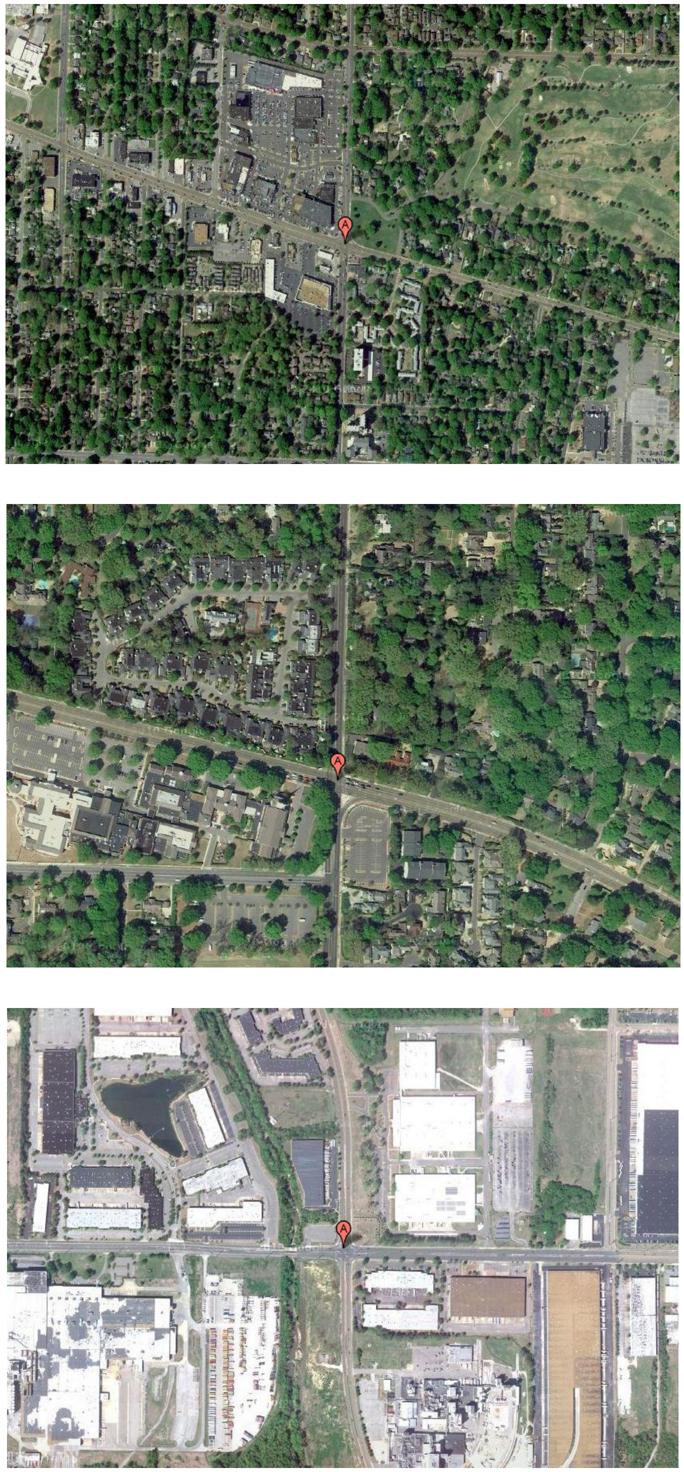

Fig. 1. Visual aspects of treated intersections-from top to the bottom: Poplar Ave & S Highland St; Poplar Ave & S Goodlett St; E Raines Rd & Mendenhall Rd.

Fig. 1-continued. Visual aspects of treated intersections-from top to the bottom: N Germantown Pkwy & Cordova Rd; N Germantown Pkwy & Trinity Rd; Winchester Rd & Riverdale Rd

Fig. 1-continued. Visual aspects of treated intersections-from top to the bottom: Winchester Rd & Hickory Hill Rd; E Shelby Dr &Getwell Rd.

Fig 2. Visual aspects of comparison intersections- from top to the bottom: S Perkins Rd & Cromwell Ave; Knight Arnold Rd & Castleman St.

3.5.2 Comparison group level of fitness

To evaluate how well the comparison sites match selected study sites, as it is outlined in Section 3.4, the odds-ratio was determined. The following ratio is calculated for each year at each intersection.

$$\frac{R_{it}/R_{it-1}}{C_{it}/C_{it-1}} \tag{20}$$

Where, R_{it} is the number of crashes in year t at intersection i of under studies sites before the treatment, and C_{it} is the number of crashes in year t at intersection i of comparison group. For each intersection, two years before the treatment year were considered to calculate the odds-ratio with the related year of comparison sites. The result is shown in figure 3. There are sixteen different values for odds-ratio, which show two numbers for each site continuously. As explained in the previous section, the closer this ratio to 1 is, the more similar the treated and comparison sites are. In general, the comparison sites seem to have an appropriate level of reliability.

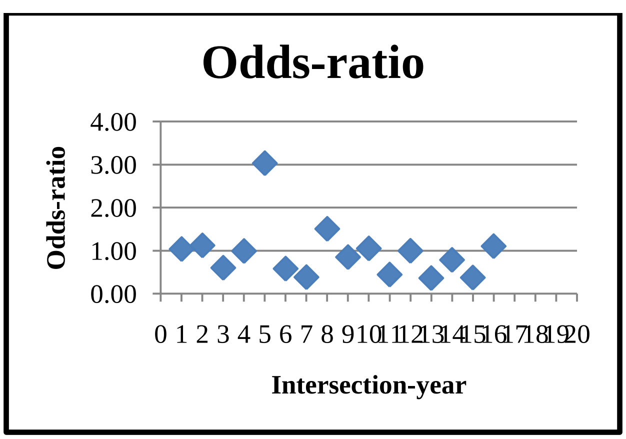

Fig. 3. Comparison group odds-ratio.

3.5.3 SPF development

Data collected following methodology from the previous sections was analyzed using the GENMOD procedure of SAS 9.2 statistical software to create the SPF. The data includes observations prior to the treatment period for both treated and comparison sites. For treated sites, data includes the year of conversion before the month of the treatment in the 'before treatment' period by applying a weighting factor to the AADT value based on the portion of the year that is considered 'before treatment'. In this case, there are 4 inputs for the before treatment period for each site (3 years of before treatment and a year of conversion for months before conversion). As mentioned before, number of crashes is the dependent variable, and AADT of the major and minor roads are considered as explanatory variables. The error structure distribution, as discussed previously, is NB. Once again, these assumptions are based on the fact that crashes are random and rare events compared to all transportation movements. This is illustrated in figure 4 where the range of the number of crashes is related to the total AADT for each site.

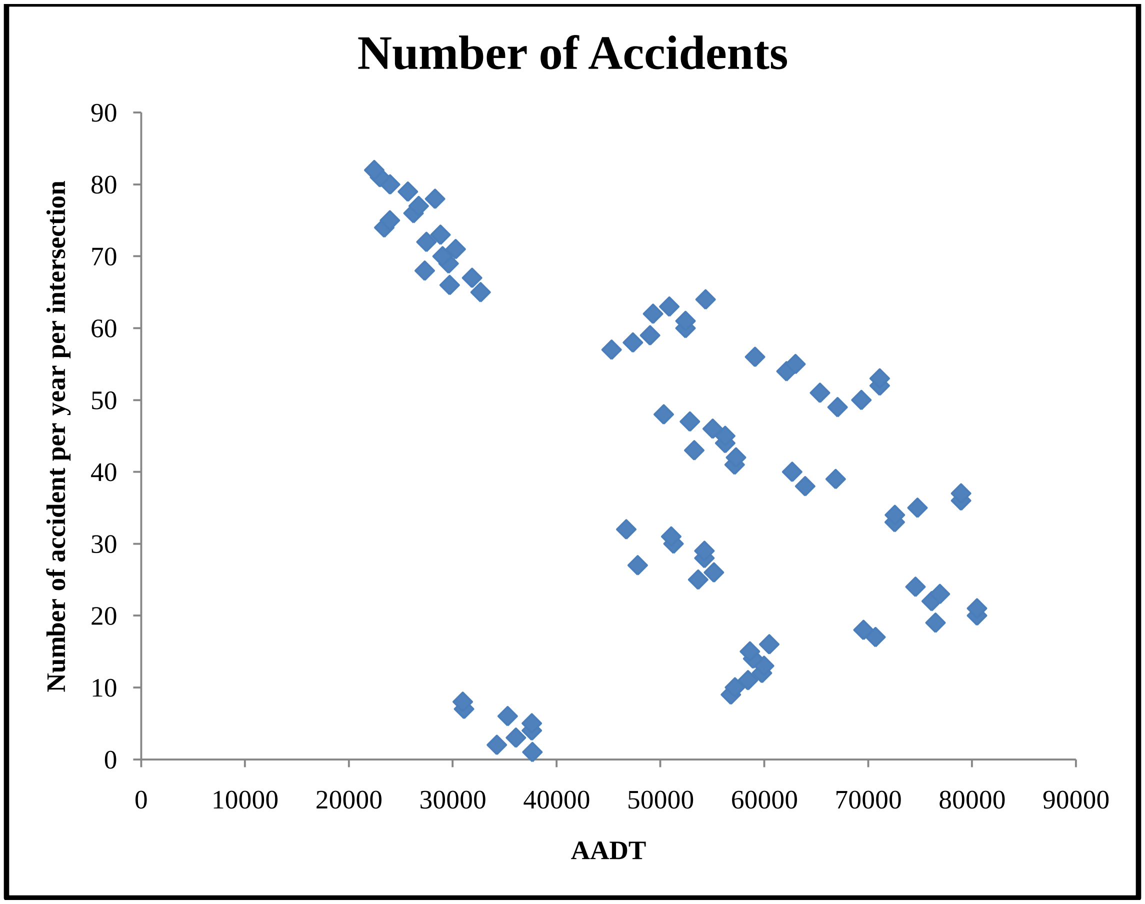

Fig. 4. Randomness Characteristic of Number of Crashes.

3.5.4 SAS 9.2 GENMOD Procedure

The SAS GENMOD procedure develops a generalized linear model by allowing selection of an error structure distribution function, which in this case is NB, and selection of a link function which represents the functional form of the regression model. For NB error structure, the link function is log by default. This link function relates the dependent and independent variables in the following format (SAS 9.2 2010):

$$E(Y) = e^{\beta 0+\beta 1X1+\beta 2X2...+\beta nXn} \qquad (21)$$

Where Y is an independent variable, $X1, X2, \dots Xn$ are explanatory variables, and $\beta 0, \beta 1, \dots \beta n$ are estimated parameters. In this case, since there are two independent variables (AADTmajor and AADTminor), the mathematical function is:

$$E(Y) = e^{\beta 0+\beta 1X1+\beta 2X2} \tag{22}$$

Where $E(Y)$ is the expected number of crashes, $X1$ and $X2$ are regarding to major and minor AADT, and $\beta 0, \beta 1, \beta 2$ are estimated parameters. Since the desired SPF format is as shown in Equations, 21 and 22 the GENMOD procedure is applied using ln(AADTmajor) and ln(AADTminor). An iterative fitting process is applied to estimate the model parameters (regression coefficients and overdispersion parameter related to the NB distribution) with the maximum likelihood method through an iterative fitting process. The maximum likelihood method determines the values for unknown parameters that produced the observed data through the model with the maximum probability based on the selected probability distribution of the dependent variable.

3.5.5 EB approach

In the next step, the EB approach is applied to address the issue related to the regression-to-the-mean bias as stated in Section 3.4. This phenomenon is presented in figure 5. The EB weight is determined based on Equation 17. These values are then applied using Equation 16 to determine the number of crashes expected for the after treatment period for comparison with the observed number of crashes to evaluate the safety implications.

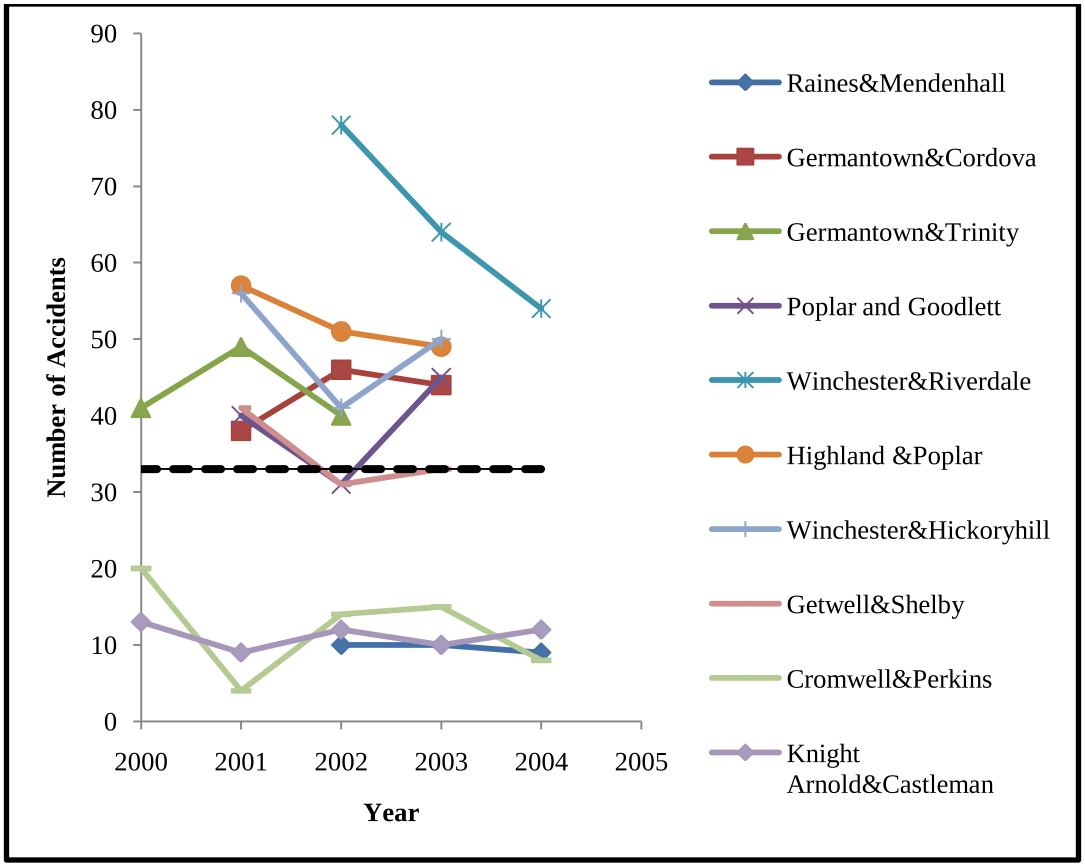

Fig. 5. Regression-to-the-mean of number of crashes

3.5.6 Safety Evaluation

To evaluate the safety, the same criterion was applied as in the Eustace et al. study, to make the comparison of the results more straightforward. The difference between the expected number of crashes after treatment and the observed number of crashes is determined by Equation 23 (Eustace, Griffin and Hovey April 2010).

$$\Delta\, crashes(\%) = (1 - \theta_u) \times 100 \qquad (23)$$

Where θ_u is the unbiased estimate of θ and is determined by (Eustace, Griffin and Hovey April 2010):

$$\theta_u = \frac{\theta}{1+\frac{\sum Var\ (B)}{(\sum B)^2}} \tag{24}$$

The corresponding variance is estimated following NCHRP 572 (Rodegerdts, et al. 2007):

$$Var(\theta_u) = \theta_u{}^2 \frac{\frac{Var\ \sum A}{\sum A^2}+\frac{Var\ \sum B}{\sum B^2}}{(1+\frac{Var\ \sum B}{\sum B})^2} \tag{25}$$

The terms in the above formula are determined as follows (Eustace, Griffin and Hovey April 2010):

$$\theta = \frac{\sum A}{\sum B} \tag{26}$$

$$Var(B) = C_y{}^2 \times PC_b \tag{27}$$

$$Var(PC_b) = \frac{\sum_{before}\ var\,(EB)}{(\sum_{before}\ C_y)^2} \tag{28}$$

Where *B* is the predicted number of crashes after the treatment if no treatment had been applied and *A* is the observed number of crashes in the after period. In addition, the variance of A, the observed number of crashes after the treatment, in Equation 25 is estimated based on Equation 13. It is noteworthy to mention that the variance of the summation of A and B are the overall summation of variances through all intersections for each single year (Rodegerdts, et al. 2007).

CHAPTER 4

RESULTS AND ANALYSIS

4.1 SPF Results

Parameters of the SPF were estimated through the GENMOD procedure in SAS 9.2 the resulting output table of SAS is shown in Table 7.

Table 7: SAS Output of Estimated Parameters for SPF

Parameter	Estimate	Standard Error	95% Confidence Limits		Z	P > $\|Z\|$
Intercept	-9.2439	1.8686	-12.9062	-5.5816	-4.95	<0.0001
AADT Major	0.7119	0.2349	0.2516	1.1722	3.03	0.0024
AADT Minor	0.5568	0.1115	0.3383	0.7753	4.99	<0.0001
Dispersion	0.0734	0.0268	0.0359	0.1500		

As a result the SPF is written as the following:

$$P = e^{-9.2439} \times AADT_{major}{}^{0.7119} \times AADT_{minor}{}^{0.5568} \qquad (29)$$

4.2 Evaluating the fit of the model

The standard error columns in the output table are one of the criteria that are used to measure the error in the prediction procedure. The value of corresponding standard errors of estimated parameters indicates the amount of variability of observed data from the predicted values due to the SPF in each site. Therefore, the lower this value compared to the related estimated value is, the better the model fits the data. Considering the output table, these values seem to be reasonably acceptable compared to the estimated values for each parameter, as most are within ±30% of the estimated value, which compares well with other published research. Another way to evaluate how well the model fits the data is through computing confidence limits. The smaller the intervals are, the less this value varies among various sites and therefore the better the model fits the data. Again the confidence limits indicate an acceptable evaluation of fitness of the model. The last value that is used to evaluate the goodness of fit of the model is the p value (the last column of output table). The p value is determined based on the type of the test that is used to evaluate the goodness of fit of the model. In the GENMOD procedure, the z-test was applied, and the resulting p-values indicate a very significant relationship between the dependent and explanatory variables. P-values less than 0.05 are typically used to determine significance, which referring to the output table; p-values are significantly small and verify that the SPF appropriately fits the data. In addition, the overdispersion parameter also indicated the statistical reliability of the SPF, as values for the overdipersion parameter close to zero indicate statistical reliability of the SPF (FHWA 2010).

4.3 EB Result

The SPF and observed number of crashes for the period prior to treatment were combined to conduct the EB procedure as explained in the previous section. Applying Equation 29, the projected number of crashes for each site in each year is determined. Using Equations 17 to 19, the predicted number of accidents due to the EB procedure is estimated. The result for each site is shown in Table 8. The estimated parameters and final safety evaluation are also presented in Table 9. The EB weight in Table 9 indicates the contribution of the observed data to the predicted value. The smaller weight means that the predicted number of accidents was determined more due to the observed data.

And finally, the unbiased safety estimation shows a 47.3% increase in the number of crashes (negative reduction in expected crashes), which means a reduction in terms of safety based on the data analyzed.

Table 8: Observed and Predicted number of crashes for each intersection (after treatment period).

Intersection	Year	Observed Number of crashes (A)	Predicted Number of Crashes due to SPF	Predicted number of Crashes Due to EB (B)
E Raines Rd and S Mendenhall Rd	2005	12	14	17
	2006	11	23	28
	2007	10	20	23
	2008	13	20	23
N Germantown Pkwy and Cordova Rd	2004	8	5	4
	2005	42	41	31
	2006	47	40	30
	2007	48	42	32
N Germantown Pkwy and Trinity Rd	2003	33	28	21
	2004	53	48	35
	2005	56	49	36
	2006	48	48	35
Poplar Ave and S Goodlett St	2004	12	5	4
	2005	57	38	29
	2006	37	38	28
	2007	28	34	25

Table 8-continued: Observed and predicted number of crashes for each intersection (after treatment period).

Intersection	Year	Observed Number of crashes (A)	Predicted Number of Crashes due to SPF	Predicted number of Crashes Due to EB (B)
Winchester Rd and Hickoryhill Rd	2004	47	39	21
	2005	58	51	28
	2006	79	53	30
	2007	48	49	27
New Gatewell Rd and E Shelby Dr	2004	36	29	20
	2005	45	42	29
	2006	37	40	27
	2007	34	37	26
Winchester Rd and Riverdale Rd	2005	31	16	9
	2006	46	49	28
	2007	48	50	28
	2008	55	46	26
N Highland St and Poplar Ave	2004	25	26	25
	2005	40	37	34
	2006	34	37	35
	2007	51	41	39

Table 9: Safety Analysis Results

Parameter	Value
EB weight	0.005
Total observed number of crashes after LED replacement	1229
Total predicted number of crashes after LED replacement due to EB procedure	834
Standard Deviation	4.15
Unbiased θ	1.47
Standard Deviation	0.042
Total crash reduction (%)	-47.3

CHAPTER 5

DISCUSSION

The purpose of this research was to evaluate the safety effect of LED module replacement at signalized intersections by conducting a widely accepted before-after analysis procedure. The result shows an increase in the number of crashes after the installation of LED modulus in traffic signals at study site locations, which corresponds to a reduction in safety. The procedure was applied in a similar way as the study that was conducted by Eustace et al. since that was the only research that has been conducted to date to evaluate the safety effect of LEDs. The same number of sample size (both treated sites and comparison group) in the current study was used for the other published research. By using a similar procedure, the comparison of results is more transparent and a more reliable general conclusion due to this retrofit can be achieved.

The result of Eustace et al. also shows an increase in the number of crashes after LED traffic signal retrofitted by 70.66%. Although both studies indicate a reduction in safety, the Ohio study yielded a significantly larger increase in crashes after LED installation. This difference might have been caused due to the inability of LED lights to melt snow as mentioned in the Dinesh study (Dinesh 2010), since Ohio has more significant snow events than Memphis, TN. This issue could be evaluated if data had been categorized in a way that the weather conditions for each crash were available. One other factor that might affect the visibility of LED signal lights could be evaluated, which is the impact of sunlight. In other words, LED lights could be less visible when there is direct sunlight on them. It could be also more beneficial to evaluate the performance of LEDs in other weather conditions such as foggy, cloudy, and rainy conditions. In general, having more details about factors that may contribute to crashes could lead to more accurate results.

The procedure that has been applied in this project has some limitations, which are mainly related to the small sample size. One main reason for not collecting a larger dataset was the lack of an easily accessible crash database for the City of Memphis. The data collection process is complex and lengthy in order to obtain essential information. Working with a larger dataset would definitely lead to a more reliable result that would make a more general statement about the safety impact of LED conversions more defensible. If sufficient data were available, a full Bayesian approach could be applied which may yield more reliable results. Recalling Table 1 from the literature review, there are many different procedures that have been developed by researchers to get the most reliable estimation in before-after road safety studies, which could have been conducted if more data was available.

CHAPTER 6

CONCLUSION

LED traffic signal retrofits has been conducted widespread due to the huge energy efficiency. The purpose of this research was to evaluate the safety impact of this nationwide replacement at signalized intersection which has not been considered as much. A before-after crash analysis was applied to evaluate the safety. The result was based on a small sample size and did not take account for the impact of crash types and weather conditions. However; the SPF created in this project was recognized to properly fit the data.

Regardless of all limitations, the results from this study and that conducted for Ohio (Eustace, Griffin and Hovey April 2010) indicated a safety decrease after LED conversion at signalized intersections (with a significantly larger decrease in Ohio). Since this conversion has been officially legislated due to the huge energy efficiency, this raises significant questions concerning whether saving energy would be worth the apparent decrease in safety. It is essential that further research be conducted to determine conclusively if LED retrofits are contributing to significantly increased crash rates at intersections where they have been installed.

6.1 Future Research

As it was mentioned before, the HSM also provided a comprehensive methodology to create the most reliable SPF considering more factors such as pedestrian volumes, geometric classification of the intersection, and etc. Since there was a shortcoming in collecting data, not all recommended factors by FHWA were considered in this study, and future research could include a more robust analysis.

Because of the potential safety impacts of these massive retrofit projects in all states, further studies with larger sample sizes are warranted to lead to a more generalized and defensible conclusion about the safety impact of LED traffic signals on signalized intersections. In addition, the specific factors (i.e. weather conditions, tethering (is it required now that LEDs be tethered to keep them from swaying, time since installation (due to gradual fading of LED bulbs)) that may contribute to difficulties in visibility of LED signals should be investigated to determine their impact on intersection safety.

Other studies are also recommended in terms of economical evaluation to investigate whether energy savings outweigh the cost of increased crash risk.

REFERENCES

SafetyAnalyst. n.d. http://www.safetyanalyst.org/docs.htm. (accessed 2001).

AASHTO. *Highway Safety Manual, Volume1*. 2010.

Abdel-Aty, Mohamed, Wang Xuesong, and Joseph B Santos. "Identifying Intersection-Related Traffic Crashes for Accurate Safety Representation." *ITE Journal*, Dec 2009.

Bonneson, James A., and Patric T. McCoy. "Estimation of Safety at Two-Way Stop-Controlled Intersections on Rural Highways." *Transportation Research Record, No.1401*, 1993: 83-89.

Brabander, Bram, and Lode Vereeck. "Safety effects of roundabouts in Flanders: Signal type,speed limits and vulnerable road users." *Accident Analysis and Prevention 39*, 2007: 591-599.

Breunning, S. M., and V. H. Surti. "Interchange Accident Exposure." *Highway Research Borad Bulletin 240, HRB, National Research Council, Washington, D.C.*, 1959: 44-52.

Bullough, John D., Jeremy D. Snyder, Aaron M. Smith, Terence R. Klein, Lighting Research Center, and Rensselaer Polytechnic Institute. *NCHRP Web-Only Document 146: Replacement Processes for Light Emitting Diode (LED) Traffic Signals.* Troy, NY: Transportation Research Board of The National Academies, n.d.

Butler, John P. *State Energy Program Case Studies.* U.S. Department of Energy., 2004.

Ceder, A. "Relationship Between Road Accidents and Hourly Traffic Flow--II, Probabilistic Approach." *Accident Analysis and Prevention, Volume14, No.1*, 1982: 35-44.

Ceder, A., and M. Livneh. "Relationship Between Road Accidents and Hourly Traffic Flow --I, Analysis and Interpretation." *Accident Analysis and Prevention, Volume14. No.1*, 1982: 19-34.

Department of Energy. "Energy Conservation Standards for Certain Consumer Products and Commercial and Industrial Equipment, Final Rule." *Federal Register Volume70. No.200*, October 18, 2005.

Dinesh, Ramde. "Energy-Efficient Traffic Lights Can’t Melt Snow", *ABC NEWS* . Online News Story, 2010. http://abcnews.go.com/US/wireStory?id=9345450 (accessed 2010).

Erza Hauer, Douglas W. Harwood, Forrest M. Council. "Estimating Safety by the Empirical Bayes Method: A Tutorial." *Transportation Research Record No.1784*, 2002: 126-131.

Eustace, Deogratias, Valerie Griffin, and Peter Hovey. "Analyzing the Effects of LED Traffic Signals on Urban Intersection Safety." *ITE Journal*, April 2010: 22-27.

FHWA. *Highway safety Manual, Volume2.* 2010.

FHWA Safety. n.d. http://safety.fhwa.dot.gov/intersection/ (accessed 2011).

Guo, Feng, Xuesong Wang, and Mohamed A. Abdel-Aty. "Modeling signalized intersection safety with corridor-level spatial correlations." *Accident Analysis and Prevention 42*, 2010: 84-92.

Hakkert, A. S., and D. Mahalel. "Estimating the Number of Accidents at Intersections from a Knowledge of the Traffic Flows on the Approaches." *Accident Analysis and Prevention, Volume10*. 1978: 69-79.

Harwood, D., Council, F.M., Hauer, E., Hughes, W.E., and Vogt,A., D. Harwood, F. M. Councul, E. Hauer, W. E. Hughes, and A. Vogt. *Prediction of the Expected.* McLean, VA: Federal Highway Administration, December 2000.

Hauer, Ezra. *Observational before-after studies in road safety.* Elsevier Science Ltd, 1997.

Hauer, Ezra, Jerry C.N. NG, and Jane Lovel. "Estimating of Safety at Signalized Intersection." *Transportation Research Record, 1185*, 1988.

Institute of Transportation Engineers. "ITE Policy Recommendations." n.d. http://www.ite.org/government/ITEPolicyPaper.pdf (accessed 2010).

Iwasaki, Randell H. "LED Traffic Signal Modules as as Incandescent Lapm Alternative." *ITE Journal, Volume73, No.4*, 2003: 42-45.

Jovanis, Paul P., and Hsin-Li Chang. "Modeling the Relations of Accidents to Miles Traveled." *Transportation Research Record,1068*, 1986: 42-51.

Lighting Research center, and Rensselaer Polytechnic Institute. *Increasing Market Penetration of LED Traffic Signal in New York State: Review of Articles and Information on LED Traffic Signals.* The New York State Energy Research and Development Authority, July 2000.

Lord, Dominique, and Fred Mannering. "The Statistical analysis of crash-frequency data: A review and assessment of methodological alternatives." *Transportation Research Part A*, 2010: 291-305.

Lord, Dominique, Simon P. Washington, and John N. Ivan . *Statistical Challenges With Modeling Motor Vehicle Crashes: Understanding The Implications of Alternative Approaches.* Research Report, Center for Transportation Safety, Texas Transportation Institute, n.d.

McDonald, J. W. "Relationship Between Number of Accident and Traffic Volumes at Divided Highway Intersections." *Highway Research Board Bulletin 74, HRB, National Research Council, Washington, D.C.*, 1966: 7-17.

Miaou, S. P., and D. Lord. "Modeling traffic crash-flow realtionships for intersections: dispersion parameter, functional form, and Bayes versus empirical Bayes methods." *Transportation Research Record No.1840*, 2003: 31-40.

Navigant Consulting Inc. *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications.* U.S. Department of Energy, September 2008.

NCHRP 387. *NCHRP Synthesis 387, LED Traffic Signal Monitoring, Maintenance, and Replacement Issues.* Transportation Research Board, 2008.

Pei, Xin, S. C. Wong, and N. N. Sze. "A joint-probability approach to crash prediction models." *Accident Analysis and Prevention, Volume43, Issue 3*, 2011: 1160-1166.

Poch, M., and F. L. Mannering. "Negative binomial analysis of intersection accidents frequency." *Journal of Transportation Engineering, Volume122, No.2*, 1996: 105-113.

Rodegerdts, Lee, et al. *NCHRP REPORT 572 Roundabouts in the United States.* Washington, D.C: Transportation Research Board , 2007.

SAS 9.2. Cary, NC, USA.: SAS Institute Inc., 2010.

Sayed, Tarek, and Felipe Rodriguez. "Accident Prediction Models for Urban Unsignalized Intersections in British Columbia." *Transportation Research Record, No.1665*, 1999: 93-99.

Schoenecker, Ted. "LED Traffic Signals Washington County Case Study." *NextStep.* 2009. http://www.nextstep.state.mn.us/energyconference/090122schoenecker.pdf. (accessed 2010).

Smith, W. L. "Probability Study of High-Accident Locations in Kansas City, Missouri." *Traffic Engineering, Volume40, No.7*, 1970: 42-49.

Starr, Ray A., Wayne H. Sandberg, and Yuzhe Guan. "Does Color Blindness Affect the Perception of Green LED Signal Indications." *ITE journal*, August 2004: 32-42.

Surti, V. H. "Accident Exposure for At-Grade Intersections." *Traffic Engineering, Volume36, No.3*, 1965: 26-27, 53.

Tarek Sayed, Felipe Rodriguez. "Accident Prediction Models for Urban Unsignalized Intersections in British Columbia." *Transportation Research Record 1665*, 1999: 93-99.

Tennesse Department of Transportation. n.d. http://ww3.tdot.state.tn.us/.

The City of Portland, Oregon. "Energy Efficiency Success Story." 2001.

The National Renewable Energy Laboratory. "State Energy Program Case Studies, California Says"Go" to Energy-Saving Traffic Lights." 2004.

Thorpe, J. D. "Traffic Accident Measurements." *Journal of the Institution of Engineers, Australia, Volume35*, 1963.

Traffic Engineering Division. *Conventional Vs LED Traffic Signals; Operational Characteristics and Economic Feasibility.* Arkansas Department of Economic Development, 2003.

U.S. Department of Transportation. "Manual on Uniform Traffic Control Devices." *FHWA.* n.d. http://mutcd.fhwa.dot.gov/ (accessed 2010).

Va´zquez-Molinı´, D., A. A´ lvarez Ferna´ndez-Balbuena, E. Bernabe´u, and J. Alda. "Louvers design for LED displays for sunny days." *Displays, Volume28,* 2007: 167-173.

Webb, G. M. "The Relationship Between Accidents and Traffic Volumes at Signalized Intersections." *Proc., Institute of Traffic Engineers*, 1955: 149-160.

Worsey, G. "Predicting Urban Accident Rates from Road and Traffic Characteristics." *ITE Journal*, December 1985.

Young, John P., and Thomas Hicks. "LEDs in light-Emitting Highway Devices in Maryland." *ITE journal*, April 2003: 32-36.

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Najmeh Jami (njami)

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Sent:	Monday, May 16, 2011 11:48 AM
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Subject:	Request regarding your paper

Dear Professors,
I'm a graduate student in Civil Engineering at the University of Memphis, and currently working on my thesis about before-after accident study of LED traffic signal retrofit. I'm writing this email since I found your recent review of methodological alternatives in crash-frequency data very useful to my literature review. I'd like to know if you would let me put the tables in that paper "The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives" in my thesis. I'd really appreciate your consideration.

Best Regards,
Najmeh Jami

Najmeh Jami (njami)

From:	Lord, Dominique <d-lord@TTIMAIL.TAMU.EDU>
Sent:	Monday, May 16, 2011 12:35 PM
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Best regards,

--
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Associate Professor
Zachry Department of Civil Engineering
Texas A&M University
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