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Evaluation of Bypass Lane Safety, Operations, and Design in Kansas

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<tr><td colspan="6">16 Abstract
The construction of bypass lanes at rural intersections has typically been considered a low-cost highway safety improvement by the transportation community. However, this needs to be quantitatively evaluated so that decisions can be made on whether to continue adding bypass lanes. Highway safety analyses utilize two common approaches to evaluate the effectiveness of a treatment: before-and-after study and cross-sectional study, both of which were utilized in this study. For the before-and-after study approach, this research performed paired sample t-test statistical analysis to estimate changes in total crash frequencies, crash rates, Equivalent Property Damage Only (EPDO) crash frequencies, and EPDO crash rates at intersections 3 to 5 years after the addition of bypass lanes, compared to 3 to 5 years before bypass lane additions. Crash data between 1990 and 2011 were obtained from the Kansas Crash and Analysis Record System (KCARS), maintained by the Kansas Department of Transportation (KDOT). For the cross-sectional study, intersections with bypass lanes were compared to intersections with no bypass lanes, for which crash data were obtained for more than 1,100 intersections in Kansas.
According to the before-and-after study, bypass lanes improve safety at unsignalized rural intersections. Total number of crashes and crash severity decreased after bypass lane additions, but these reductions were not statistically significant at a 95% confidence level for the majority of cases. For intersection-related crashes, however, a statistically significant reduction in crash rates occurred after the addition of bypass lanes at three-legged intersections. By lowering the confidence level to 90%, however, more categories become significant for both three-legged and four-legged intersections.
In the cross-sectional study, number of crashes and crash severities were lower at three-legged intersections with bypass lanes compared to three-legged intersections without bypass lanes, even though these reductions were not statistically significant at a 95% level. When considering a 300-ft intersection box, statistically significant crash reductions occurred at four-legged intersections, for all considered crash and crash rate categories. When considering 90% level, crash reduction at three-legged intersections was also statistically significant when considering a 300-ft intersection box.
Crash Modification Factors (CMFs) calculated to evaluate safety effectiveness of bypass lanes at unsignalized rural intersections in Kansas showed values less than 1.0 for almost all cases, indicating safety benefits of bypass lanes.
Overall, this study concludes that bypass lanes are beneficial in improving safety in rural areas, even though they may not be advisable in high volume conditions. Accordingly, there is no harm in continuing with the practice of adding shoulder bypass lanes at rural unsignalized intersections where the traffic volumes are relatively low.</td></tr>
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Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

The construction of bypass lanes at rural intersections has typically been considered a low-cost highway safety improvement by the transportation community. However, this needs to be quantitatively evaluated so that decisions can be made on whether to continue adding bypass lanes. Highway safety analyses utilize two common approaches to evaluate the effectiveness of a treatment: before-and-after study and cross-sectional study, both of which were utilized in this study. For the before-and-after study approach, this research performed paired sample *t*-test statistical analysis to estimate changes in total crash frequencies, crash rates, Equivalent Property Damage Only (EPDO) crash frequencies, and EPDO crash rates at intersections 3 to 5 years after the addition of bypass lanes, compared to 3 to 5 years before bypass lane additions. Crash data between 1990 and 2011 were obtained from the Kansas Crash Analysis and Reporting System (KCARS), maintained by the Kansas Department of Transportation (KDOT). For the cross-sectional study, intersections with bypass lanes were compared to intersections with no bypass lanes, for which crash data were obtained for more than 1,100 intersections in Kansas.

According to the before-and-after study, bypass lanes improve safety at unsignalized rural intersections. Total number of crashes and crash severity decreased after bypass lane additions, but these reductions were not statistically significant at a 95% confidence level for the majority of cases. For intersection-related crashes, however, a statistically significant reduction in crash rates occurred after the addition of bypass lanes at three-legged intersections. By lowering the confidence level to 90%, however, more categories become significant for both three-legged and four-legged intersections.

In the cross-sectional study, number of crashes and crash severities were lower at three-legged intersections with bypass lanes compared to three-legged intersections without bypass lanes, even though these reductions were not statistically significant at a 95% level. When considering a 300-ft intersection box, statistically significant crash reductions occurred at four-legged intersections, for all considered crash and crash rate categories. When considering 90% level, crash reduction at three-legged intersections was also statistically significant when considering a 300-ft intersection box.

Crash Modification Factors (CMFs) calculated to evaluate safety effectiveness of bypass lanes at unsignalized rural intersections in Kansas showed values less than 1.0 for almost all cases, indicating safety benefits of bypass lanes.

Overall, this study concludes that bypass lanes are beneficial in improving safety in rural areas, even though they may not be advisable in high volume conditions. Accordingly, there is no harm in continuing with the practice of adding shoulder bypass lanes at rural unsignalized intersections where the traffic volumes are relatively low.

Acknowledgement

The authors greatly appreciate the funding support provided by the Kansas Department of Transportation (KDOT), which made this study possible. Assistance, support, and suggestions provided by Project Monitors Dr. Howard Lubliner, KDOT District One, and Mr. Brian Gower, KDOT Bureau of Transportation Safety and Technology, are very much appreciated. Thanks are also extended to Mr. Jim Brewer, Bureau of Road Design, and Mr. Steven Buckley, Bureau of Transportation Safety and Technology, both also at KDOT, whose contributions made the successful completion of this project a possibility.

Table of Contents

List of Tables

List of Figures

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Chapter 1: Introduction

1.1 Background

Increased population density in urban areas and high Annual Average Daily Traffic (AADT) of urban roads cause crashes to occur more frequently in urban areas compared to rural areas. However, higher speed limits, lack of traffic signs and signals, lower enforcement levels, and many other factors increase crash severity on rural roadways. In 2010, a total of 30,196 fatal crashes occurred in the United States, resulting in 32,885 fatalities. Fifty-four percent of fatal crashes and 55% of fatalities occurred in rural areas, although only 19% of the United States population lives in rural areas. Urban areas accounted for 45% of fatal crashes and 44% of fatalities. In 2010, the fatality rate per 100 million vehicle miles traveled was 2.5 times higher in rural areas than in urban areas (NHTSA, 2012).

According to a census in 2010, 36% of all motor vehicle crashes in Kansas occurred in rural areas; however, 69.7% of fatal crashes occurred in rural areas, demonstrating increased crash severity on rural roadways (KDOT, 2013a). Figures 1.1 and 1.2 show the proportion of rural and urban crashes compared to all crashes and fatal crashes in Kansas from 2005 to 2010.

Nearly 30% of crashes in Kansas occurred at intersections or were intersection-related (KDOT, 2013a). Opportunity for vehicle crashes increases at intersections, because vehicles approach the intersection from multiple directions. Figure 1.3 shows the proportion of intersection-related crashes compared to all crashes between the years 2007 and 2013.

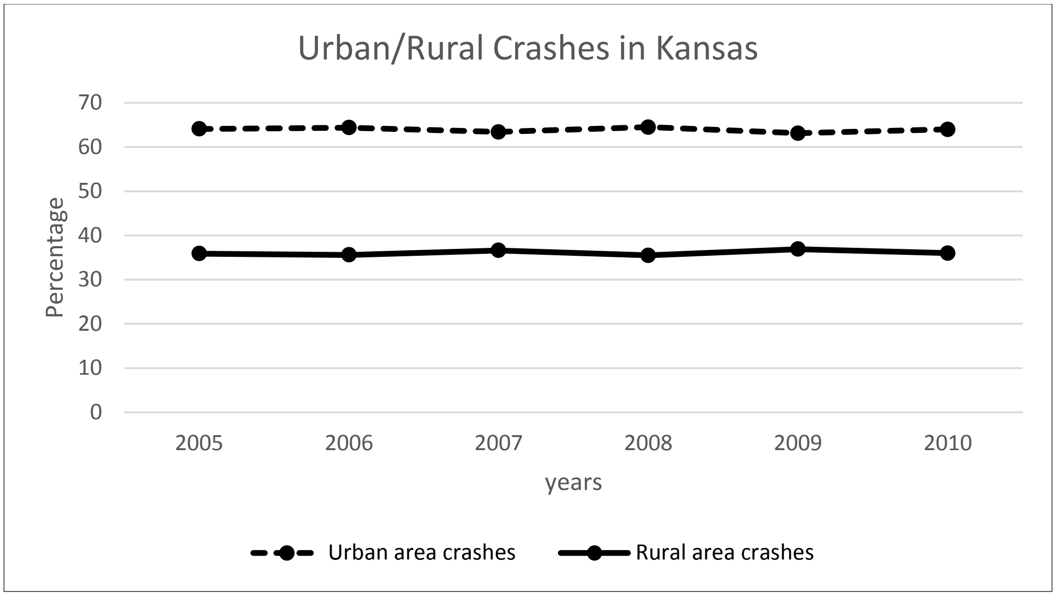


Figure 1.1: Proportion of Urban and Rural Crashes in Kansas

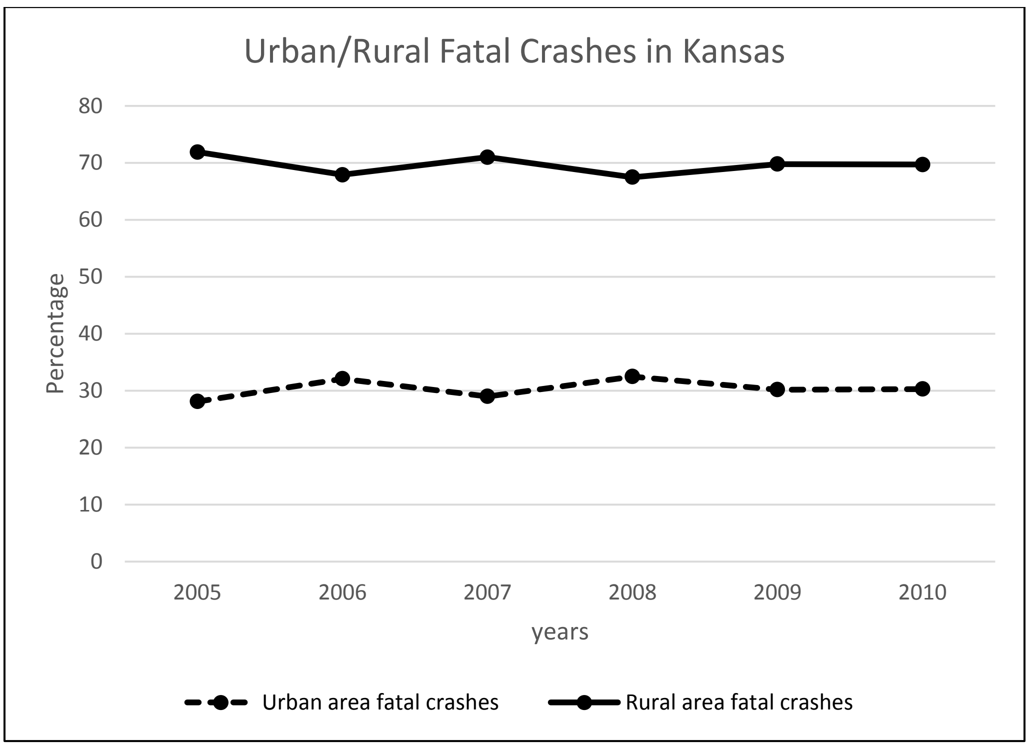


Figure 1.2: Proportion of Urban and Rural Fatal Crashes in Kansas

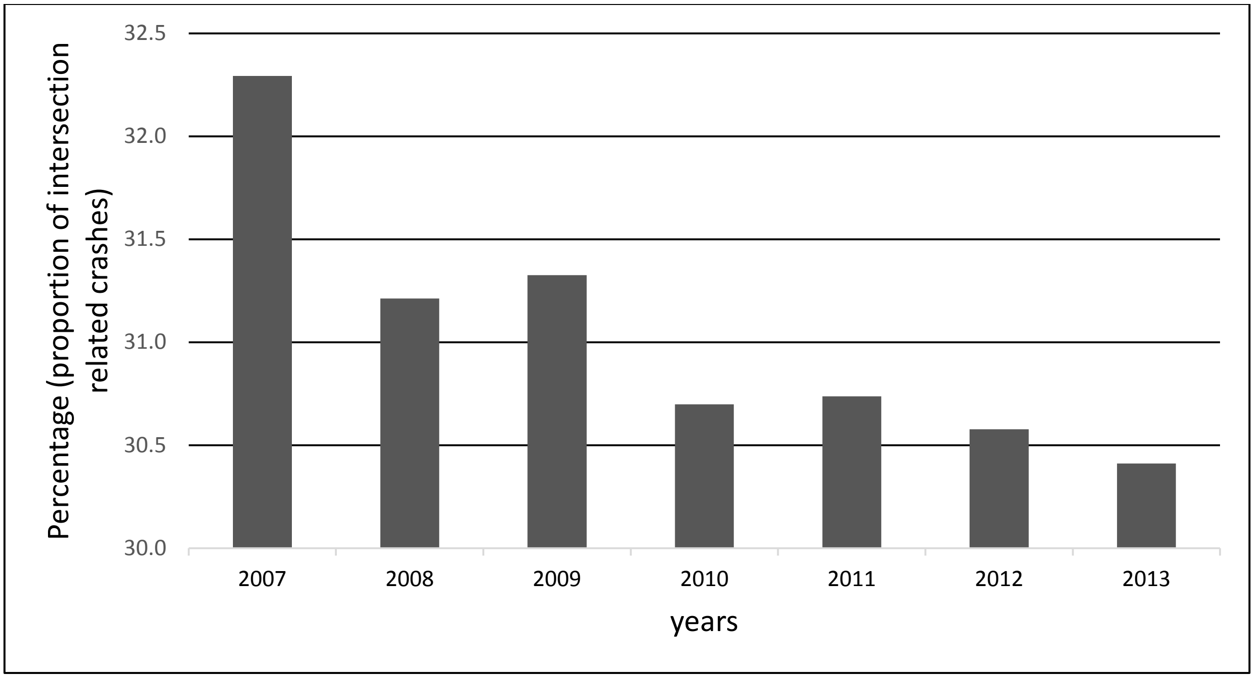


Figure 1.3: Proportion of Intersection-Related Crashes Compared to All Crashes

1.2 Overview

In order to avoid confusion, safety must be defined before the safety level of a transportation facility can be evaluated. Objective measures, such as the number of crashes and crash severity, and subjective perception, such as drivers' perceived level of safety when utilizing a transportation system, are commonly associated with road safety. However, increased perception of roadway safety may not necessarily translate into enhanced road safety in reality. In fact, in some cases, increased perception of safety may result in reduced safety because the road user feels safer and consequently exercises less caution when driving (Izadpanah, Hadayeghi, & Zarei, 2009). Perception that low AADT values on rural roadways decrease the probability of a crash might cause drivers to feel safer on rural roadways, making them less cautionary. Lower law enforcement levels that are typically prevalent in vast rural areas might also be contributing to changes in driver behavior in such areas. These elevated levels of safety concerns in rural areas make it necessary to look at low cost approaches to improving highway safety.

Accordingly, this study focused on evaluating safety effectiveness of bypass lane additions at rural unsignalized intersections. Urban high-traffic intersections typically contain a dedicated lane for drivers turning left, but this lane is not commonly present at rural intersections. When a driver approaches an unsignalized intersection behind a left-turning vehicle, the driver must decrease vehicle speed and stop. Bypass lanes provide a through-traffic driving lane in which the following driver can bypass the left-turning vehicle. If a vehicle in a through-travel lane is stopped to turn left, following vehicles are able to utilize the shoulder bypass lane to avoid stopping (Fitzpatrick, Parham, & Brewer, 2002). To increase highway safety at three-legged or four-legged rural intersections in which a portion of the paved shoulder may be marked as a lane for through traffic, installation of bypass lanes have been identified as a low-cost safety improvement. Figure 1.4 shows a typical bypass lane at three-legged and four-legged rural intersections on a two-lane highway.

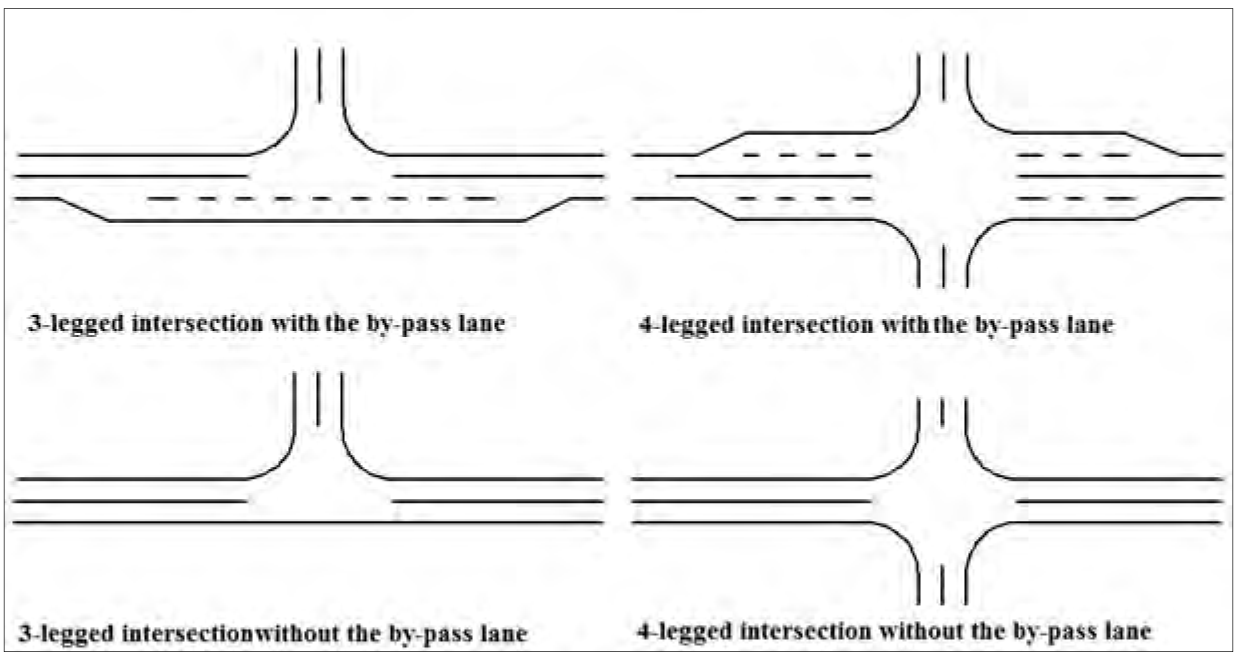


Figure 1.4: Configuration of a Typical Bypass Lane

The Kansas Department of Transportation (KDOT) has utilized bypass lanes at rural intersections for a considerable period of time. Because bypass lanes are fairly common on Kansas roadways, this study was necessary to determine benefits of the continued addition of bypass lanes. This study serves that purpose by quantitatively evaluating the safety effectiveness of bypass lanes by considering several different approaches and criteria.

1.3 Objectives

The primary objective of this study was to draw statistically reliable conclusions relative to comparison of operational and safety characteristics of rural unsignalized intersections by specifically focusing on three-legged and four-legged rural intersections in Kansas. This report discusses results of a before-and-after study and a cross-sectional study. In the before-and-after study, crashes that occurred after the addition of bypass lanes were compared to crashes that occurred before the addition of bypass lanes. In the cross-sectional study, intersections were categorized as intersections with bypass lanes and intersections without bypass lanes, and statistical analyses were utilized to determine the safety effectiveness of having bypass lanes at those intersections.

Chapter 2: Literature Review

Chapter 1 defined bypass lanes at intersections and discussed national and state statistics which demonstrate the need for countermeasures at rural unsignalized intersections. Chapter 2 discusses previously published research regarding safety evaluation of bypass lanes at intersections.

2.1 Studies Related to Bypass Lanes

Sebastian and Pusey (1982) published a report that investigated bypass lanes after the passage of legislation in Delaware in 1976 that allowed drivers to pass a stopped, left-turning car on the right, using the shoulder as necessary. This law did not designate a required paved shoulder width, so Delaware drivers utilized roadway shoulders to pass vehicles on the right on two-lane roads. At that time, Delaware did not mandate standard widths of travel lanes, bypass lane installation requirements, or pavement markings. This study investigated the savings of user costs, such as operating costs, time/delay, and fuel consumption, as well as vehicle emissions and crash prevention, in order to warrant the use of bypass lanes in designated left-turn lanes.

Data were collected at 16 locations for three 2-hour peak periods: morning, noon, and evening. Average Daily Traffic (ADT) was calculated using the Delaware Department of Transportation's (DelDOT) annual summary report, and crashes were reviewed based on 3-year crash experiences obtained from DelDOT's traffic crash records. Results indicated that bypass lanes primarily prevented rear-end crashes. Conclusions of this report also included statistical proof of the benefits of legalizing pass-on-the-right-lanes in order to reduce user operating costs, fuel consumption, travel delays, emissions, and rear-end crashes (Sebastian & Pusey, 1982).

The Minnesota Department of Transportation (MnDOT) funded a research project with BRW, Inc., to investigate the safety and use of rural intersections without turn lanes, with bypass lanes, and with left-turn lanes in order to determine whether or not bypass lanes should be used as a safety measure at unsignalized intersections. Data on three-legged intersections were collected using a survey sent to 212 government entities within Minnesota. Eighty-two completed surveys were returned. Another survey for four-legged intersections was sent to 22 government entities, and 14 were completed and returned. Results of these surveys indicated that a majority of counties and cities did not reference MnDOT design guidelines. In addition, it was noted that most counties and cities implemented inconsistent pavement markings, that three-legged bypass lanes had advantages in terms of delay, and that four-legged intersection bypass lanes should not be used (Preston & Schoenecker, 1999).

A legal review of bypass lane implementation also occurred because Minnesota revised its highway design to include a required 10-ft paved shoulder. Consequently, users of rural roads began using the shoulder as a bypass lane to avoid turning vehicles, although the intersection was not intended to include bypass lanes. Minnesota then outlawed passing on the right unless performed on a main-traveled lane of the roadway, thus requiring MnDOT to evaluate design regulations and implementation requirements for signage and marking (Preston & Schoenecker, 1999).

Preston and Schoenecker (1999) conducted safety analysis using crash data from between 1995 and 1997 for the following categories:

- Total and average number of intersection crashes
- Average crash rate for volume categories of:
    - 0-4,000 vehicles per day
    - 4,000-10,000 vehicles per day
    - >10,000 vehicles per day
- Distribution by severity and type

Three- and four-legged intersections were reviewed and categorized into:

- No turn lanes
- Bypass lanes
- Left-turn lanes

An additional before-and-after study was conducted in the same study, which included 6 years of crash data: 3 years prior to installation of bypass lanes and 3 years post-installation of bypass lanes. Sixty-nine intersections were used for the sample size, and crash data used was from between 1983 and 1994 (Preston & Schoenecker, 1999).

A safety summary of the 2,700 reviewed intersections stated that three-legged intersections had fewer vehicle crash occurrences compared to four-legged intersections. The number of crashes did not appear to be a function of entering traffic volume, but crash severity was affected by the volume. No statistical significance was evident between design types, and intersections with left-turn lanes had the lowest percentage of rear-end crashes. The before-and-after study summary also showed no statistically significant differences, and intersections with bypass lanes had a lower overall crash rate than the state average crash rate. Analysis concluded that safety improvements due to bypass lanes are not statistically significant, suggesting that it is not possible to conclude that bypass lanes should not be used as a safety device (Preston & Schoenecker, 1999).

Bruce and Hummer (1991) reviewed delay data to investigate effectiveness of a left-turn bypass lane on a two-lane rural T-intersection. Left-turn bypass lanes are defined as a paved area to the right of the travel lane on a major road, opposite the minor road at a T-intersection on a rural two-lane roadway, as shown in Figure 2.1. Bypass design was designated as a 300-ft taper out to a 12-ft-wide lane; 700 ft of 12-ft-wide lane with 600 ft from the end of the run out taper to the minor road centerline and then 100 ft past centerline; and a 600-ft taper to a single-lane travel way. The experiment relied on traffic simulation using TRAF-NETSIM, a detailed, stochastic, microscopic model developed by the Federal Highway Administration (FHWA). Eight factors were identified for use in the simulation: volume of opposing traffic on the major street, volume of right-turning traffic from the minor street, left-turn volume, through volume, speed of vehicles, distance from T-intersection to nearest controlled intersection upstream/downstream, and the presence of a bypass lane. With eight factors, the experiment had a total of 256 combinations, but for efficiency, only 64 combinations were tested.

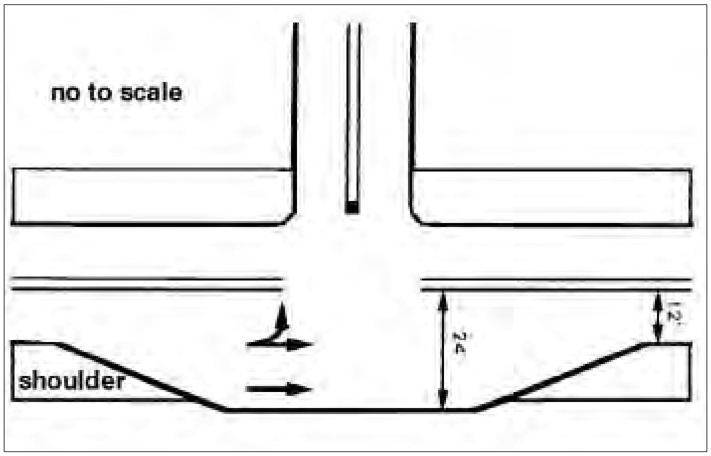


Figure 2.1: Left-Turn Bypass Concept
Source: Bruce & Hummer, 1991

Significant variables found through analysis results included through traffic volume, opposing volume, left-turn volume, speed, upstream signal distance, and presence of the bypass lane. Average travel time saved was found to be 0.50 seconds per vehicle (Bruce & Hummer, 1991).

2.2 Studies Related to Crash Modification Factors

A Crash Modification Factor (CMF) evaluates the safety effectiveness of any given countermeasure. A CMF value less than 1.0 shows an expected reduction in vehicle crashes due to a countermeasure, but a CMF value greater than 1.0 indicates an increase in crashes after countermeasure implementation (Gross, Persaud, & Lyon, 2010). Although a before-and-after study approach is typically used to develop the CMF, alternative methods for CMF calculation were required. In a before-and-after study, CMF is defined by comparing observed crash frequency after countermeasure implementation to crash frequency before countermeasure installation. However, CMFs derived from cross-sectional data are based on a certain time period, such as 3 years, assuming that the ratio of average crash frequencies for sites with and without a feature is an estimate of CMF for implementing that particular feature (Gross & Donnell, 2011).

Gross and Donnell (2011) applied case-control and cross-sectional method to developed CMF for roadway lighting and shoulder width. Four years of data (from 2001 to 2004) were used to estimate CMF for road lighting, including 6,464 intersections in Minnesota. Only 13.7% of the intersections had signal control, and the remainder of the intersections operated with stop signs. Approximately 49% of the intersections were four-legged, 40% were three-legged, and 11% were four-legged skewed intersections. The analysis database included 38,437 crash reports that occurred at the selected intersections. Based on the case-control method, CMF for intersection lighting was 0.886, while calculated CMF for the cross-sectional study was 0.881. In addition, CMFs developed for lane and shoulder widths were similar when the two methods were directly compared. This study suggested that case-control and cross-sectional studies produce consistent results, especially when the before-and-after study was impractical due to data limitations.

Gross and Jovanis (2007) applied the case-control method to evaluate the safety effectiveness of lane and shoulder width. Their study estimated CMF as a common acceptable ratio to measure safety effectiveness by comparing the number of crashes with countermeasure implementation and the number of crashes without a countermeasure. The study considered more than 28,000 rural two-lane undivided highways in Pennsylvania from the years 1997 to 2001. The paper provided a matched case-control design, while adjusting for variables such as speed limit, AADT, and segment length. CMF was provided for a wide range of shoulder widths. Results showed that segments without shoulders are safer than segments with shoulder width from 0 to 1.83 meters. However, CMF is less than 1.0 for shoulder width greater than 1.83 meters. Case-control estimation could advantageously estimate confidence levels, thereby conveying variability in safety effectiveness. Safety effectiveness range can be considered in an economic analysis of alternative action.

2.3 Studies Related to Estimation of Annual Average Daily Traffic

Traffic volume of a road is identified by Average Annual Daily Traffic (AADT). AADT, one of the most important traffic variables for analysis of traffic crash rates, is widely used in a majority of traffic engineering and safety related studies (Pan, 2008). The most accurate method for AADT estimation is traffic counting using permanent or temporary stations; however, this method is not always practical or feasible due to the huge amount of time and cost associated with it. In such situations, researchers have attempted to estimate AADT when the actual value is not available.

Mountain, Fawas, and Jarrett (1996) developed a model to predict crash rates on roads with minor junctions in which traffic counts on minor approaches were not available. The study was based on data for 3,800 km of highway in the United Kingdom with more than 5,000 minor junctions. A generalized linear model was used to develop regression estimates. When combined with crash counts, the empirical Bayes procedure improved the estimates. The empirical Bayes model was utilized to remedy lack of AADT, especially when traffic data were not available for minor roads, by using data including information such as highway characteristics, crash counts, and traffic flow for 5 to 15 years. However, the study was limited to injury crashes only, because property damage crashes were not reported in the U.K. Analysis did not include major junction components because this study modeled minor junctions and links between minor junctions. Three methods were reviewed: crash count, predictive model, and empirical Bayes. Modeling results showed that crashes on highway links were not proportional to traffic flow and link length, and crash frequencies are non-linear functions of traffic flow. The empirical Bayes method was superior to the crash count method, followed by the predictive model, and it was also the only method to produce unbiased estimates of high-risk sites.

Lubliner (2011) validated the Highway Safety Manual (HSM) prediction model for rural two-lane highway segments in Kansas. This study identified the differences between Kansas highway system characteristics and HSM recommendations of model application. A model was calibrated using HSM procedure and a new procedure by considering nineteen 10-mile highway sections in Kansas. The study used the Interactive Highway Safety Design Model (IHSDM) to select homogeneous two-lane highway segments. The Control Section Analysis System (CANSYS) Kansas State Highway System Database for 2007 was utilized to find AADT at each homogeneous segment. Because AADT values varied over the analysis period, additional AADTs were gathered from KDOT historical traffic maps from 2005 to 2006. The study developed correlation between AADT and the observed/predicted (OP) crashes ratio for six districts in Kansas. The two highest OP ratios belonged to rural Districts Three and Six, which had similar population density and travel demand.

Pan (2008) attempted to estimate AADT on all roads in Florida. This study used 26,721 traffic counts provided by the Florida Department of Transportation (FDOT) to develop six AADT predictor models. Two types of databases, including seven social-economic and 14 independent variables, were utilized to estimate AADT. Pan used 10 years of social-economic data between the years of 1995 and 2005, collected for all 67 counties in Florida. Geometric road characteristics were gathered from various Geographical Information System (GIS) data layers provided by FDOT. The study used the stepwise regression method on independent variables which were significant with 90% level of confidence. Six linear regression models were developed for highways in large metropolitan areas, local streets in large metropolitan areas, highways in small-medium urban areas, local streets in small-medium urban areas, highway models in rural areas, and local streets in rural areas. R-square of prediction models varied from 0.166 to 0.418.

Chapter 3: Methodology

3.1 Background of Observational Studies

Researchers either design an experiment or conduct an observational study to answer a specific question or to test whether a certain hypothesis is correct. Experiments are studies implemented in a laboratory context; however, in observational studies, study parameters cannot be completely controlled by researchers (Izadpanah et al., 2009). Road safety studies are classified as observational studies because, in general, a crash is comprised of random circumstances and researchers are unable to control crashes. Observational studies can be categorized as before-and-after studies and cross-sectional studies.

In road safety studies, parameters that potentially influence safety may change during before-and-after periods. For example, weather conditions and traffic regulations may change, just like traffic conditions in any given transportation system. Attributes such as geometric designs of the road are expected to remain the same during each before or after period. However, in cross-section based observational studies, safety effects of one group of facilities are compared to another group. These two groups of facilities should have similar features, except the feature that is being studied, so that the safety effect of dissimilar feature could be evaluated (Izadpanah et al., 2009).

3.2 Before-and-After Studies

Agencies commonly evaluate safety effects of a specific roadway improvement by comparing a crash occurrence associated with the transportation facility before and after treatment implementation. Before-and-after designs include a treatment introduced at some point in time, and a comparison of safety performance before and after treatment for a site or group of sites (Gross et al., 2010). However, these studies are rather challenging to complete because crashes are random and change each year, unlike laboratory experiments in which the analyst controls extraneous conditions (Izadpanah et al., 2009).

The before-and-after study approach is commonly used to measure safety effects of a specific treatment or a combination of treatments for highway safety (Hauer, 1997). In controlled and fully-randomized study design, a before-and-after study is deemed superior to cross-sectional studies, because many other attributes linked to converted sites with implemented treatment remain unchanged. Other parameters that affect facility safety, such as traffic volume and weather conditions, change over time. Consequently, specific evaluation techniques must account for changes in order to estimate the true effects of safety improvements.

Although not perfect, the before-and-after study approach offers better control for estimating treatment effects. The before-and-after study assumes that a change occurs between the “before” and “after” conditions (Hauer, 1997). This section provides an overview of four of the most commonly used methods in before-and-after studies (Izadpanah et al., 2009).

3.2.1 Naïve Before-and-After Study

The naïve before-and-after study is the simplest technique for this type of observational study. In a naïve before-and-after study, “after” period crashes are compared to the “before” period crashes; therefore, the treatment effect can be considered as the difference between crash counts in the after period and the before period (Izadpanah et al., 2009).

3.2.2 Before-and-After Study with Yoked Comparison

In yoked comparison, evaluated treatment effects refer to the treatment site and comparison site, respectively (Griffin & Flowers, 1997). The treatment group is similar to the comparison group with a one-to-one correspondence between each member of the comparison group and the treatment group. Therefore, similar groups must be selected for this type of study. For example, if the treatment facility is a roundabout, the comparison should be a roundabout with respect to area type (urban or rural), number of lanes, geometric design characteristics, and traffic volume. The comparison site should not have undergone any other geometric change or traffic control improvement during the before and after periods for accurate evaluation of safety due to the treatment (Harwood et al., 2002).

Figure 3.1 represents the one-to-one correspondence between each member of the comparison group and the treatment group.

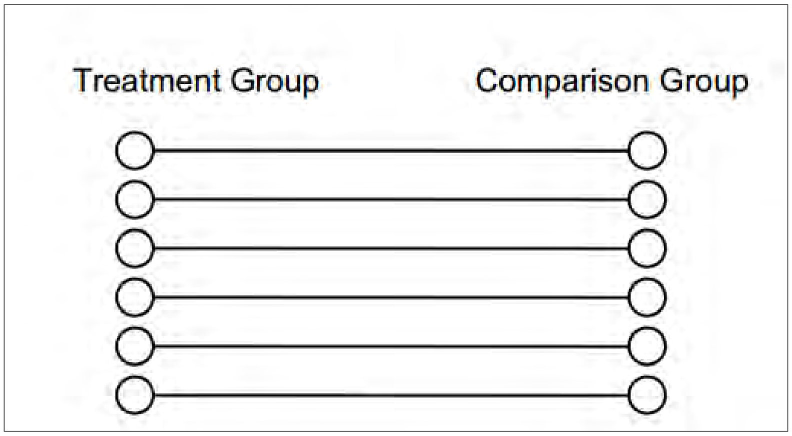


Figure 3.1: Relationship Between Treatment and Comparison Groups for Yoked Method
Source: Izadpanah et al., 2009

Unknown casual factors are a critical issue in any safety evaluation; therefore, in this method, unknown casual factors were anticipated to have identical effects on the comparison group and treatment group. Although safety experience during the after period may change without any improvement as well, based on the change in crash experience in the comparison site, the after to before crash ratio is calculated in this method. Crash frequency during the after period is calculated by crash frequency during the before period, multiplied by the after to before crash ratio. This calculated value is the crash frequency during the after period with no improvement. The difference between predicted frequency of crashes for the after period and the actual after period crash frequency demonstrates treatment effects (Izadpanah et al., 2009).

3.2.3 Before-and-After Study with Comparison Group

The before-and-after study with comparison group approach follows the same rationale as the yoked comparison method, but the comparison group and treatment group have different sample sizes. The comparison group has a larger sample size and no one-to-one matching (Izadpanah et al., 2009). Figure 3.2 is a graphical representation of the treatment and comparison groups.

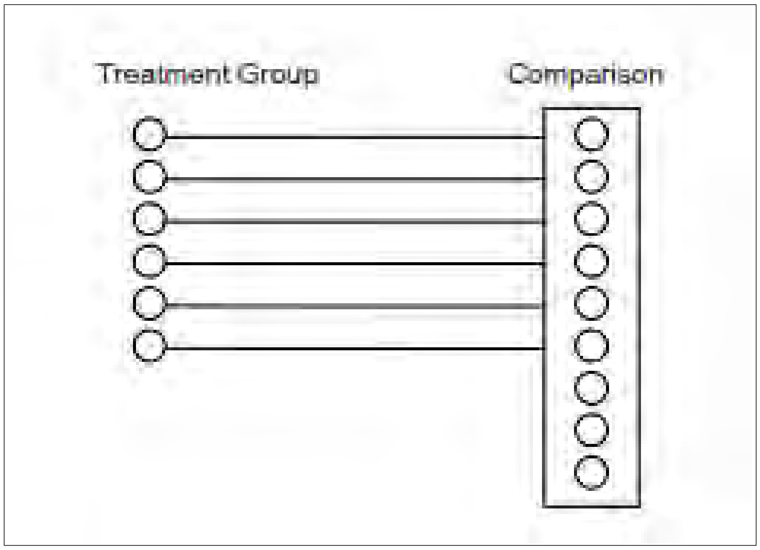


Figure 3.2: Relationship Between Treatment Group and Comparison Group—Before-and-After Study with Comparison Group
Source: Izadpanah et al., 2009

In this approach, however, facilities in the comparison group do not have to be identical to the facilities in the treatment group, but the treatment and comparison groups must have similar crash history during the before period. In addition, this technique is similar to the yoked comparison approach, because it cannot determine treatment effectiveness if crash counts in the before or after period in the comparison group equal zero. However, this situation is unlikely to occur because of the multiple comparison sites, rather than only one comparison site for each specific treatment site (Izadpanah et al., 2009).

3.2.4 Before-and-After Study with the Empirical Bayes Approach

In general, safety treatments are applied for locations with high crash rates. However, if the selection of sites for treatment implementation is carried out based on a short-term high occurrence of crashes, a lower crash rate might be expected in the after period, even if no improvement has been implemented. In literature, this effect is known as regression-to-the-mean, in which a regression line with an appropriate coefficient of each relevant factor is determined to predict the crash rate for the treatment group. Safety performance functions (SPFs) are used to estimate crash frequencies and explain the relationship between crash frequency and explanatory variables, such as traffic volume of the facility (Izadpanah et al., 2009). Figure 3.3 shows a graphical representation of the treatment and comparison function for this method.

In this empirical Bayes approach, crash frequency in the after period, with no treatment, can be estimated based on observed frequency in the before period and the SPF function developed for the comparison group (Izadpanah et al., 2009). Therefore, the difference between expected future crashes and actual crashes in the after period reveals the effects of the treatment.

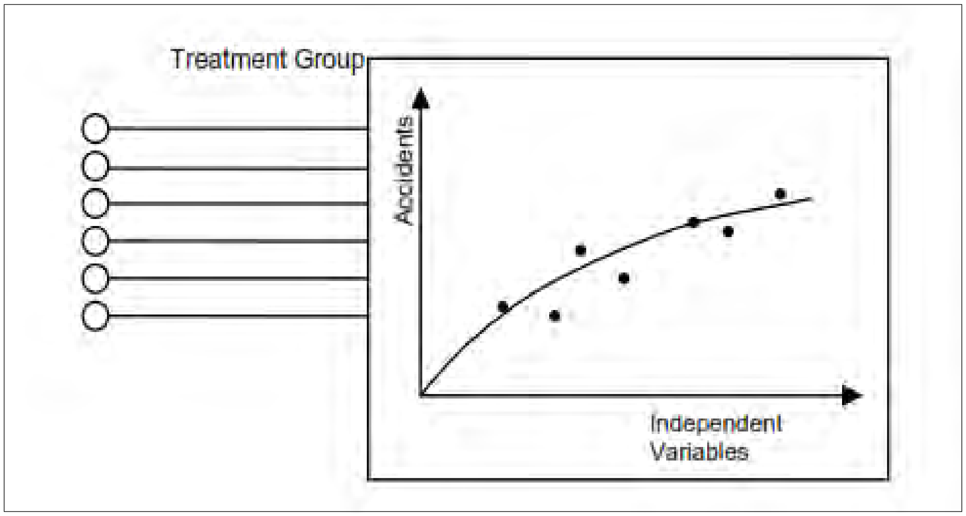


Figure 3.3: Relationship Between Treatment Group and Comparison Group—Empirical Bayes Approach
Source: Izadpanah et al., 2009

3.3 Cross-Sectional Studies

A cross-sectional study, a common observational study in transportation safety evaluations, compares safety performance of a site or group of sites with the treatment of interest to similar sites without treatment at a single point in time, such as present time (Gross et al., 2010). Cross-sectional studies divide intersections into two major groups:

- Intersections with a treatment, such as bypass lanes
- Intersections without the treatment

As mentioned, one challenge inherent to observational studies is that crashes are random and change from year to year (Izadpanah et al., 2009). In addition, other parameters that affect facility safety, such as traffic volume and weather conditions, vary for each intersection. In order to evaluate safety effectiveness of a specific treatment, the HSM recommends a 3-year to 5-year comparison of crash data at sites with implemented treatment versus sites without a countermeasure (AASHTO, 2010).

3.4 Statistical Analysis Using *t*-test

The *t*-distribution is a symmetrical distribution similar to normal distribution, but has thicker tails, making it shorter and flatter. The *t*-distribution is useful for analyzing the mean of an approximately normally distributed population when the population standard deviation is unknown (Martz & Paret, n.d.).

Consider crash frequency at intersections with bypass lanes as the subject case. If the average crash frequency per intersection before and after adding the bypass lane is μ_1 and μ_2, respectively, the *t*-test can be used to determine whether a significant change occurs between average crash frequency per intersection in the before and after period. Therefore, the null hypothesis is:

$$H_0 : \mu_1 = \mu_2$$

Depending on the issue being analyzed, the alternative hypothesis can take one of the following forms:

$$H_1 : \mu_1 > \mu_2 \ (one - tailed\ test)$$
$$H_1 : \mu_1 < \mu_2 \ (one - tailed\ test)$$
$$H_1 : \mu_1 \neq \mu_2 \ (two - tailed\ test)$$

When the critical area of the distribution is one-sided, either greater than or less than a certain value, it is called a one-tailed test. A two-tailed test would be used to determine if two means are different. The *t*-value can be computed from Equation 3.1 (Ruxton, 2006).

$$T = \frac{\bar{X}_1 - \bar{X}_2}{S_p^2 \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$ **Equation 3.1**

Where:

$\bar{X}_1 and\ \bar{X}_2$ = Sample means

$n_1\ and\ n_2$ = Sample size

S_p = Square root of the pooled variance given by Ruxton (2006)

$$S_p{}^2 = \frac{(n_1-1)S_1{}^2+(n_2-1)S_2{}^2}{n_1+n_2}$$ **Equation 3.2**

Where:

S_1 and S_2 = Variance of the population

The degree of freedom and level of significance (α) affect the value of *t*. The degree of freedom for t-distribution is $(n_1 + n_2 - 2)$, and the level of significance is the probability of rejecting the null hypothesis. When the null hypothesis is true and rejected, it is typically referred to as Type 1 error. If the null hypothesis is not true and is accepted, error Type 2 is said to occur. The most commonly used "α" value in traffic safety studies is 5%, although 10% is occasionally used. When the *t*-test is one-tailed, the *t*-value is selected for "α"; when the test is two-tailed, the *t*-value is selected for "α/2." Rejection of the null hypothesis is shown in Table 3.1.

Table 3.1: Rejection of Null Hypothesis Based on *t*-value

Alternative hypothesis	Rejection region for H_0
$H_1 : \mu_1 > \mu_2$ $(one - tailed\ test)$	$T\ > t_\alpha$
$H_1 : \mu_1 <\ \mu_2$ $(one - tailed\ test)$	$T\ > t_\alpha$
$H_1 : \mu_1 \neq \mu_2$ $(two - tailed\ test)$	$\|T\|\ > t_{\propto/2}$

The null hypothesis is rejected if the sample *t*-value is more than the critical *t*-value, meaning that the probability of obtaining a *t*-value at least as critical *t*-value is less than 5% (or any other α value); therefore, the null hypothesis is not true. In other words, a significant reduction exists between two sample means. The null hypothesis is not rejected if the sample *t*-value is less than the critical *t*-value, meaning that the probability of obtaining a *t*-value at least as critical *t*-value is greater than 5% (or any other α value). Therefore, the null hypothesis could be true or no significant difference exists between the population's means (Ruxton, 2006).

3.4.1 p-value vs. α value

The standard level of significance, known as alpha (α), is typically set at 0.05. Assuming that the null hypothesis is true, the null hypothesis may be rejected only if observed data are so unusual that they occurred by chance at a maximum of 5% of the time. Each statistic has an associated probability value (*p*-value) which is the likelihood of an observed statistic occurring due to chance, given sampling distribution. Instead of comparing *t*-critical and *t*-statistical values to determine significant difference, *p*-value may be used to compare significance levels (Martz & Paret, n.d.). A large *t*-value means a large difference between sample means; therefore, a larger *t*-value is associated with a smaller *p*-value. Table 3.2 shows rejection regions of the null hypothesis.

Table 3.2: Rejection of Null Hypothesis Based on *p*-value

Alternative hypothesis	Rejection region for H_0
$H_1 : \mu_1 > \mu_2$ $(one - tailed\ test)$	$\alpha\ > p - value$
$H_1 : \mu_1 <\ \mu_2$ $(one - tailed\ test)$	$\alpha\ > p - value$
$H_1 : \mu_1 \neq \mu_2$ $(two - tailed\ test)$	${}^{\propto}/_{2}\ > p - value$

Significance level sets the standard for how extreme data must be before rejecting the null hypothesis, and *p*-value indicates how extreme the data are (Martz & Paret, n.d.). A comparison of *p*-value and significance level determines whether the observed data are statistically significantly different from the null hypothesis:

- If the *p*-value is less than or equal to the alpha (*p*-value ≤ α), the null hypothesis is rejected, or a significant difference exists between samples means.
- If the *p*-value is greater than alpha (*p*-value > α), the null hypothesis is not rejected, or no significant reduction exists between samples means.

3.4.2 Confidence Interval

Confidence interval (CI) is an interval estimation of the population to indicate reliability of the estimation. CI provides an estimated range of values likely to include an unknown population parameter; the estimated range is calculated from a given set of sample data. As shown in Figure 3.4, confidence level, or (1 - α), associated with CI, is typically calculated as 95%, but occasionally 90%, 99%, or another usable CI are utilized (Sharabati, 2009).

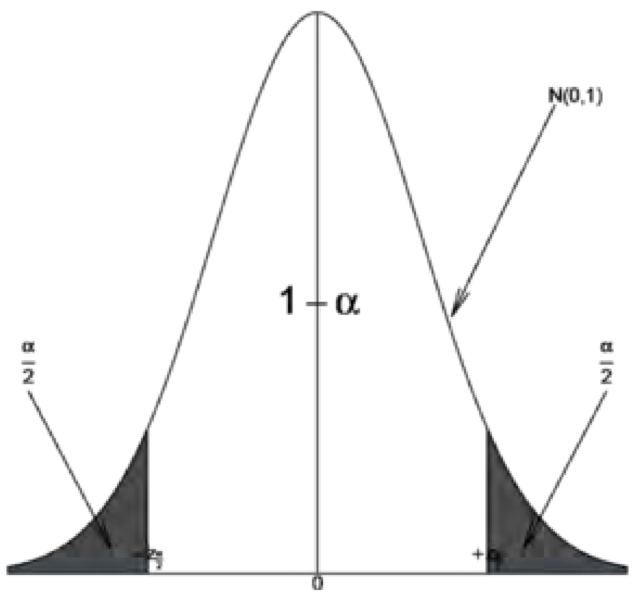


Figure 3.4: Confidence Interval Representation
Source: Sharabati, 2009

3.5 Crash Modification Factor

Transportation professionals, such as traffic engineers, transportation planners, and designers, can use CMF to evaluate effectiveness of a given countermeasure (Gross et al., 2010). More specifically, CMF can be used to estimate the cost or the benefit associated with a certain treatment. CMF application can be used for all crashes and locations or for specific crashes and locations, such as collisions with animals at two-lane rural highways. In general, CMF application may change with various crash characteristics, such as crash severity, crash type, crash frequency, and crash location in rural or urban areas.

CMF can also be used to compute the number of crashes after implementation of a countermeasure in order to compute the effect of that countermeasure at specific site locations. A

CMF value greater than 1.0 indicates an expected increase in crashes, demonstrating that the countermeasure decreased safety in that location. In contrast, a CMF less than 1.0 indicates a reduction in crashes after implementation of a given countermeasure, demonstrating that the countermeasure improved highway safety in that location (Gross et al., 2010).

CMF function is a formula to compute CMF for each site. Based on site characteristics, a different CMF could be estimated for each site. A countermeasure may have several levels, so different CMF formulas offer accurate ratios to estimate safety effectiveness of each step (Gross et al., 2010).

3.5.1 Before-and-After with Comparison Group to Estimate Crash Modification Factors

In the before-and-after with comparison group approach to estimate, an untreated comparison group similar to treated groups is used to account for crash changes irrelevant to countermeasures. The unrelated effect is calculated by changes in crash frequency in the after period compared to the before period in the comparison group. The observed crash frequency multiplied by the comparison ratio provides the expected number of crashes in the after period without treatment implementation. The difference between the expected number of crashes in the after period and the actual number demonstrates the safety effectiveness of the specific treatment (Gross et al., 2010). However, a perfect comparison group is difficult to achieve, because the change in crashes at treatment sites without treatment cannot be known (Hauer, 1997). Figure 3.5 illustrates the similarity and suitability of a comparison group. In this example, the treatment has been implemented after 2000.

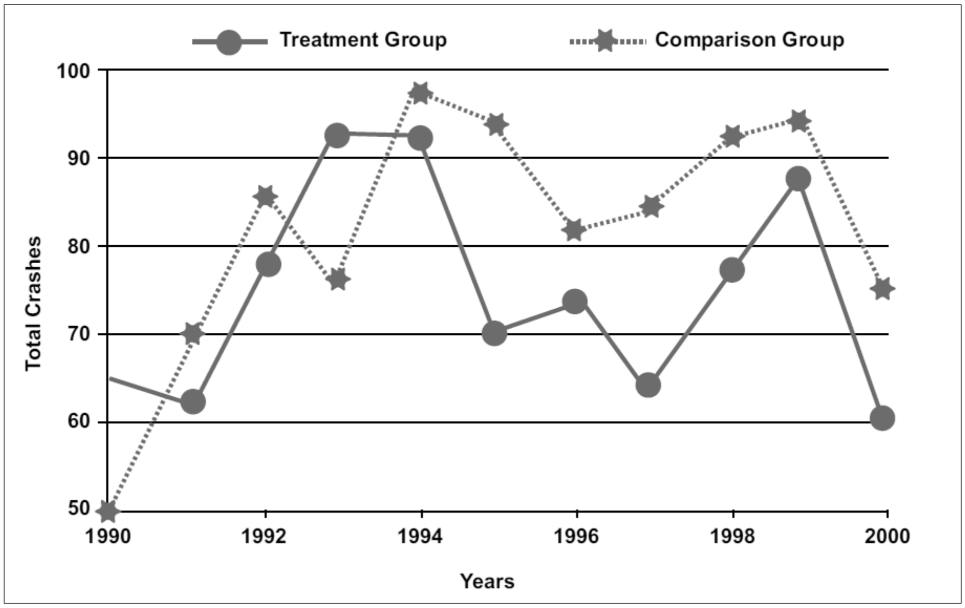


Figure 3.5: Time Series Plot of Crashes in Treatment and Comparison Groups

Hauer (1997) proposed a ratio to assess suitability of comparison groups compared to treatment groups. Sample odds ratios were computed for each before-and-after pair in the time series before treatment was implemented. From this sequence of sample odds ratios, the sample mean and standard error were determined. If this sample mean was sufficiently close to 1.0 (i.e., subjectively close to 1.0 and the CI included the value of 1.0), then the candidate reference group was deemed suitable.

$$sample\ odds\ ratio$$
$$= \frac{(treatment_{before} \times comparison_{after}) \times (treatmenttreatment_{after} \times comparison_{before)}}{1 + \frac{1}{treatment_{after}} + \frac{1}{comparison_{before}}}$$

Equation 3.3

Where:

Treatment before = total crashes for the treatment group in year i

Treatment after = total crashes for the treatment group in year j

Comparison before = total crashes for the comparison group in year i

Comparison after = total crashes for the comparison group in year j

Additional requirements of a suitable comparison group, as outlined by Hauer (1997), include:

1. Before and after periods for the treatment and comparison group should be identical.
2. The reason for change in factors, such as traffic volume changes that influence safety rather than the studies where treatments are the same in the treatment and comparison groups, should be evident.
3. Crash counts must be sufficiently large.

Table 3.3: Before-and-After with Comparison Group Study

Risk Factor	Number of Cases	Number of Controls
Before	No. observed, T, B	No. observed, C, B
Absence	No. observed, T, A	No. observed, C, A

Where:

No. observed, T,B = observed number of crashes in the "before" period for the treatment group

No. observed, T,A = observed number of crashes in the "after" period for the treatment group

No. observed, C,B = observed number of crashes in the "before" period in the comparison group

No. observed, C,A = observed number of crashes in the "after" period in the comparison group

The comparison ratio (No. Observed,C,A/No. Observed,C,B) indicates how crash counts are expected to change in the absence of treatment. CMF can be derived from Equations 3.4 to 3.7, which shows safety effectiveness of the specific treatment.

$$No.Expected_{TA} = No.Observed_{TB} \times \frac{No.Observed_{CA}}{No.Observed_{CB}}$$ **Equation 3.4**

$$VAR\ (No.Expected_{TA}) = \ No.Expected_{TA}{}^{2} \times \left(\frac{1}{No.Observed_{TB}} + \frac{1}{No.Observed_{CB}} + \frac{1}{No.Observed_{CA}}\right)$$

Equation 3.5

$$CMF = \left(\frac{No.Observed_{TA}}{No.Expected_{TA}}\right) / \left(1 + \left(\frac{VAR\ (No.expected_{TA})}{No.Expected_{TA}{}^{2}}\right)\right)$$ **Equation 3.6**

$$VAR(CMF) = CMF^2 \times \left[\left(\frac{1}{No.Observed_{TA}}\right) + \left(\frac{VAR\ (No.expected_{TA})}{No.Expected_{TA}{}^{2}}\right)\right] / \left[1 + \left(\frac{VAR\ (No.expected_{TA})}{No.Expected_{TA}{}^{2}}\right)\right]^2$$
Equation 3.7

3.5.2 Case-Control Studies to Estimate CMF

Many studies have been carried out on various aspects of highway safety, but few of those studies have been on geometric design aspects. However, case-control studies have recently been employed in the evaluation of geometric design elements (Gross & Jovanis, 2007). In case-control studies, samples are selected based on their status (risk factor present or not) and treatment is determined. Cases defined as intersections with crash and control sites were identified as intersections without a crash during the study period.

Application of this method could be explained using the tabulation of data presented in Table 3.4.

Table 3.4: Tabulation of Data for Case-Control Analysis

Risk Factors	Number of Cases	Number of Controls
Present	A	B
Absence	C	D

$$Odds\ Ratio(CMF) = \frac{A/B}{C/D} = \frac{A \times D}{B \times C}$$ **Equation 3.8**

Where:

A = number of cases with risk factor present

B = number of controls with risk factor present

C = number of cases with risk factor absent

D = number of controls with risk factor absent

However, case-control studies cannot be used to measure exact probability of an event, such as crash or severe injury, in terms of expected frequency. Instead, these studies are often used to demonstrate relative effects of treatments (Gross et al., 2010).

3.6 Data Collection

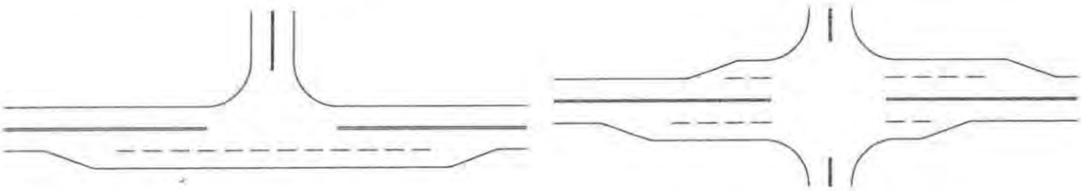
This section discusses all data elements collected for this current study, including data source and data collection procedure. The following sections include additional discussion that explicitly demonstrates the need for each data element.

3.6.1 Survey Forms

For administrative purposes, KDOT has geographically divided the state into six districts; each district has been further divided into areas, for a total of 26 areas in Kansas. In the initial stages of the study, survey forms were sent to area and district engineers in order to identify the locations and to determine characteristics of rural unsignalized intersections with bypass lanes. Questions on the survey form sought to identify specific information, such as road names, AADT, speed limits, pavement markings, and dates when bypass lanes were added. A sample of the survey form is shown in Figure 3.6. A total of 563 completed survey forms were received. Figure 3.7 shows the number of received survey forms by districts. Categorization of received surveys by districts was used primarily to ensure accurate geographical data distribution throughout the state.

Bypass Lanes at Unsignalized Rural Intersections Survey

Section 2: Intersection Inventory (Please make additional copies as required)



X Three-Legged *Intersection Bypass ____ Four-Legged *Intersection Bypass

(Please modify the sketch as necessary)

*Intersection bypass lanes are described as any additional pavement added to the shoulder of an intersection that is not designated or marked as a lane.

Please indicate if intersection information below is for a three or four-legged design

Main Road Information	Minor (Cross) Road Information
Name: US-281	Barber County Name: NW Elm Mills

If additional information is available, please assist with any of the following:

Main Road Information cont.	Minor (Cross) Road Information cont.
ADT: 1460	ADT: N/A
Speed: 65	Speed: 55

What date/year was this intersection bypass lane added? 1994

What kind of signing is used on the main road?
Pass With Care Road Narrows None Other (Please Describe)

What type of pavement marking is used in delineating the shoulder bypass?
Solid White Skip White None Other (Please Describe)

What kinds of pavement messages are used?
Thru Arrow "BYPASS ONLY" None Other (Please Describe)

What kind of pavement design do you require for the shoulder?
Standard Reinforced Road Lane Design Other (Please Describe)

Figure 3.6: Example of a Completed Survey Form

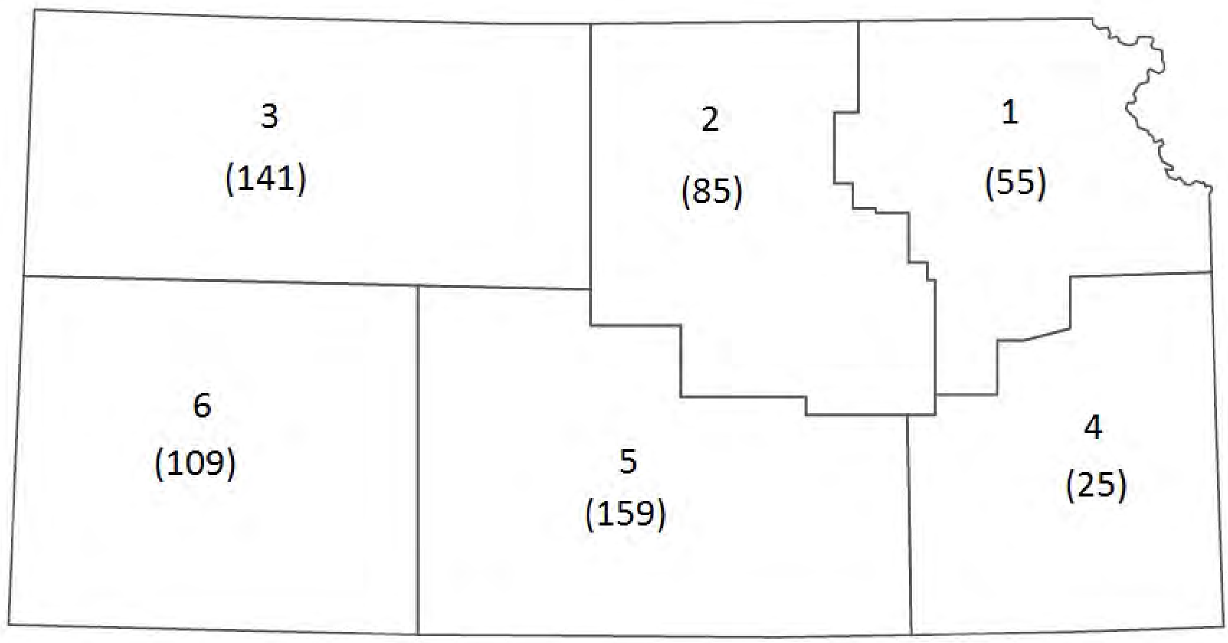


Figure 3.7: Distribution of Completed Survey Forms by Districts

3.6.2 Kansas Crash Analysis and Reporting System

The safety effectiveness of any countermeasure is quantified by a reduction in the number of crashes or crash severity caused by treatment implementation. The Kansas Crash Analysis and Reporting System (KCARS) database was utilized in this study to determine crashes at each intersection. KDOT maintains the KCARS database of all vehicle crashes on the Kansas highway system, and this database is coded in accordance with the Kansas Motor Vehicle Crash Report (850A). A report is completed for every incident involving the Kansas Highway Patrol (KHP). For this study, every crash record filed from 1990 to 2011 was gathered to evaluate the effectiveness of bypass lanes. For data collection, the HSM recommends utilization of a 3- to 5-year time period, because time periods less than 3 years are subject to high variability due to the randomness of crashes and periods longer than 5 years are subject to the introduction of bias due to changes in reporting standards or physical changes to roadway features (AASHTO, 2010).

3.6.2.1 Crash ID

KCARS contains a field that identifies the location and specific identification number of each crash. Crash ID is a unique value for each crash, which can be used to combine crash characteristics from KCARS and other databases, such as CANSYS, so that information regarding highway geometric characteristics could be added.

3.6.2.2 Crash Location

Several fields in KCARS represent crash location, including county milepost and distance from a named intersection. Because incident responders do not typically have precise positioning equipment to determine the specific milepost of an incident, this value often contains inaccuracies. Two additional KCARS columns provide longitude and latitude of the crash location.

3.6.2.3 Crash Severity

KCARS contains three primary types of crash severity, with five total subdivided injury severity levels (KDOT, 2005):

1. Fatal crashes
2. Injury crashes:
    a. Possible injury
    b. Injury, non-incapacitating
    c. Disable, incapacitating
3. Property Damage Only (PDO)

Multiple vehicle crashes can have varying severity levels based on personal injury severities. In such cases, each crash is assigned to the most severe level experienced by persons involved in the crash.

<u>Fatal Injury</u>

Fatal injury is defined as any injury that results in death to a person within 30 days of the crash. If a person dies of a medical condition that is not a result of an injury sustained due to the motor vehicle crash or after the 30-day limit, the injury checkbox is marked in crash reports (not fatal), and injury severity is shown as possible injury (KDOT, 2005).

Possible Injury

A possible injury is defined as any reported or claimed injury which is not fatal, incapacitating, or non-incapacitating, including momentary unconsciousness, claim of injuries not evident, limping, complaint of pain, nausea, or hysteria (KDOT, 2005).

Injury (Non-Incapacitating)

A non-incapacitating injury is defined as any injury, other than a fatal injury or incapacitating injury, which is evident to observers at the scene of the crash at which the injury occurred (KDOT, 2005).

Disable (Incapacitating)

An incapacitating injury is defined as any injury, other than fatal, which prevents the injured person from walking, driving, or normally continuing activities he or she was capable of before the injury occurred—including severe lacerations, broken or distorted limbs, skull or chest injuries, abdominal injuries, unconsciousness at the time of the crash or when taken from the crash scene, or inability to leave the crash scene without assistance (KDOT, 2005).

Property Damage Only (PDO)

Crashes resulting in damages under the $1,000 property damage threshold with no injuries are not submitted to KDOT. Any crash with a property damage of more than $1,000 is included the KCARS database, even if there is no personal injury involved (KDOT, 2005).

3.6.3 Equivalent Property Damage Only Crashes

In order to compare and rank severity of crashes at each location, the total number of crashes can be expressed in terms of Equivalent Property Damage Only (EPDO) crashes. In this approach, a weight is assigned to each fatal or injury crash to represent crash severity of the location (Knapp & Campbell, 2005).

$$Number\ of\ EPDO\ crashes$$
$$= no.PDO\ Crashes + W_1 \times no.Injury\ Crashes + W_2 \times no.Fatal\ Crashes$$

Equation 3.9

Where:

$$w_1 = weight\ factor\ to\ convert\ injury\ crashes\ to\ PDO\ crashes$$
$$= \frac{Average\ Injury\ crash\ cost}{Average\ PDO\ crash\ cost}$$
$$w_2 = weight\ factor\ to\ convert\ fatal\ crashes\ to\ PDO\ crashes$$
$$= \frac{Average\ Fatal\ crash\ cost}{Average\ PDO\ crash\ cost}$$

In Kansas: $W_1 = W_2 = 15$

3.6.4 Relevant Crashes

The focus of this study was unsignalized rural three-legged and four-legged intersections in Kansas. In order to determine relevant crashes to be considered in evaluating the effectiveness of bypass lanes, two methods were utilized.

1. Consideration of crashes within a fixed distance of 300 ft along each approach leading to the intersections, regardless of whether or not crashes are intersection-related.
2. Consideration of the column in KCARS that distinguishes whether or not crashes are intersection-related, no matter how far away from the intersection the crash occurred.

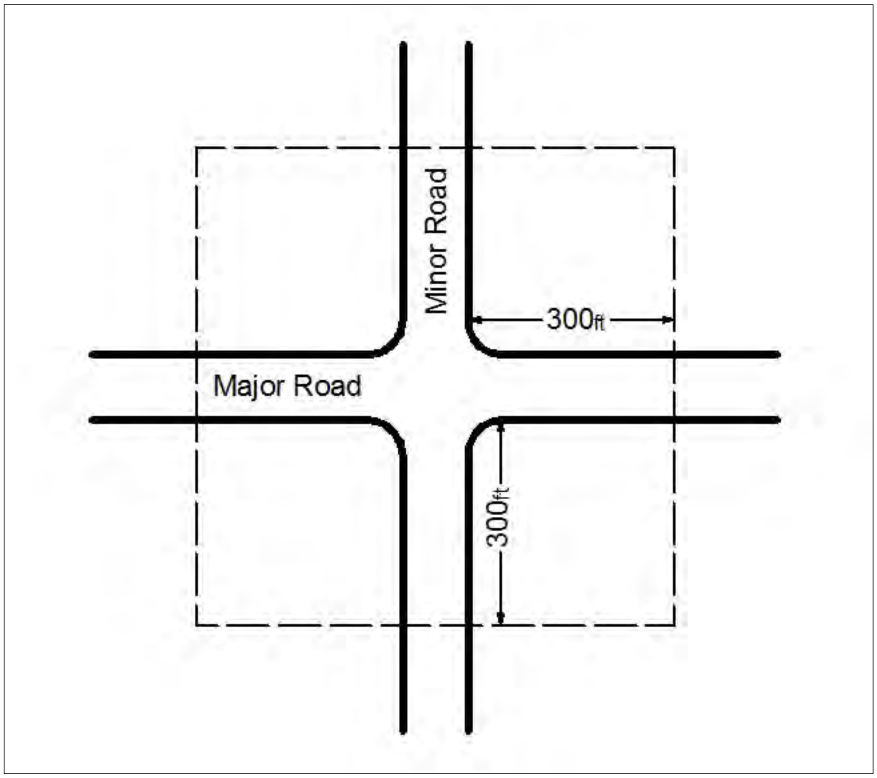


Figure 3.8: Intersection Box to Identify Crashes at the Location

3.7 KDOT Traffic Count Maps

Crash rate can be an effective parameter to evaluate highway safety of geographic region or a location. For an intersection, combination of crash frequency and traffic volume results in crash rates, which can be used to compare relative safety at intersections. The traffic volume for each approach is needed to calculate the crash rate at an intersection (Green & Agent, 2003). Traffic counts shown in Figure 3.9 represent AADT for the year 2012. These AADTs were primarily derived from 24-hr volume recorded traffic counters. Short-term counts were adjusted for day of the week and seasonal variations, and axle correction factor was applied to each short-term count. Heavy commercial volumes were derived from short-term vehicle classification counts (Izadpanah et al., 2009). Rural intersections considered in this study included minor local roads not included in traffic flow maps of the Kansas state highway system.

In addition to traffic count state maps, AADT values of county major collector rural roads are available on the KDOT website, which provide minor road AADT in some cases.

These roads are labeled with Road Secondary (RS) numbers. Because RS numbers differ from road names, the RS route had to be matched with Google Maps to identify the road name of each RS number. After determining the RS route from the district map, Google Maps was checked simultaneously. A city along the route was chosen on the county map and then side roads were counted to match those on the county map and Google Maps. Figure 3.10 shows the match-up between the RS map and Google Maps. As shown in the figure, RS 1924 is Anderson Avenue which runs right through Manhattan, KS.

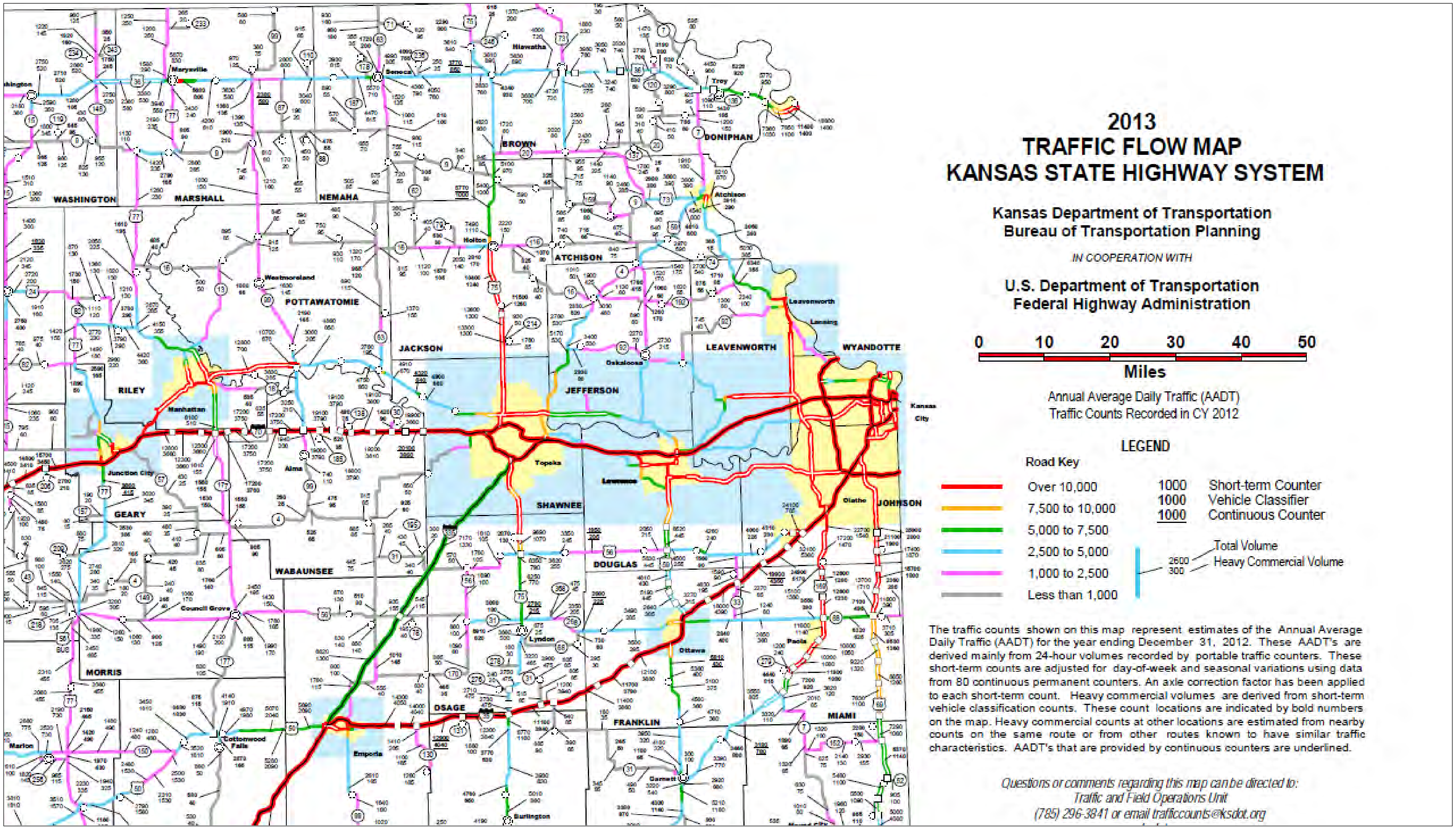
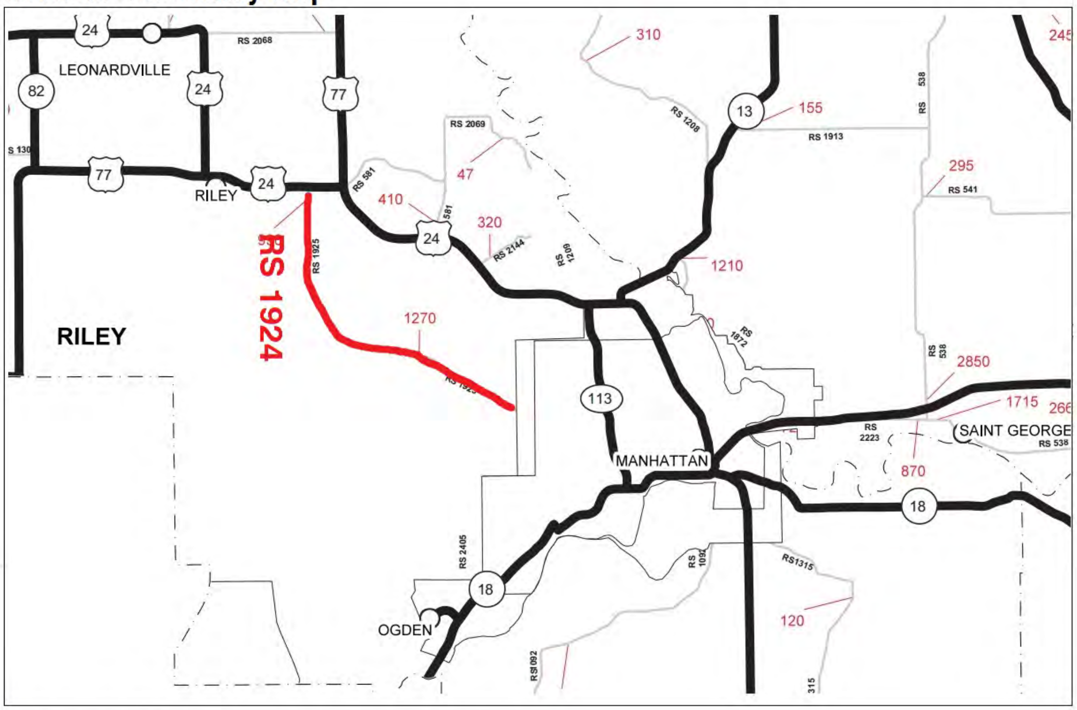


Figure 3.9: Traffic Flow Map, Showing Part of the Kansas State Highway System
Source: KDOT, 2013b

a: Road Secondary Map



b: Google Map

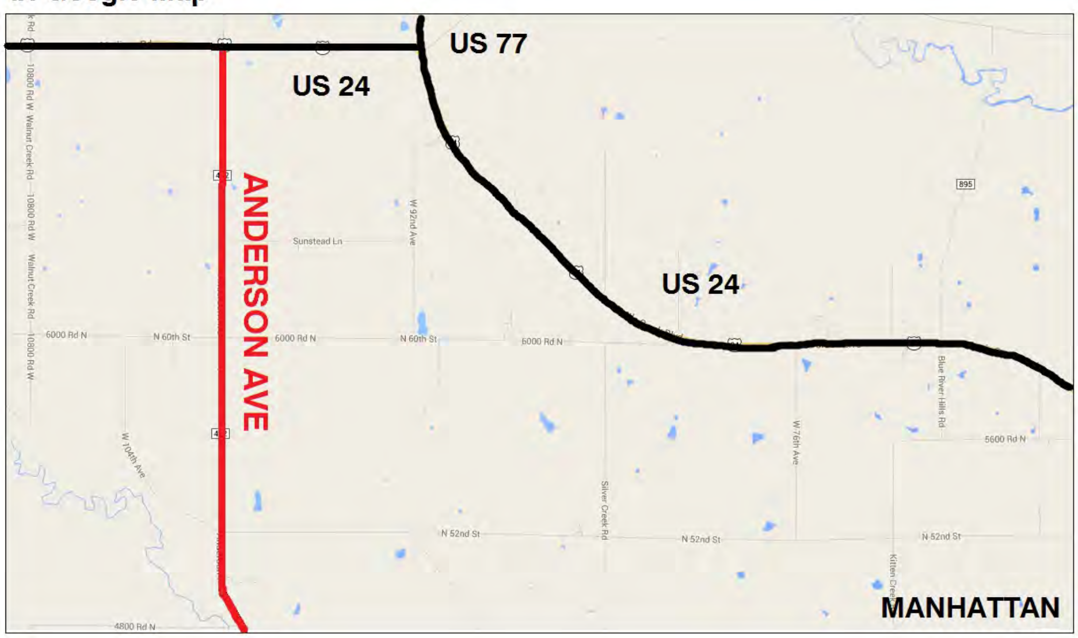


Figure 3.10: Traffic Flow Maps and Google Maps
Source: KDOT, n.d.; Google Maps, n.d.

3.8 Video Recording

Video capturing has been carried out in this study to quantitatively calculate speed reduction and delays caused by the absence of bypass lanes at intersections. However, traffic counting at intersections is challenging, especially when speed reduction and delay must be recorded. In order to capture driver maneuvers by video recording, 10 different locations were selected among intersections with and without bypass lanes, as shown in Figure 3.11.

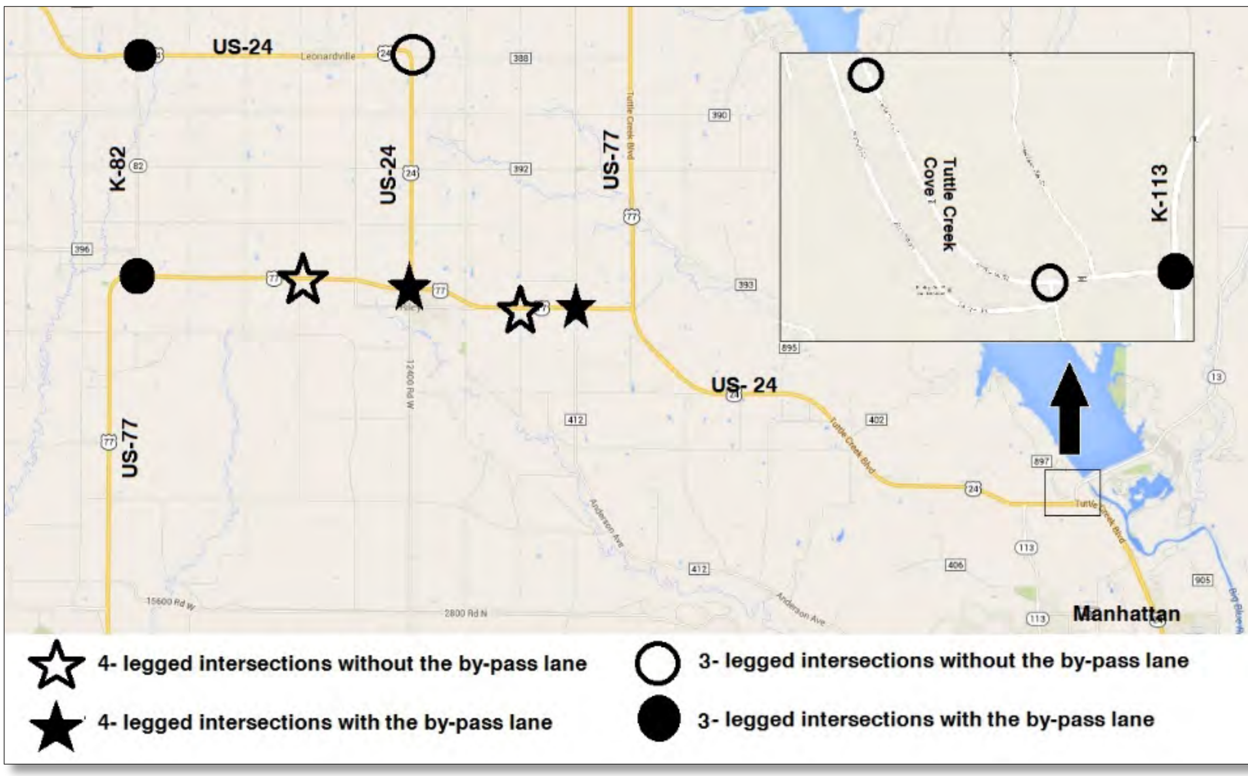


Figure 3.11: Intersection Locations for Video Recording

Locations were selected according to similar traffic volume and driver behaviors. A video camera was installed on a pole, sign, or tripod near each intersection in order to record traffic movements. Figure 3.12 shows an installed camera at one of the sites.

Figure 3.12: Go-Pro Camera on a Pole for Traffic Recording

3.9 Calibrating a Prediction Model to Estimate Minor Road AADT

State traffic count maps, RS maps, KCARS, and survey forms were used as resources in this study in order to determine AADT of the intersecting roads at intersections; however, AADT of 35% of the minor roads remained unknown even after using all those sources. According to some past studies, one feasible method to estimate AADT involves calibrating a prediction model. AADT prediction models are classified into two major types: time series models and linear regression models (Pan, 2008).

Based on available historical AADT data, time series models estimate AADT growth; however, AADT values on such roads can be estimated using multiple linear regression models or other transportation demand estimating models (Pan, 2008).

In order to calibrate a linear regression model, data gathering was carried out to obtain potential factors impacting AADT. Two types of data were collected from various sources: socio-economic data and intersection-characteristics data. Most intersection-characteristics data used in this study were related to the type of intersection (e.g., whether or not the intersections contained bypass lanes). Intersections were then categorized into groups related to the whether the intersection was three-legged or four-legged. Because Kansas has a hierarchical highway system with interstate roads, U.S. roads, Kansas roads, RS roads, and local roads, each intersection belonged to a different category based on the classification of approaching roads. All categories are listed from X_1 to X_{12} in Table 3.5.

Social-economic data for all 105 counties in Kansas were collected from the Kansas Statistical Abstract 2012 (KU Institute for Policy & Social Research, 2013). Social-economic data categories, including population, number of registered cars, income, median age of residence, number of households, labor force, number of people per household, number of people employed/unemployed, geographic area, and urban/rural proportion, were considered for each county. All social-economic variables are also listed in Table 3.5 from X_{13} to X_{27}.

Table 3.5: Input Variables to Calibrate an AADT Prediction Model

x_1	Intersection with the bypass = 1, Intersection without the bypass = 0	x_{15}	Total road miles within the county
x_2	Four-legged intersections = 1, Three-legged intersections = 0	x_{16}	Per capita personal income in the county per year
x_3	If minor road crosses minor roads = 1, Otherwise = 0	x_{17}	Median age of residence in the county
x_4	If US highway crosses US highway = 1, Otherwise = 0	x_{18}	Number of households in the county
x_5	If US highway crosses K highway = 1, Otherwise = 0	x_{19}	Number of people per household
x_6	If K highway crosses K highway = 1, Otherwise = 0	x_{20}	Labor force
x_7	If US highway crosses RS road = 1, Otherwise = 0	x_{21}	Number of employed within the county
x_8	If K highway crosses RS road = 1, Otherwise = 0	x_{22}	Number of unemployed within the county
x_9	If RS road crosses RS road = 1, Otherwise = 0	x_{23}	Area of the county in square miles
x_{10}	If US highway crosses minor road = 1, Otherwise = 0	x_{24}	Urban proportion in percent
x_{11}	If K highway crosses minor road = 1, Otherwise = 0	x_{25}	Rural proportion in percent
x_{12}	If RS road crosses minor road = 1, Otherwise = 0	x_{26}	Urban area in square miles
x_{13}	County population	x_{27}	Rural area in square miles
x_{14}	Number of registered cars within the county	Y	Total Entering Volume (TEV) at intersection

The backward regression model is one method that can be used select the significant set of predictors in the final model. Backward regression removes non-significant variables from the regression model in order to identify a useful subset of the predictors. In this method, the initial model starts with all variables, and, at each step, the variable that is least significant is removed. In other words, variables with *p*-values greater than the significance level (α) are removed. This process continues until no non-significant variable remains.

Chapter 4: Results

This chapter documents a comprehensive crash analysis to evaluate safety effectiveness of bypass lane additions. Two approaches were utilized: before-and-after study and cross-sectional study.

In addition, CMF value was also estimated to evaluate the safety effectiveness of bypass lane additions. A comparison crash analysis was conducted to determine basic crash characteristics for two categories of intersections: three-legged intersections and four-legged intersections.

Moreover, results of video recording that shows driver maneuvers and delays caused by the absence of bypass lanes at intersections are discussed in Section 4.1.

4.1 Video Recording

Videos were recorded at the selected locations during morning peak hours (8:00 a.m. to 10:00 a.m.) and evening peak hours (4:00 p.m. to 6:00 p.m.) in order to capture maximum traffic flow and increased use of bypass lanes. Even though AADT of the selected roads was greater than 1,000 vehicles per hour, only on a few occasions did a car reach the intersection when another car was waiting to turn left, thereby limiting the number of useful observations. Figure 4.1 shows an example of a following driver who utilized the bypass lane when the lead car decreased speed to turn left at the intersection.

Figure 4.1: Use of Bypass Lane

Table 4.1: Results of Video Capturing

Intersection Types	K-13 – Tuttle Cove (Three-legged intersection with bypass lane)	Tuttle Cove – Freeman (Three-legged intersection without bypass lane)	US-24 – Falcon (Four-legged intersection with bypass lane)
Travel time (seconds)			
Drivers proceeded straight when no car was ahead	9.3	3.0	16
Drivers used bypass lane	9	-	-
Drivers who did not use bypass lane	11.5	4.72	17.1
Distance considered (ft)	480	180	920
No. of drivers who did not use bypass lane	7	5	5
No. of drivers who used bypass lane	7	-	-

According to Table 4.1, drivers at the three-legged intersection with bypass lane at K-13 and Tuttle Cove needed 9.3 sec to pass 480 ft along K-13. During video capturing, seven drivers used the bypass lane to pass a stopped car ahead, and seven drivers did not use the bypass lane. The average time to pass the fixed distance was 9 and 11.5 seconds, respectively. Therefore, absence of the bypass lane caused a 2.2 second delay. Delay times at the intersections of Tuttle Cove and Freeman and Main and Falcon were 1.7 and 1.1 seconds, respectively. Video recordings showed that even when bypass lanes were present, some drivers did not use the lanes, indicating the lack of understanding among some of the drivers.

4.2 Before-and-After Study

A before-and-after crash analysis was conducted to evaluate the safety effectiveness of bypass lane additions. The HSM recommends a period of 3 to 5 years be utilized (AASHTO, 2010). Accordingly, 5-year, 4-year, and 3-year analyses were all carried out to see the impact. Crash data for the before-and-after study were extracted from KCARS from 1990 to 2011.

4.2.1 Five-Year Consideration

This section documents the analysis results using crash data from 5 years before construction of the bypass lane and 5 years after bypass construction (not including the year in which bypass lanes were constructed). Crash data were collected for a total of 61 intersections (22 three-legged intersections and 39 four-legged intersections) in which bypass lanes were constructed between 1990 and 2011.

4.2.1.1 Comparison of Crash Frequency

For a 300-ft intersection box, a total of 20 crashes (0.328 crashes per intersection) occurred before adding bypass lanes, and 13 crashes (0.213 crashes per intersection) occurred after adding bypass lanes. For intersection-related crashes, a total of 21 crashes (0.344 crashes per intersection) occurred before adding bypass lanes, and 18 crashes (0.295 crashes per intersection) occurred after adding bypass lanes. A paired *t*-test under 95% confidence level was conducted on the total number of crashes at each intersection. Table 4.2 shows statistical analysis of crash frequency when considering a 5-year period before and after bypass lane installation.

Table 4.2: Statistical Analysis of Reduction in Crash Frequency within 5-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash frequency (before)	0.500	0.636	0.231	0.179
Mean crash frequency (after)	0.409	0.318	0.103	0.282
Mean crash frequency difference	0.091	0.318	0.128	-0.103
***t*-value**	0.460	1.670	1.300	-0.750
***p*-value**	0.324	0.055	0.100	0.772

Positive values of the mean difference show a reduction of crash frequency after adding bypass lanes. In contrast, the negative value of mean difference shows an increase in crash frequency. Furthermore, *p*-values are greater than 0.05, indicating no statistically significant difference under 95% confidence level in crash frequency after adding bypass lanes. The addition of bypass lanes at three-legged intersections caused higher safety improvement, which is supported by the *p*-value, which is close to 0.05.

4.2.1.2 Comparison of Equivalent Property Damage Only Crash Frequency

For a 300-ft intersection box, total EPDO crash frequency was equal to 146 (2.393 per intersection) before adding bypass lanes, and EPDO crash frequency after adding bypass lanes was 55 (0.902 per intersection). For intersection-related crashes, the total EPDO crash frequencies after adding bypass lanes and before construction of bypass lanes were 105 and 130, respectively, or 1.721 and 2.131 per intersection. A paired *t*-test under 95% confidence level was conducted on EPDO crash frequency at each intersection. Table 4.3 shows statistical analysis on EPDO crash frequency when considering a 5-year period before and after bypass lane installation.

Table 4.3: Statistical Analysis of Reduction in EPDO Crash Frequency within 5-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash frequency (before)	3.680	3.18	1.667	0.897
Mean EPDO crash frequency (after)	1.680	2.86	0.462	1.718
Mean reduction in EPDO crash frequency	2.000	0.320	1.205	-0.821
***t*-value**	0.890	0.150	1.380	-1.04
***p*-value**	0.192	0.442	0.088	0.847

Positive value of the mean difference shows a reduction of EPDO crashes after adding bypass lanes, while the negative value of mean difference shows an increase in EPDO crashes. Furthermore, *p*-values are greater than 0.05, indicating no statistically significant difference under 95% confidence level in EPDO crash frequency after adding bypass lanes.

4.2.1.3 Comparison of Crash Rates

Crash rates for rural intersections were calculated in terms of crashes per Million Entering Vehicle (MEV; Green & Agent, 2003).

$$Crash\ rate = \frac{Average\ no.of\ Crashes\ per\ year \times 10^6}{\sum AADT \times 365} \qquad \textbf{Equation 4.1}$$

For a 300-ft intersection box, the total crash rate per MEV was 3.69 (0.061 per intersection) before adding bypass lanes, and 1.79 (0.294 per intersection) after adding bypass lanes. For intersection-related crashes, crash rates after adding bypass lanes and before adding bypass lanes were 3.82 and 3.7, respectively, or 0.0626 and 0.061 per intersection. A paired *t*-test under 95% confidence level was conducted on crash rates at each intersection. Table 4.4 shows statistical analysis results when considering a 5-year period before and after bypass lane installation.

Table 4.4: Statistical Analysis of Reduction in Crash Rates within 5-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash rates (before)	0.060	0.079	0.061	0.055
Mean crash rates (after)	0.044	0.046	0.021	0.069
Mean difference in crash rates	0.016	0.033	0.040	-0.016
***t*-value**	0.650	1.870	1.380	-0.460
***p*-value**	0.262	0.038	0.087	0.675

Positive values of the mean difference show a reduction of crash rates after adding bypass lanes, and the negative value of mean difference shows an increase in crash frequency. Furthermore, *p*-values are greater than 0.05, indicating no statistical difference under 95% confidence level in crash rates after adding bypass lanes. However, for intersection-related crashes, a significant reduction occurred at three-legged intersections.

4.2.1.4 Comparison of Equivalent Property Damage Only Crash Rates

EPDO crash rates were calculated as follows for rural intersections in crashes per MEV.

$$EPDO\ rate = \frac{Average\ EPDO\ per\ year \times 10^6}{\sum AADT \times 365} \qquad \textbf{Equation 4.2}$$

For a 300-ft intersection box, total EPDO crash rate per MEV was 29.108 (0.477 per intersection) before adding bypass lanes, and the total EPDO crash rate was 8.455 (0.139 per intersection) after adding bypass lanes. For intersection-related crashes, EPDO crash rates before and after adding bypass lanes were 24.848 and 34.136, respectively, or 0.407 and 0.56 per intersection. A paired *t*-test under 95% confidence level was conducted on EPDO crash rates at each intersection. Table 4.5 shows statistical analysis on EPDO crash rates when considering a 5-year period before and after bypass lane installation.

Table 4.5: Statistical Analysis of Reduction in EPDO Crash Rates within 5-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash rates (before)	0.407	0.451	0.517	0.383
Mean EPDO crash rates (after)	0.224	0.561	0.09	0.559
Mean difference in EPDO crash rates	0.182	-0.11	0.040	-0.176
***t*-value**	0.96	-0.3	1.48	-0.85
***p*-value**	0.174	0.617	0.074	0.799

Positive values of the mean difference show a reduction of EPDO crash rates after adding bypass lanes. In contrast, the negative value of mean difference shows an increase in EPDO crash rates. Furthermore, *p*-values are greater than 0.05, indicating no statistically significant difference under 95% confidence level in EPDO crash rates before and after adding bypass lanes.

4.2.2 Four-Year Consideration

This section documents results of crash data analysis based on 4 years before bypass lane construction and 4 years after bypass lane construction (not including the year bypass lanes were constructed). Crash data was collected for a total of 68 intersections (24 three-legged intersections and 44 four-legged intersections) in which bypass lanes were constructed between 1990 and 2011. Figure 4.3 shows the proportion of intersection types during the 4-year consideration.

4.2.2.1 Comparison of Crash Frequency

For a 300-ft intersection box, a total of 20 crashes (0.294 crashes per intersection) occurred before adding bypass lanes, and 15 crashes (0.221 crashes per intersection) occurred after adding bypass lanes. For intersection-related crashes, a total of 26 crashes (0.382 crashes per intersection) occurred before adding bypass lanes, and 18 crashes (0.265 crashes per intersection) occurred after adding bypass lanes. A paired *t*-test under 95% confidence level was conducted for the total number of crashes at each intersection. Table 4.6 shows statistical analysis of crash frequency when considering a 4-year period before and after bypass lane installation.

Table 4.6: Statistical Analysis of Reduction in Crash Frequency within 4-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash frequency (before)	0.417	0.500	0.227	0.318
Mean crash frequency (after)	0.375	0.250	0.136	0.273
Mean crash frequency difference	0.042	0.250	0.091	0.045
***t*-value**	0.200	1.370	0.810	0.360
***p*-value**	0.420	0.093	0.210	0.360

Positive values of the difference show the reduction in crash frequency after adding bypass lanes. Because *p*-values are greater than 0.05, reductions are not statistically significant under 95% confidence level.

4.2.2.2 Comparison of Equivalent Property Damage Only Crash Frequency

For a 300-ft intersection box, total EPDO crash frequency was 174 (2.559 per intersection) before adding bypass lanes, and EPDO crash frequency after adding bypass lanes was 71 (1.044 per intersection). For intersection-related crashes, total EPDO crash frequency after adding bypass lanes and before bypass lane construction was 180 and 130, respectively, or 2.647 and 1.912 per intersection. A paired *t*-test under 95% confidence level was conducted on EPDO crash frequency at each intersection. Table 4.7 shows statistical analysis of EPDO crash frequency for the 4-year period before and after bypass lane installation.

Table 4.7: Statistical Analysis of Reduction in EPDO Crash Frequency within 4-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash frequency (before)	3.330	3.420	2.136	2.230
Mean EPDO crash frequency (after)	1.540	2.000	0.773	1.860
Mean difference in EPDO crash frequency	1.790	1.420	1.360	0.360
***t*-value**	0.870	0.710	1.240	0.350
***p*-value**	0.196	0.242	0.111	0.366

Positive values of the difference show reduction in EPDO crash frequency after adding bypass lanes. However, *p*-values are greater than 0.05, indicating no statistical difference under 95% confidence level in EPDO crash frequency after adding bypass lanes.

4.2.2.3 Comparison of Crash Rates

For a 300-ft intersection box, the total crash rate per MEV was 4.712 (0.069 per intersection) before adding bypass lanes, and 3.029 (0.101 per intersection) after adding bypass lanes. For intersection-related crashes, crash rates after adding bypass lanes and before bypass lane construction were 6.895 and 4.809, respectively, or 0.045 and 0.071 per intersection. A paired *t*-test under 95% confidence level was conducted on crash rates at each intersection. Table 4.8 shows statistical analysis of crash rates for a 4-year period before and after bypass lane installation.

Table 4.8: Statistical Analysis of Reduction in Crash Rates within 4-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash rates (before)	0.056	0.084	0.076	0.111
Mean crash rates (after)	0.051	0.040	0.041	0.087
Mean difference in crash rates	0.005	0.044	0.035	0.24
***t*-value**	0.180	1.55	0.860	0.590
***p*-value**	0.429	0.067	0.198	0.281

Positive values of the difference show a reduction in crash rate after adding bypass lanes. However, *p*-values are greater than 0.05, indicating no statistically significant difference under 95% confidence level in crash rate after adding bypass lanes.

4.2.2.4 Comparison of Equivalent Property Damage Only Crash Rates

For a 300-ft intersection box, the total EPDO crash rate per MEV was 37.845 (0.557 per intersection) before adding bypass lanes, and total EPDO crash rate was 14.772 (0.217 per intersection) after adding bypass lanes. For intersection-related crashes, EPDO crash rates before and after adding bypass lanes were 54.439 and 35.833, respectively, or 0.801 and 0.527 per intersection. A paired *t*-test under 95% confidence level was conducted on EPDO crash rates at each intersection. Table 4.9 shows statistical analysis of EPDO crash rates for a 4-year period before and after bypass lane installation.

Table 4.9: Statistical Analysis of Reduction in EPDO Crash Rates within 4-Year Range

Statistical Parameters	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash rates (before)	0.36	0.68	0.664	0.866
Mean EPDO crash rates (after)	0.206	0.335	0.224	0.632
Mean difference in EPDO crash rates	0.154	0.346	0.44	0.234
***t*-value**	0.91	0.84	1.21	0.68
***p*-value**	0.187	0.206	0.117	0.251

The positive value in mean difference shows a reduction in EPDO crash rates after adding bypass lanes. However, because *p*-values are greater than 0.05, reductions are not statistically significant under 95% confidence level.

4.2.3 Three-Year Consideration

This section documents crash data analysis for 3 years before and 3 years after bypass lanes construction (not including the year bypass lanes were constructed). Crash data were collected for a total of 88 intersections (27 three-legged intersections and 61 four-legged intersections) in which bypass lanes were constructed between the years 1990 and 2011.

4.2.3.1 Comparison of Crash Frequency

For a 300-ft intersection box, a total of 16 crashes (0.182 crashes per intersection) occurred before adding bypass lanes, and 14 crashes (0.159 crashes per intersection) occurred after adding bypass lanes. For intersection-related crashes, a total of 22 crashes (0.25 crashes per intersection) occurred before adding bypass lanes, and 13 crashes (0.148 crashes per intersection) occurred after adding bypass lanes. A paired *t*-test under 95% confidence level was conducted on total number of crashes at each intersection. Table 4.10 shows statistical analysis of crash frequency for a 3-year period before and after bypass lane installation.

Table 4.10: Statistical Analysis of Reduction in Crash Frequency within 3-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash frequency (before)	0.259	0.370	0.148	0.197
Mean crash frequency (after)	0.259	0.111	0.115	0.164
Mean crash frequency difference	0.000	0.259	0.033	0.033
***t*-value**	0.000	1.370	0.420	0.390
***p*-value**	0.500	0.091	0.337	0.349

Positive values of the difference clearly show the reduction in crash frequency after adding bypass lanes. However, *p*-values are greater than 0.05, indicating no statistically significant difference under 95% confidence level in crash frequency after adding bypass lanes.

4.2.3.2 Comparison of Equivalent Property Damage Only Crash Frequency

For a 300-ft intersection box, total EPDO crash frequency was 142, or 1.614 per intersection, before adding bypass lanes. EPDO crash frequency after adding bypass lanes was 70, or 0.795 per intersection. For intersection-related crashes, total EPDO crash frequency after adding bypass lanes and before bypass lane construction was 162 and 111, respectively, or 1.841 and 1.261 per intersection. A paired *t*-test under 95% confidence level was conducted on EPDO crash frequency at each intersection. Table 4.11 shows statistical analysis results of EPDO crash frequency for a 3-year period before and after bypass lanes installation.

Table 4.11: Statistical Analysis of Reduction in EPDO Crash Frequency within 3-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash frequency (before)	0.850	2.960	1.066	1.344
Mean EPDO crash frequency (after)	1.300	0.150	0.574	1.311
Mean difference in EPDO crash frequency	1.550	0.810	0.492	0.033
***t*-value**	0.850	1.060	0.680	0.050
***p*-value**	0.201	0.150	0.249	0.482

Positive values of the difference show a reduction in EPDO crashes after adding bypass lanes. However, *p*-values are greater than 0.05, indicating no statistically significant difference under 95% confidence level in EPDO statistical parameters after adding bypass lanes.

4.2.3.3 Comparison of Crash Rates

For a 300-ft intersection box, the total crash rate per MEV was 5.162 (0.059 per intersection) before adding bypass lanes, and 3.889 (0.044 per intersection) after adding bypass lanes. For intersection-related crashes, crash rates after adding bypass lanes and before bypass lane construction were 7.958 and 4.625, respectively, or 0.09 and 0.053 per intersection. A paired *t*-test under 95% confidence level was conducted on crash rates at each intersection. Table 4.12 shows statistical analysis of crash rates for a 3-year period before and after bypass lane installation.

Table 4.12: Statistical Analysis of Reduction in Crash Rates within 3-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash rates (before)	0.043	0.072	0.066	0.099
Mean crash rates (after)	0.049	0.026	0.042	0.064
Mean difference in crash rates	-0.006	0.045	0.023	0.035
***t*-value**	-0.150	1.170	0.600	0.920
***p*-value**	0.559	0.127	0.275	0.181

Positive values of the mean difference show a reduction of crash rates after adding bypass lanes. In contrast, the negative value of mean difference shows an increase in crash rates. Furthermore, *p*-values are greater than 0.05, indicating no statistical difference under 95% confidence level in crash rates after adding bypass lanes.

4.2.3.4 Comparison of Equivalent Property Damage Only Crash Rates

For a 300-ft intersection box, the total EPDO crash rate per MEV was 5.162 (0.059 per intersection) before adding bypass lanes, and the total EPDO crash rate was 3.889 (0.044 per intersection) after adding bypass lanes. For intersection-related crashes, EPDO crash rates before and after adding bypass lanes were 7.958 and 4.625, respectively, or 0.09 and 0.053 per intersection. A paired *t*-test under 95% confidence level was conducted on EPDO crash rates at each intersection. Table 4.13 shows statistical analysis results for EPDO crash rates for a 3-year period before and after bypass lane installation.

Table 4.13: Statistical Analysis of Reduction in EPDO Crash Rates within 3-Year Range

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash rates (before)	0.403	0.779	0.483	0.736
Mean EPDO crash rates (after)	0.232	0.283	0.218	0.588
Mean difference in EPDO crash rates	0.171	0.496	0.265	0.149
***t*-value**	0.84	1.02	0.79	0.46
***p*-value**	0.204	0.159	0.216	0.325

A positive value in the mean difference shows a reduction in EPDO crash rate after adding bypass lanes. Because *p*-values are greater than 0.05, reductions are not statistically significant under 95% confidence level.

4.3 Cross-Sectional Study

Analysis was conducted to determine the safety effectiveness of bypass lanes by comparing crash statistics at intersections with bypass lanes to intersections with no bypass lanes and no left-turn lane. Intersections with bypass lanes were obtained from returned survey forms. Due to incomplete information in some of the survey forms, out of a total of 574 forms returned, only 558 intersections could be taken into account in analysis. As the comparison group, 579 intersections without bypass lanes were selected. These intersections were identified by using Google Earth and were located in proximity to intersections with bypass lanes to have similar traffic volume and driver behaviors. Figure 4.2 shows the proportion of three-legged and four-legged intersections in the two samples.

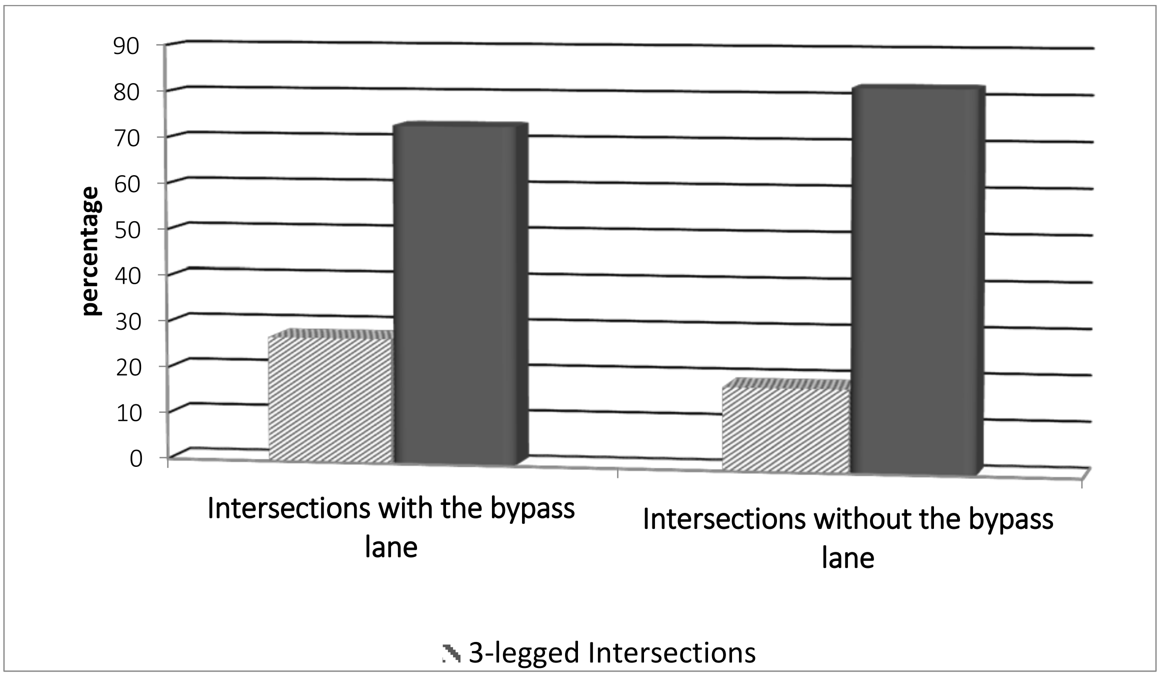


Figure 4.2: Proportion of Intersection Types in Cross-Sectional Study

Crash data from 2009 to 2011 were extracted from KCARS, and then a two-sample *t*-test was conducted to evaluate significance of differences in the number of crashes, EPDO crashes, crash rates, and EPDO crash rates. A comparison crash analysis was conducted to determine basic crash characteristics for two categories of intersections: three-legged intersections and four-legged intersections.

4.3.1 Comparison of Crash Frequency

A two-sample *t*-test under 95% confidence level was conducted on crash frequency at each intersection. Table 4.14 shows statistical analysis of crash frequency reduction within 300 ft along each approach leading to the intersections and intersection-related crashes.

Table 4.14: Comparison of Crash Frequency

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash frequency (With)	0.670	0.521	0.870	0.503
Mean crash frequency (Without)	0.493	0.42	0.463	0.51
Mean crash frequency difference	0.177	0.101	0.407	-0.007
***t*-value**	1.30	0.82	5.71	-0.13
***p*-value**	0.098	0.207	0.001	0.55

Positive values of the mean difference show a reduction of crash frequency within 300 ft along each approach leading to three-legged intersections and intersection-related crashes. However, according to *p*-values greater than 0.05, none of the differences are significant. Because *p*-values are less than 0.05 at four-legged intersections, reduction in the number of crashes at intersections with bypass lanes is significant, when considering intersection boxes. However, for intersection-related crashes, a change in crash frequency is not significant at 5% confidence level.

4.3.2 Comparison of Equivalent Property Damage Only Crash Frequency

A two-sample *t*-test under 95% confidence level was conducted on EPDO crash frequency at each intersection. Table 4.15 shows statistical analysis results of EPDO crash differences 300 ft along each approach leading to intersections and intersection-related crashes.

Table 4.15: Comparison of EPDO Crash Frequency

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash frequency (With)	2.16	3.35	3.87	3.71
Mean EPDO crash frequency (Without)	1.89	3.03	2.45	4.0
Mean difference in EPDO crash freq.	0.266	0.318	1.423	-0.305
***t*-value**	0.37	0.33	2.85	-0.43
***p*-value**	0.358	0.372	0.002	0.667

Positive values of the mean difference show a reduction of EPDO crash frequency within 300 ft along each approach and intersection-related crashes for three-legged intersections. However, since *p*-values are greater than 0.05, none of the changes are statistically significant at 5% level. When considering a 300 ft intersection box for four-legged intersections, *p*-values less than 0.05 show a significant reduction in EPDO crash frequency at intersections with bypass lanes. In contrast, for intersection-related crashes, EPDO crash frequency at four-legged intersections with bypass lanes was slightly higher than intersections without bypass lanes, though it was not statistically significant.

4.3.3 Comparison of Crash Rates

As mentioned, actual AADT for 35% of intersections of minor roads are unknown. Using only the intersections for which AADTs were available, a two-sample *t*-test under 95% confidence level was conducted on crash rates at each intersection. Table 4.16 shows statistical analysis of crash rate difference within 300 ft along each approach leading to intersections and intersection-related crashes.

Table 4.16: Comparison of Crash Rates

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash rate (With)	0.276	0.188	0.310	0.123
Mean crash rate (Without)	0.194	0.131	0.157	0.153
Mean difference in crash rates	0.082	0.056	0.153	-0.03
***t*-value**	1.04	0.78	4.78	-1.12
***p*-value**	0.151	0.218	0.001	0.869

Positive values of the mean difference show a reduction of crash rates within 300 ft along each approach leading to three-legged intersections and intersection-related crashes. However, since *p*-values are greater than 0.05, none of reductions are significant. With a *p*-value less than 0.05, reduction of crash rates for 300 ft along each approach leading to four-legged intersections with bypass lanes are significant. However, for intersection-related crashes, differences in crash rates at four-legged intersections with and without bypass lanes are not significant.

4.3.4 Comparison of Equivalent Property Damage Only Crash Rates

Similar to crash rate analysis, a two-sample *t*-test under 95% confidence level was conducted on EPDO crash rates at each intersection in which Total Entering Volume (TEV) could be calculated. Table 4.17 shows statistical analysis of EPDO crash rate difference within 300 ft along each approach leading to intersections and intersection-related crashes.

Table 4.17: Comparison of EPDO Crash Rates

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash rates (With)	0.84	0.131	1.09	0.75
Mean EPDO crash rates (Without)	0.93	0.147	0.77	0.99
Mean difference in EPDO crash rates	-0.097	-0.016	0.32	-0.242
***t*-value**	-0.25	-0.66	1.69	-1.29
***p*-value**	0.60	0.744	0.046	0.901

Negative values of the mean difference show higher EPDO crash rates at intersections with bypass lanes, using both 300 ft along each approach and intersection-related crashes for three-legged intersections. However, since the *p*-value is greater than 0.05, both differences are not significant. When considering 300 ft along each approach leading to four-legged intersections, *p*-value less than 0.05 shows a significant reduction of EPDO crash rates at four-legged intersections with bypass lanes. In contrast, for intersection-related crashes, differences in EPDO crash rates with and without bypass lanes are not significant at three-legged intersections.

4.3.5 Model Calibration

A predictor model was calibrated in order to estimate the TEV for 35% of the intersections for which the AADT values were not available for the minor street. Two types of data, socio-economic data and intersection-characteristics data, were collected for calibrating the model, as listed in Table 3.5. The test of independency was applied on the initially identified input data to find the independent variables. Based on the results, four variables were a linear combination of other variables, as shown in Table 4.18, and accordingly they were removed from further consideration.

Table 4.18: Results of Dependency Test

X12 =	Intercept - X3 - X4 - X5 - X6 - X7 - X8 - X9 - X10 - X11 - 531E-19 × X14
X22 =	217E-14 × X13 + 534E-15 × X14 + X20 - X21
X25 =	100 × Intercept - 685E-17 × X13 + 38E-16 × X14 - 699E-14 × X17 + 539E-16 × X20 - 508E-16 × X21 - X24
X27 =	172E-15 × X13 - 192E-14 × X20 + 17E-13 × X21 + X23 - X26

After removing those four variables, variables with significant effect on the predictor variable were found using the *p*-value test, where the results are shown in Table 4.19. By considering 95% confidence level, variables with *p*-values greater than 0.05 were removed from the final model. A total of 693 intersections with known AADTs were used to estimate the TEV of intersections. Initially an attempt was made to estimate the actual TEV, or sum of the roads' AADTs, but the test of normality showed that residuals distribution did not follow normal distribution. However, when an estimation of $\log_{10} TEV$ was attempted, residuals followed normal distribution. Therefore, $\log_{10} TEV$ was estimated instead of actual TEV value.

Table 4.19: Test Results to Identify Significant Variables in Predicting TEV

Variable	*p*-value	Variable	*p*-value	Variable	*p*-value
X1	<.0001	X10	<.0001	X19	0.161
X2	0.0107	X11	<.0001	X20	<.0001
X3	<.0001	X12	dropped	X21	<.0001
X4	<.0001	X13	<.0001	X22	dropped
X5	<.0001	X14	0.0071	X23	0.0001
X6	<.0001	X15	<.0001	X24	0.0377
X7	<.0001	X16	0.0485	X25	dropped
X8	<.0001	X17	<.0001	X26	0.291
X9	<.0001	X18	0.4466	X27	dropped

Regression results of AADT prediction model are given in Equation 4.3. The R-square value of the model was 0.69, which is acceptable for this type of modeling situations.

$$\log_{10} TEV = 3.768 + 0.095x_1 + 0.062x_2 + 0.832x_3 + 0.788x_4 + 0.63x_5 + 0.442x_6 + 0.6x_7 + 0.38\,x_8 - 0.339x_9 + 0.64x_{10} + 0.432x_{11} - 4 \times 10^{-5}x_{13} + 9 \times 10^{-7}x_{14} + 1.6 \times 10^{-5}x_{15} - 4 \times 10^{-6}x_{16} - 0.022x_{17} + 3 \times 10^{-4}x_{20} - 3 \times 10^{-4}x_{21} - 3 \times 10^{-4}x_{23} + 0.028x_{24} \qquad \textbf{Equation 4.3}$$

Where:

TEV= Total Entering Volume at intersection,

and other variables are as defined earlier.

4.3.6 Comparison of Estimated Crash Rates

After estimating the unknown TEV at 35% of the remaining intersections using the developed model shown in Equation 4.3, crash rates were calculated and a two-sample *t*-test under 95% confidence level was conducted on crash rates at each intersection. Table 4.20 shows statistical analysis of estimated crash rate reduction within 300 ft along each approach leading to the intersections and intersection-related crashes.

Table 4.20: Comparison of Estimated Crash Rates

Statistical Parameters	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash rates (With)	0.276	0.188	0.299	0.138
Mean crash rates (Without)	0.194	0.131	0.151	0.147
Mean difference in crash rates	0.0821	0.057	0.148	-0.009
***t*-value**	1.04	0.78	5.02	-0.36
***p*-value**	0.151	0.218	0.001	0.639

Positive values of the mean difference show a reduction of crash rates within 300 ft along each approach and intersection-related crashes at three-legged intersections. However, since *p*-values are greater than 0.05, these differences are not significant. For a 300-ft intersection box, with a *p*-value less than 0.05 at four-legged intersections, reduction in crash rates at intersections with bypass lanes are significant. However, when considering intersection-related crashes at four-legged intersections, the differences are not significant.

4.3.7 Comparison of Estimated Equivalent Property Damage Only Crash Rates

Similar to statistical analysis of estimated crash rates, a two-sample *t*-test under 95% confidence level was conducted on EPDO crash rates. Table 4.21 shows statistical analysis of estimated EPDO crash rate differences 300 ft along each approach leading to the intersections and intersection-related crashes.

Table 4.21: Comparison of Estimated EPDO Crash Rates

Statistical Parameter	Three-Legged Intersections		Four-Legged Intersections	
	Crash Selection Criteria		Crash Selection Criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash rates (With)	0.58	0.88	1.08	0.84
Mean EPDO crash rates (Without)	0.87	1.03	0.74	0.95
Mean difference in EPDO crash rates	-0.289	-0.155	0.346	-0.114
***t*-value**	-0.99	-0.48	2.04	-0.67
***p*-value**	0.839	0.684	0.021	0.749

Differences of EPDO crash rates within 300 ft along each approach and intersection-related crashes are not significant for three-legged intersections. When considering 300 ft along each approach leading to four-legged intersections, *p*-values less than 0.05 show a significant reduction of EPDO crash rates at intersections with bypass lanes. In contrast, for intersection-related crashes, difference in EPDO crash rates is not significant at four-legged intersections with bypass lanes versus four-legged intersections without bypass lanes.

4.4 Crash Modification Factors

CMF is used to compute the expected number of crashes after a countermeasure is implemented at a specific site. A CMF value greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after implementation of the countermeasure. For example, a CMF value of 0.9 indicates an expected safety benefit, specifically a 10% expected reduction in crashes. A CMF value of 1.1 indicates an expected decrease in safety, specifically a 10% expected increase in crashes. Table 4.22 shows the results of case-control study to calculate the CMF for the implementation of bypass lanes.

Table 4.22: Case-Control CMFs Based on Data from 2009 to 2011

Risk Factors	Intersection Types	Case		Control		CMF
		With bypass lane	Without bypass lane	With bypass lane	Without bypass lane	
		A	C	B	D	
Crashes within 300 ft from intersection	Three-legged intersections	46	35	104	59	0.75
	Four-legged intersections	123	225	285	260	0.50
Intersection related crashes	Three-legged intersections	35	34	115	60	0.54
	Four-legged intersections	112	157	296	328	0.79

According to the case-control method utilized in the cross-sectional study, all calculated CMF values are less than 1.0, indicating that future crashes are expected to decrease with the addition of bypass lanes at rural intersections.

CMF values were also calculated based on the before-and-after study approach, and the results are shown in Table 4.23. The only CMF greater than 1.0 was found for intersection-related crashes at four-legged intersections with a 5-year consideration before and after adding bypass lanes. Even then, however, when the sample size increased to 3- and 4-year consideration, the CMF became less than 1.0. All other calculated CMF were less than 1.0, so future crashes are expected to reduce after adding bypass lanes at rural unsignalized intersections.

Table 4.23: Before-and-After CMF Estimations

Categories			Treatment before	Treatment after	Comparison before	Comparison after	CMF
3-Year Consideration	3-Legged Intersection	Crashes within 300 ft	7	7	2	2	0.88
		Intersection-related crashes	5	3	2	3	0.22
	4-Legged Intersection	Crashes within 300 ft	9	7	11	9	0.83
		Intersection-related crashes	12	10	24	19	0.96
4-Year Consideration	3-Legged Intersection	Crashes within 300 ft	10	9	3	6	0.36
		Intersection-related crashes	7	6	1	3	0.18
	4-Legged Intersection	Crashes within 300 ft	10	6	11	15	0.32
		Intersection-related crashes	14	12	27	22	0.97
5-Year Consideration	3-Legged Intersection	Crashes within 300 ft	11	9	4	6	0.45
		Intersection-related crashes	14	7	2	2	0.39
	4-Legged Intersection	Crashes within 300 ft	9	4	9	10	0.25
		Intersection-related crashes	7	11	25	31	1.18

Chapter 5: Summary and Conclusions

The primary objective of this study was to present a statistically reliable conclusion regarding the effect of adding bypass lanes at rural unsignalized intersections.

To measure delay caused by the lack of a bypass lane, video capturing was performed at 10 locations near Manhattan, Kansas. Videos were recorded during morning peak hours (8:00 a.m. to 10:00 a.m.) and evening peak hours (4:00 p.m. to 6:00 p.m.) to capture maximum traffic flow and, hence, increased use of bypass lanes. Due to low traffic volumes, the necessity and the usage of a bypass lane was minimal during the observation times and few drivers utilized bypass lanes. According to captured videos, locations with bypass lanes experienced relatively shorter delay, as compared to locations without bypass lanes. However, this finding is not very reliable due to the small sample sizes. Another general observation was that not all drivers are familiar with the usage of the bypass lanes and some drivers did not utilize bypass lanes even when they were present.

A before-and-after study was conducted within 3, 4, and 5 years before and after the construction of bypass lanes at unsignalized rural intersections in order to evaluate the safety effectiveness of bypass lanes. A summary of results is shown in Table 5.1 for a 5% level of significance. When considering the 3- and 4-year before-and-after studies, bypass lane construction reduced crash frequency, EPDO crash frequency, crash rates, and EPDO crash rates; however, these reductions were not statistically significant under 95% confidence level. When considering a 300-ft intersection box at three-legged intersections, crash rates slightly increased after adding bypass lanes, but it was not statistically significant under 95% confidence level.

Table 5.1: Summary of Before-and-After Study Results at 5% Level

Parameters	Crash types	5-Year Consideration				4-Year Consideration				3-Year Consideration			
		3-Legged Intersection		4-Legged Intersection		3-Legged Intersection		4-Legged Intersection		3-Legged Intersection		4-Legged Intersection	
		Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant
Crash frequency	300 ft	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
	Intersection-related	YES	NO	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO
EPDO crash frequency	300 ft	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
	Intersection-related	YES	NO	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO
Crash rates	300 ft	YES	NO	YES	NO	YES	NO	YES	NO	NO	NO	YES	NO
	Intersection-related	YES	YES	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO
EPDO crash rates	300 ft	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
	Intersection-related	NO	NO	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO

In the 5-year before-and-after study, when considering a 300-ft intersection box, crashes and crash severity were not statistically significant under 95% confidence level. For intersection-related crashes, similar results were seen in crash frequency and EPDO crash frequency at three-legged intersections. The increase in crashes and crash severity observed at four-legged intersections was not statistically significant, but crash rates at three-legged intersections experienced a statistically significant reduction under 95% confidence level. EPDO crash rates at three-legged intersections increased, but they were not statistically significant under 95% confidence level. Calculated CMF values less than 1.0 also demonstrated the expected reduction in crashes after adding bypass lanes at unsignalized rural intersections.

A cross-sectional study was also performed on crash data from 2009 to 2011 extracted from KCARS. Analysis results are summarized in Table 5.2. A modest decrease in crash frequency, EPDO crash frequency, and crash rates occurred at three-legged intersections with bypass lanes, but these reductions were not statistically significant under 95% confidence level. EPDO crash rates at three-legged intersections increased, but they were not statistically significant under 95% confidence interval.

Table 5.2: Summary of Cross-Sectional Study Results at 5% Level

Intersection Types	Crash types	Crash frequency		EPDO crash frequency		Crash rates		EPDO crash rates		Est. crash rates		Est. EPDO rates	
		Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant
Three-Legged Intersections	300 ft	YES	NO	YES	NO	YES	NO	NO	NO	YES	NO	NO	NO
	Intersection-related	YES	NO	YES	NO	YES	NO	NO	NO	YES	NO	NO	NO
Four-Legged Intersections	300 ft	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	Intersection-related	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

When considering a 300-ft intersection box at four-legged intersections, significant reductions occurred in total crash frequency, EPDO crash frequency, crash rates, and EPDO crash rate. However, when considering intersection-related crashes, the presence of bypass lanes caused slight increases in crash frequency, EPDO crash frequency, crash rates, and EPDO crash rates, but none of those are significant at 5% level. According to the case-control study, CMF values were calculated to estimate the changes in crashes associated with the addition of bypass lanes at intersections. CMF values lower than 1.0 for all cases except one category (four-legged intersections when considering intersection-related crashes) indicate an expected reduction in crashes after adding bypass lanes.

Summary of the analysis results based on 10% level are shown in Table 5.3 and 5.4 for the before-and-after study and the cross-sectional study, respectively. Even though 5% level is most commonly used, due to the random nature of crashes, lower traffic volumes at the considered locations making exposure levels relatively low, quality and reliability of crash data obtained from the crash database, and other assumptions that were required to be made, 10% level could be considered as acceptable in this study. This change in confidence level makes few more reductions of crashes and crash rates to be significant due to the presence of bypass lanes.

By looking at the crashes and crash rates at locations considered in this study, it appears that with increased AADT and TEV, the number of crashes and crash rates typically increase even with the presence of bypass lanes. However, the overall conclusion of this study is that bypass lanes are beneficial in terms of improving safety, and helpful in reducing crashes and crash rates in almost all cases and circumstances considered in this study.

Table 5.3: Summary of Before-and-After Study Results at 10% Level

Parameters	Crash types	5-Year Consideration				4-Year Consideration				3-Year Consideration			
		Three-Legged Intersection		Four-Legged Intersection		Three-Legged Intersection		Four-Legged Intersection		Three-Legged Intersection		Four-Legged Intersection	
		Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant
Crash Frequency	300 ft	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
	Intersection-related	YES	YES	NO	NO	YES	YES	YES	NO	YES	YES	YES	NO
EPDO Crash Frequency	300 ft	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	NO
	Intersection-related	YES	NO	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO
Crash Rates	300 ft	YES	NO	YES	YES	YES	NO	YES	NO	NO	NO	YES	NO
	Intersection-related	YES	YES	NO	NO	YES	YES	YES	NO	YES	NO	YES	NO
EPDO Crash Rates	300 ft	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	NO
	Intersection-related	NO	NO	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO

Table 5.4: Summary of Cross-Sectional Study Results at 10% Level

Intersection Types	Crash Types	Crash Frequency		EPDO Crash Frequency		Crash Rates		EPDO Crash Rates		Est. Crash Rates		Est. EPDO Rates	
		Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant
Three-Legged Intersections	300 ft	YES	YES	YES	NO	YES	NO	NO	NO	YES	NO	NO	NO
	Intersection-related	YES	NO	YES	NO	YES	NO	NO	NO	YES	NO	NO	NO
Four-Legged Intersections	300 ft	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	Intersection-related	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

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