Safety Evaluation of Shoulder Bypass Lanes at Unsignalized Intersections on Rural Two-Lane Roadways Using Cross Sectional Analysis

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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 the decisions could be made on whether to continue with adding bypass lanes. Highway safety analyses utilize two common approaches to evaluate the effectiveness of a geometric treatment: before-and-after study and cross-sectional study. This paper explains the results using a cross-sectional study approach, where 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. Both 3-legged and 4-legged intersections were taken into consideration separately by looking at intersection-related crashes and crashes within an intersection box.

According to the results, the number of crashes and crash severities were lower at 3-legged intersections with bypass lanes compared with 3-legged intersections without bypass lanes, even though these reductions were not statistically significant at 95% level. When considering a 300-ft. intersection box, statistically significant crash reductions were observed at 4-legged intersections, for all considered crash and crash rate categories. When considering 90% level, crash reduction at 3-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. Accordingly, it is beneficial to continue with the practice of adding shoulder bypass lanes at rural unsignalized intersections on two-lane roads where the traffic volumes are relatively low.

INTRODUCTION

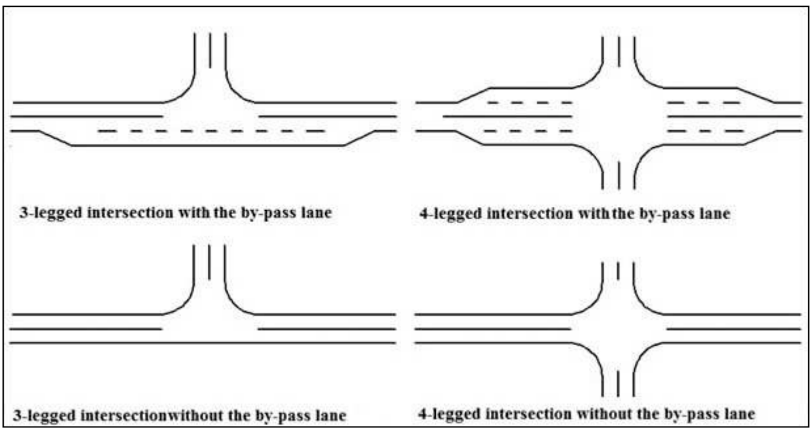
Increased population density in urban areas and higher annual average daily traffic (AADT) of urban roads cause crashes to occur more frequently in urban areas compared with rural areas (NHTSA 2016). However, higher speed limits, lack of traffic control devices, lower enforcement levels, and many other factors increase crash severity on rural roadways. In 2014, 29,989 fatal crashes occurred in the United States, resulting in 32,675 fatalities. Fifty-four percent of fatal crashes and 55% of fatalities occurred in rural areas, although only 19% of the U.S. population lives in rural areas. Urban areas accounted for 45% of fatal crashes and 44% of fatalities. At the same time, the fatality rate per 100 million vehicle miles traveled was 2.5 times higher in rural areas than in urban areas (NHTSA 2016). These statistics clearly show that crashes in rural areas are more severe in nature.

According to statistics from 2010, only 36% of all motor vehicle crashes in Kansas occurred in rural areas; however, in contrast, 69.7% of fatal crashes occurred in rural areas (KDOT 2013a), demonstrating increased crash severity on rural roadways. Nearly 30% of crashes in Kansas occurred at intersections or were intersection-related (KDOT 2013a). Opportunity for crashes increases at intersections, because vehicles approach the intersection from multiple directions making it possible to have more conflicts. 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, which might eventually lead to crashes (Izadpanah, Hadayeghi and Rezaie 2009). 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 at intersections in rural areas make it necessary to look at low-cost approaches to improve highway safety.

Accordingly, this study focused on evaluating safety effectiveness of bypass lanes at rural unsignalized intersections on two-lane roads. 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 reduce speed and stop. Bypass lanes provide a through-traffic lane in which the following driver can bypass the slow or stopped 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, and Brewer 2002). To increase highway safety at 3-legged or 4-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 shows typical bypass lane configurations at 3-legged and 4-legged rural intersections on a two-lane highway and an example site location on how it is actually used.

Figure 1: Typical Bypass Lane Configurations and an Example Site

(a) Typical Configurations



(b) An Example Site

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 some Kansas roadways, this study was necessary to quantitatively determine the safety benefits (if any) of the continued addition of bypass lanes on two-lane roadways. The study described in this paper served that purpose by quantitatively evaluating the safety effectiveness of bypass lanes by considering the cross-sectional study approach. In this approach, intersections were categorized as intersections with bypass lanes and intersections without bypass lanes, and statistical analyses were utilized to quantitatively determine safety effectiveness of having bypass lanes at those intersections.

In addition, crash modification factor (CMF), which is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site, is becoming increasingly popular with the introduction of the Highway Safety Manual (AASHTO 2010). Accordingly, CMF for bypass lane additions was calculated in this study by using case-control methodology.

No study of this nature has been previously conducted to evaluate the safety effectiveness of bypass lanes in rural areas, and, accordingly, practitioners can make the policy decision on whether to proceed with this practice of adding shoulder bypass lanes, which is very low-cost countermeasure in general.

LITERATURE REVIEW

Studies Related to Bypass Lanes

Even though the studies related to safety and operational effects of bypass lanes are not very common or comprehensive in the literature, a limited number of studies that are available are described here in detail. Sebastian and Pusey (1982) published a report that investigated bypass lanes after 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 (Sebastian and Pusey 1982). 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, fuel consumption, and vehicle emissions and crash prevention, in order to warrant the use of bypass lanes in designated left-turn lanes (Sebastian and Pusey 1982).

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

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 (Preston and Schoenecker 1999). Data on 3-legged intersections were collected using a survey sent to 212 government entities within Minnesota. Eighty-two completed surveys were returned. Another survey for 4-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, survey results revealed that most counties and cities implemented inconsistent pavement markings, that 3-legged bypass lanes had advantages in terms of delay and that 4-legged intersection bypass lanes should not be used (Preston and Schoenecker 1999).

A legal review of bypass lane implementation also occurred because Minnesota revised 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 finally 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 and Schoenecker 1999).

Preston and Schoenecker (1999) conducted safety analysis using crash data between 1995 and 1997 under the following categories: 1. Total and average number of intersection crashes, 2. 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, and 3. Distribution by severity and type. Three- and 4-legged intersections were reviewed and categorized into (Preston and Schoenecker 1999) no-turn lanes, bypass lanes and left-turn lanes. An additional before-and-after study was conducted in the same study, which included six years of crash data: three years prior to installation of bypass lanes and three years post-installation of bypass lanes. Sixty-nine intersections were used for the sample size, and crash data used were between 1983 and 1994 (Preston and Schoenecker 1999).

A safety summary of the 2,700 reviewed intersections stated that 3-legged intersections had fewer vehicle crash occurrences compared with 4-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 (Preston and Schoenecker 1999). 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 (Preston and Schoenecker 1999). 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 and 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 and opposite the minor road at a T-intersection on a rural two-lane roadway. (Bruce and Hummer 1991). Bypass design was designated as a 300-ft. taper out to a 12-ft. lane; 700-ft., a 12-ft lane with 600-ft. from end of run out taper to minor road centerline and then 100-ft. past centerline; and a 600-ft. taper to a single-lane travel way (Bruce and Hummer 1991). The experiment relied on traffic simulation using software called 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 (Bruce and Hummer 1991).

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

Studies Related to Crash Modification Factors

A crash modification factor evaluates safety effectiveness of any given countermeasure. It is calculated by dividing number of crashes with a treatment with number of crashes without the treatment. A CMF value less than 1.0 shows an expected reduction in vehicle crashes due to a countermeasure, but CMF greater than 1 indicates an increase in crashes after countermeasure implementation (Gross, Persaud, and 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 three 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 and Donnell 2011).

Gross and Donnell (2011) applied case control and cross-sectional method to develop CMF for roadway lighting and shoulder width. Four years (2001-2004) of data 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 4-legged, 40% were 3-legged, and 11% were 4-legged skewed intersections, where the two streets were not meeting at right angles. 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 was 0.881 for the cross-sectional study. 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 Donnell 2011).

Gross and Jovanis (2007) applied case-control method to evaluate 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 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. According to the authors, case-control estimation could advantageously estimate confidence levels, thereby conveying variability in safety effectiveness. Safety effectiveness range can be considered in economic analysis of alternative action.

METHODOLOGY AND DATA

Background of Observational Studies

Researchers either design an experiment or conduct an observational study to answer a specific question or test whether a certain hypothesis is correct. Typically, 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 involves 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 design characteristics of the road are expected to remain the same during each before or after time period. However, in cross-section-based observational studies, safety effects of one group of facilities are compared to another group of facilities. These two groups of facilities should have similar features, except the feature that is being studied, so that the safety effect of the dissimilar feature could be evaluated (Izadpanah et al. 2009).

Cross-sectional Studies

A cross-sectional study, which is a common observational study in transportation safety evaluations, compares the safety performance of a site or group of sites with the treatment of interest to similar sites without the 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 and intersections without the treatment.

One challenge inherent in observational studies is that crashes are random events 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, could also vary for each intersection or study location. In order to evaluate safety effectiveness of a specific treatment, Highway Safety Manual (HSM) recommends a three-year to five-year comparison of crash data at sites with implemented treatment versus sites without the treatment (AASHTO 2010).

Statistical Analysis Using t-test

In order to evaluate the differences in crash experience at two sets of sites, t-test could effectively be utilized. The t-distribution is a symmetrical distribution similar to normal distribution, but has thicker tails making it shorter and flatter (Martz and Paret 2013). The t-distribution is useful for analyzing the mean of an approximately normally distributed population when the population standard deviation is unknown (Martz and Paret 2013). In this study, crash frequency at intersections with bypass lanes and without bypass lanes is the subject quantity to be analyzed. If the average crash frequencies per intersection with and without bypass lanes are μ_1 and μ_2, respectively, the t-test can be used to determine whether a statistically significant difference exists between the two sets of data. In this case, the null hypothesis becomes:

$$H_0 : \mu_1 = \mu_2$$

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

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

When the critical area of the t-distribution is one sided, either greater than or less than a certain value, it is called a one-tail test. A two-tail test would be used to determine if two means are different. The t-value can be computed from Equation 1 (Ruxton 2006).

$$(1) \qquad t = \frac{\bar{X}_1 - \bar{X}_2}{S_p^2\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

Where,

$\bar{X}_1$ and $\bar{X}_2$ = Sample means
n_1 *and* n_2 = Sample sizes
S_p = Square root of the pooled variance given by,

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

Where,

${S_1}^2$ and ${S_2}^2$ = Sample variance of the two populations

The degrees of freedom and level of significance (α) affect the value of t. The degrees 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 probability of occurrence of Type 1 error is the level of significance (α). The most commonly used "α" value in traffic safety studies is 5%, although 10% is also occasionally used. When the t-test is one-tail, the *t*-value is selected for "α"; when the test is two-tail, the *t*-value is selected for "α/2." When conducting the statistical comparison, null hypothesis is rejected if the sample t-value is more than the critical t-value; therefore, the null hypothesis is not true. In other words, a significant difference exists between two sample means (Ruxton 2006). The null hypothesis is not rejected if the sample t-value is less than the critical t-value. In this case, the null hypothesis could be true or no significant difference exists between the population means (Ruxton 2006).

Each t-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 a significant difference, p-value could be used to compare significance levels (Martz and Paret 2013). A large t-value means a large difference between sample means; therefore, a larger t-value is associated with a smaller p-value. Rejection of the null hypothesis either based on t-value or p-value is shown in Table 1.

Table 1: Rejection of Null Hypothesis Based on t-Value or p-Value

Alternative hypothesis	Rejection region for H_0
H_1: $\mu_1 > \mu_2$ $(one - tail\ test)$	$t > t_\alpha$
H_1: $\mu_1 < \mu_2$ $(one - tail\ test)$	$t > t_\alpha$
H_1: $\mu_1 \neq \mu_2$ $(two - tail\ test)$	$\lvert t \rvert > t_{\alpha/2}$
Alternative hypothesis	Rejection region for H_0
H_1: $\mu_1 > \mu_2$ $(one - tail\ test)$	$\alpha > p - value$
H_1: $\mu_1 < \mu_2$ $(one - tail\ test)$	$\alpha > p - value$
H_1: $\mu_1 \neq \mu_2$ $(two - tail\ test)$	$\alpha/2 > p - value$

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 and Paret 2013). 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 selected alpha (p-value ≤ α), the null hypothesis is rejected, or a significant difference exists between sample means.
- If the p-value is greater than the selected alpha (p-value > α), the null hypothesis is not rejected, or no significant difference exists between sample means.

Crash Modification Factors (CMF)

Transportation professionals, such as traffic engineers, transportation planners, and designers, can use CMF to evaluate the effectiveness of a given countermeasure. 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 (Gross et al. 2010). A CMF greater than 1.0 indicates an expected increase in the number of crashes, demonstrating that the countermeasure deteriorated 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 at that location (Gross et al. 2010). Case-control studies have recently been employed on evaluating geometric design elements (Gross and Jovanis 2007) by computing CMFs. In case-control studies, once the treatment is determined, samples of locations with bypass lanes (cases) and number of locations without bypass lanes (controls) are selected based on their status on whether the risk factor (crashes at the location) is present or not.

Application of this method could be explained as follows:

$$(3)\quad Odds\ Ratio(CMF) = \frac{A/B}{C/D} = \frac{A \times D}{B \times C}$$

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 a crash or severe injury, in terms of expected frequency. Instead, these studies are often used to demonstrate the relative effects of treatments (Gross et al. 2010).

Data Collection

In the initial stages of the study, survey forms were sent to area and district engineers of KDOT in order to identify the locations and determine characteristics of rural unsignalized intersections with bypass lanes. Questions on the survey form sought to identify specific information such as road names, average annual daily traffic (AADT), speed limits, pavement markings, and dates when bypass lanes were added. Of those sent, 563 completed survey forms were received. Categorization of received surveys by districts was used primarily to ensure accurate geographical data distribution throughout the state, which was found to be acceptable. Later on, researchers used Google Earth to identify the other set of sites without bypass lanes in the vicinity of those sites with bypass lanes.

The safety effectiveness of any countermeasure is quantified by a reduction in the number of crashes or crash severity caused by treatment implementation. Kansas Crash Analysis and Reporting System (KCARS) database, maintained by KDOT, was utilized in this study to determine crashes at each intersection. KCARS database includes details of all police-reported crashes on the Kansas highway system, and this database is coded in accordance with the Kansas Motor Vehicle Crash Report. In this study, all crashes from 1990-2011 were gathered to evaluate the effectiveness of bypass lanes. For data collection, HSM recommends utilization of a three- to five-year time period because time periods less than three years are subject to high variability due to randomness of crashes, and periods longer than five years are subject to introduction of bias due to changes in reporting standards or physical changes to roadway features (AASHTO 2010). Some characteristics of data variables in the KCARS database are as follows:

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

Crash Location. Several fields in KCARS represent crash location, including county milepost and distance from a named intersection. Because incident responders may not typically have precise positioning equipment to determine the specific milepost of an incident, this value could contain some inaccuracies. Two additional KCARS columns provide longitude and latitude of the crash location, which could also be utilized in obtaining the location of a crash.

Crash Severity. KCARS contains three primary categories of crash severity with five total subdivided injury severity levels as (KDOT 2005): 1. Fatal crashes, 2. Injury crashes (possible injury, non-incapacitating injury, and incapacitating injury), and 3. Property damage only (PDO). When more than one person is involved in a crash, it is assigned to the most severe personal injury severity level experienced by persons involved in the crash.

Equivalent Property Damage Only Crashes

In order to account for severity of crashes at each location, 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 and Campbell 2005). Accordingly, EPDO crash numbers are calculated as follows:

(4) $$Number\ of\ EPDO\ crashes = no.PDO\ Crashes + w_1 \times no.Injury\ Crashes + w_2 \times no.Fatal\ Crashes$$

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: w1 = w2= 15

Relevant Crashes

In order to determine relevant crashes to be considered in evaluating the effectiveness of bypass lanes, two methods were utilized. This is based on a dilemma in the transportation community on whether location-related crashes should be based on distance or an “intersection-related” variable in the crash databases. This study used both methods to identify any differences/similarities.

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

KDOT Traffic Count Maps

For an intersection, a combination of crash frequency and traffic volume results in crash rates, which can be effectively used to compare relative safety at intersections. The traffic volume for each approach is needed to calculate the crash rate at an intersection (Green and Agent 2003). Traffic volumes of major roads considered in this study were mainly obtained from KDOT traffic count maps. However, 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 maps, AADT values of county major collector rural roads are available on the KDOT website, which provides 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. By matching roads like this, traffic volumes of minor roads were obtained.

Calculation of Crash Rates

Crash rates for selected rural intersections were calculated in terms of crashes and EPDO crashes per million entering vVehicles (MEV) respectively, as follows (Green and Agent 2003).

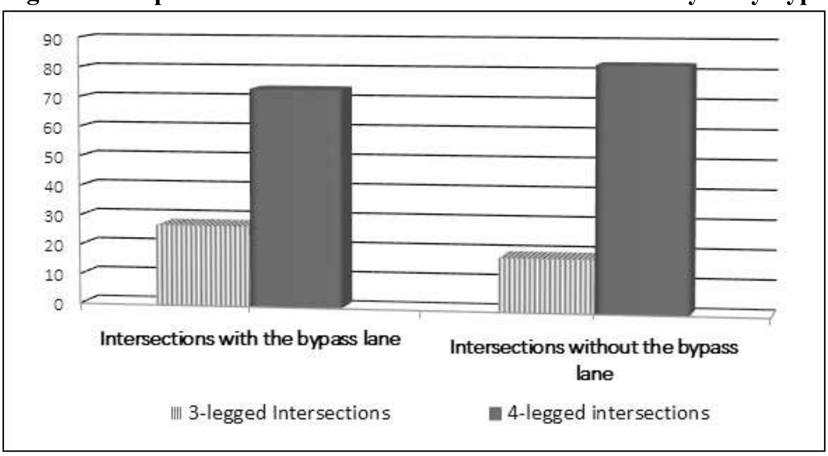
(5) $$Crash\ rate = \frac{Average\ number\ of\ Crashes\ per\ year \times 10^6}{\sum AADT\ \times 365}$$

(6) $$EPDO\ crash\ rate = \frac{Average\ EPDO\ crashes\ per\ year \times 10^6}{\sum AADT\ \times 365}$$

RESULTS

Analysis was conducted to determine the safety effectiveness of bypass lanes by comparing crash statistics at intersections with bypass lanes and intersections with no bypass lanes and no left-turn lane. Intersections with bypass lanes were obtained from the 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 the 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 of intersections with bypass lanes to have similar traffic volume and driver behaviors. Figure 2 shows the proportion of 3-legged and 4-legged intersections in the two samples, intersections with bypass lanes and intersections without bypass lanes. As shown in the figure, among the intersections with bypass lanes, 72% were 4-legged intersections; whereas the corresponding percentage for intersections without bypass lanes was even higher at 83%.

Figure 2: Proportion of Intersections Considered in the Analysis by Type



Crash data were extracted from KCARS from 2009–2011, and then a two-sample t-test was conducted to evaluate the significance of differences in the number of crashes, number of EPDO crashes, crash rates, and EPDO crash rates. A comparison crash analysis was conducted to determine basic crash characteristics for two categories of intersections: 3-legged and 4-legged.

Comparison of Crash Frequency

A two-sample t-test under 95% confidence level was conducted on crash frequency for the two sets of intersections. Table 2 shows the results of statistical comparison of crash frequency within 300 feet along each approach leading to the intersections and intersection-related crashes.

Table 2: Statistical Comparison of Crash Frequency

Statistical parameter	3-legged Intersections		4-legged Intersections	
	Crash selection criteria		Crash selection criteria	
	300ft	Intersection-related	300ft	Intersection-related
Mean crash frequency (With bypass lanes)	0.670	0.521	0.870	0.503
Mean crash frequency (Without bypass lanes)	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 feet along each approach leading to 3-legged intersections and intersection-related crashes. However, according to the p-values that are greater than 0.05, none of the differences are significant at 5% level. However, the difference is significant at 10% level since $p = 0.098$. Because p-values are less than 0.05 at 4-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.

Comparison of EPDO Crash Frequency

A two-sample t-test under 95% confidence level was conducted on EPDO crash frequency at each intersection. Table 3 shows statistical analysis results of EPDO crash differences 300 feet along each approach leading to intersections and intersection-related crashes.

Table 3: Comparison of EPDO Crash Frequency

Statistical parameter	3-legged Intersections		4-legged Intersections	
	Crash selection criteria		Crash selection criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash frequency (With bypass lanes)	2.16	3.335	3.87	3.71
Mean EPDO crash frequency (Without bypass lanes)	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 feet along each approach and intersection-related crashes for 3-legged intersections. However, since *p*-values are greater than 0.05, none of those differences are statistically significant at 5% level. When considering a 300 ft. intersection box for 4-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 4-legged intersections with bypass lanes was slightly higher than intersections without bypass lanes, even though it was not statistically significant.

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 shows statistical analysis of the crash rate difference within 300 feet along each approach leading to intersections and intersection-related crashes.

Table 4: Comparison of Crash Rates

Statistical parameter	3-legged Intersections		4-legged Intersections	
	Crash selection criteria		Crash selection criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean crash rate (With bypass lanes)	0.276	0.188	0.310	0.123
Mean crash rate (Without bypass lanes)	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 feet along each approach leading to 3-legged intersections and intersection-related crashes. However, since *p*-values are greater than 0.05, none of the reductions are significant. With *p*-value less than 0.05, reduction of crash rates for 300 feet along each approach leading to 4-legged intersections with bypass lanes are significant. However, for intersection-related crashes, differences in crash rates at 4-legged intersections with and without bypass lanes are not significant.

Comparison of EPDO 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. Table 5 shows the statistical analysis of EPDO crash rate difference within 300 feet along each approach leading to intersections and intersection-related crashes.

Table 5: Comparison of EPDO Crash Rates

Statistical parameter	3-legged Intersections		4-legged Intersections	
	Crash selection criteria		Crash selection criteria	
	300 ft	Intersection-related	300 ft	Intersection-related
Mean EPDO crash rates (With bypass lanes)	0.84	0.131	1.09	0.75
Mean EPDO crash rates (Without bypass lanes)	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 feet along each approach and intersection-related crashes for 3-legged intersections. However, since the p-value is greater than 0.05, both differences are not significant. When considering 300 feet along each approach leading to 4-legged intersections, *p*-value less than 0.05 shows a significant reduction of EPDO crash rates at 4-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 4-legged intersections.

Crash Modification Factors

As mentioned earlier, CMF is used to compute the expected number of crashes after a countermeasure is implemented at a specific site. A CMF 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. Table 6 shows the results of a case-control study conducted in this study to estimate CMF for the implementation of bypass lanes.

Table 6: Case-Control CMFs Based on Data from 2009-2011

Risk Factors	Intersection types	Number of cases under each scenario				CMF
		With bypass lane	Without bypass lane	With bypass lane	Without bypass lane	
		A	C	B	D	
Crashes within 300 ft from intersection	3-legged intersections	46	35	104	59	0.75
	4-legged intersections	123	225	285	260	0.50
Intersection related crashes	3-legged intersections	35	34	115	60	0.54
	4-legged intersections	112	157	296	328	0.79

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

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. Results of the cross sectional study are presented in Table 7 for 5% level of confidence or p=0.05. A modest decrease in crash frequency, EPDO crash frequency, and crash rates occurred at 3-legged intersections with bypass lanes, but these reductions were not statistically significant under 95% confidence level. EPDO crash rates at 3-legged intersections increased, but they were not statistically significant under 95% confidence interval. When considering a 300-ft. intersection box at 4-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, CMFs were calculated to estimate the changes in crashes associated with the addition of bypass lanes at intersections. CMFs lower than 1.0 for all cases indicates an expected reduction in crashes after adding bypass lanes.

A summary of the analysis results based on 10% level are shown in Table 8. 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 scenario. This change in confidence level makes a few more reductions of crashes and crash rates to be significant due to the presence of bypass lanes.

Table 7: Summary of Cross-Sectional Study Results at 5% Level

Intersections types	Crash types	Crash frequency		EPDO crash frequency		Crash rates		EPDO crash rates	
		Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant
3-legged intersections	300 ft.	YES	NO	YES	NO	YES	NO	NO	NO
	Intersection-related	YES	NO	YES	NO	YES	NO	NO	NO
4-legged intersections	300 ft.	YES	YES	YES	YES	YES	YES	YES	YES
	Intersection-related	NO	NO	NO	NO	NO	NO	NO	NO

Calculated CMFs less than 1 also demonstrated the expected reduction in crashes after adding bypass lanes at unsignalized rural intersections. Results obtained using CMF is much clearer in regard to the benefits of bypass lanes, in comparison to t-test results. By considering all analysis results, 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 8: Summary of Cross-Sectional Study Results at 10% Level

Intersections types	Crash types	Crash frequency		EPDO crash frequency		Crash rates		EPDO crash rates	
		Reduction	Significant	Reduction	Significant	Reduction	Significant	Reduction	Significant
3-legged intersections	300 ft.	YES	YES	YES	NO	YES	NO	NO	NO
	Intersection-related	YES	NO	YES	NO	YES	NO	NO	NO
4-legged intersections	300 ft.	YES	YES	YES	YES	YES	YES	YES	YES
	Intersection-related	NO	NO	NO	NO	NO	NO	NO	NO

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