Safety Evaluation of Signalized Restricted Crossing U-Turn Intersections

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program *Report 500 Guides* as part of the implementation of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan. The ELCSI-PFS studies provide a crash modification factor and benefit– cost (B/C) economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member States.

A restricted crossing U-turn (RCUT) intersection is defined as a three- or four-approach intersection where minor street left-turn and through movements (if any) are rerouted to one-way downstream U-turn crossovers. This study collected and analyzed crash data before and after conversion of 11 intersections from conventional to RCUT design. The intersections were in suburban areas on four- or six-lane arterials. Study results show a signalized RCUT to be effective to reduce total crashes, and reduce injury crashes since they generally reduce the more severe angle and turning crashes. The study estimated B/C ratio for installing an RCUT shows that this strategy, when considering safety and operations, is cost beneficial. This report is intended for safety engineers, highway designers, planners, and practitioners at State and local agencies involved with AASHTO Strategic Highway Safety Plan implementation.

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Acting Director, Office of Safety
Research and Development

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16. Abstract
This study evaluated restricted crossing U-turn (RCUT) intersection and was conducted by the DCMF program for the Evaluation of Low-Cost Safety Improvements Pooled Fund Study. RCUT is defined as a three-approach or four-approach intersection where minor street left-turn and through movements (if any) are rerouted to one-way downstream U-turn crossovers. RCUTs are also known as superstreets, J-turns, reduced conflict intersections, and synchronized streets. Previous research has shown that unsignalized RCUTs are generally safer than conventional options. However, there are no known studies specific to the safety of signalized RCUTs. The objective of this effort was to collect and analyze crash data to develop a crash modification factor (CMF) for signalized RCUTs.

This study collected and analyzed crash data before and after conversion of 11 intersections from conventional to RCUT design. The intersections were in suburban areas on four- or six-lane arterials. For most individual sites and groups of sites examined, odds ratio tests showed that there were high-quality comparison sites available, and regression to the mean was not an issue. The project team recommends a CMF of 0.85 for overall crashes and 0.78 for injury crashes for the conversion of a conventional intersection to an RCUT intersection.

Based on those CMFs, the project team produced an estimated benefit-to-cost ratio of 3.6 to 1.0 when considering safety and operations or 2.6 to 1.0 considering safety only.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

B/C	benefit–cost
CMF	crash modification factor
CRF	crash reduction factor
DCMF	Development of Crash Modification Factors (program)
EB	empirical Bayesian
FHWA	Federal Highway Administration
RCUT	restricted crossing U-turn

EXECUTIVE SUMMARY

A restricted crossing U-turn (RCUT) intersection is defined as a three-approach or four-approach intersection where minor street left-turn and through movements (if any) are rerouted to one-way downstream U-turn crossovers. RCUTs are also known as superstreets, J-turns, reduced conflict intersections, and synchronized streets. Ten States have installed at least 50 RCUTs since the late 1980s. At least five States have installed signalized RCUTs—those at which the major street crossover(s) and U-turn crossover(s) are under the control of traffic signals. Studies have shown RCUTs to have advantages over traditional intersections in terms of travel time and delay, signal progression, pedestrian crossing, and transit service.

While there are theoretical reasons that support the relative safety benefits of RCUTs as compared to conventional intersections, it is also possible that certain RCUT elements could diminish or negate these benefits. For example, signalized RCUTs involve a greater number of signals at the U-turn crossover(s) and require that some users travel longer overall distances. There is no known completed research on the safety of signalized RCUTs.

The objective of this evaluation was to develop a crash modification factor (CMF) for the replacement of a traditional signalized intersection with a signalized RCUT. The project team also intended for the evaluation to conduct a qualitative analysis of crash data at signalized RCUTs to provide information to designers on expected crash patterns and trends. Finally, the research team developed a benefit–cost (B/C) ratio.

The project team selected the before–after analysis with comparison sites methodology for this evaluation. The method accounts for simultaneous event biases, which the project team thought to be the most threatening potential bias to the evaluation. Simultaneous event biases that could have been important include the recession of the late 2000s and development in the area of the study sites. An empirical Bayesian methodology was unnecessary in this case because regression to the mean was not a serious threat to the validity of the analysis. The method relies on high-quality comparison sites, and the quality of the comparison sites is testable. The project team collected data from 11 treatment sites in 4 States: Alabama, North Carolina, Ohio, and Texas. The treatment sites were all in suburban areas, on four-lane or six-lane divided arterials, and characterized by high-speed traffic and minimal crossing pedestrians. The project team analyzed four potential comparison sites per treatment site. In addition to the before–after analyses of all reported crashes, the project team conducted a before–after analysis of fatal and injury crashes.

The research resulted in estimated CMFs of 0.85 for overall crashes and 0.78 for injury crashes. These CMFs are not statistically significant at the 95- or 90-percent confidence level. The injury CMF is significantly different from 1.0 at the 68-percent confidence interval. This is the first effort to develop a CMF for this strategy. Future evaluations can expand the sample size and use more robust methods that may result in CMFs with higher confidence. The CMFs suggest that signalized RCUTs will generally produce a crash reduction.

Economic analysis resulted in an estimated total annualized RCUT cost of $369,000. The estimated costs included costs for construction and signal operation and maintenance. The estimated benefits included savings of travel time and crashes. The 11 RCUTs were estimated to save 103 hours of motorist time per workday, which equates to $388,000 per year. The safety benefit was a savings of 3.0 property-damage-only crashes per year and 2.3 injury and fatal crashes per year, which results in an annual monetary savings of $948,000. Thus, the B/C ratio was 2.6 to 1.0 considering the safety benefits only and 3.6 to 1.0 considering the combined safety and operational benefits.

CHAPTER 1. INTRODUCTION

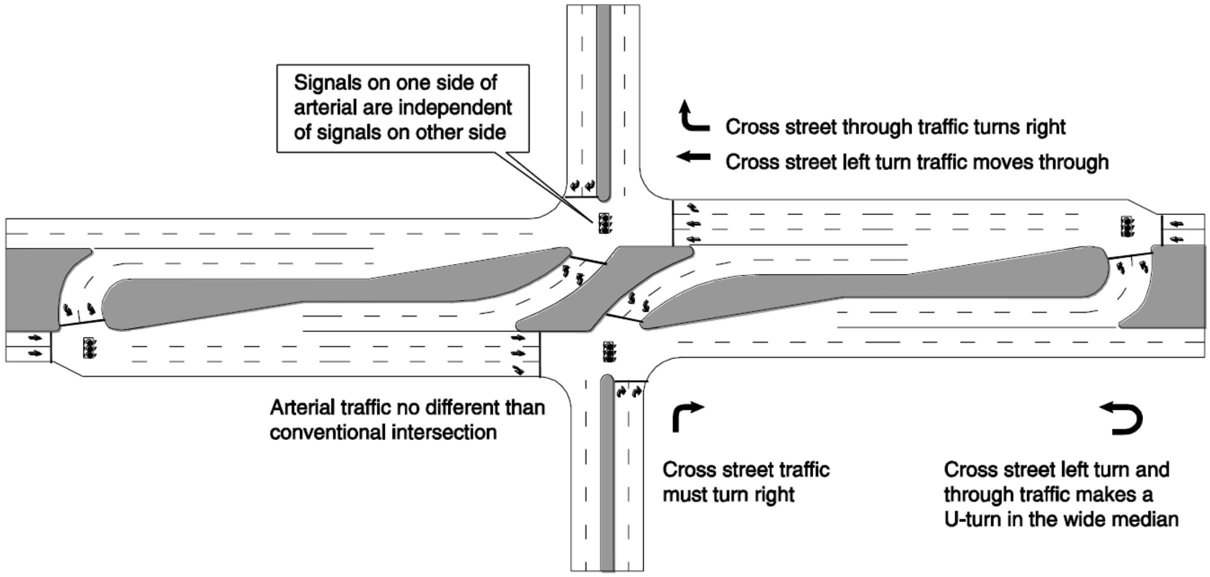
BACKGROUND ON STUDY

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements. Forty State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study, which functions under the DCMF program.

The restricted crossing U-turn (RCUT) intersection strategy was selected for evaluation as part of this effort.

BACKGROUND ON STRATEGY

An RCUT is defined as a three-approach or four-approach intersection where minor street left-turn and through movements (if any) are rerouted to one-way downstream U-turn crossovers. RCUTs are also known as superstreets, J-turns, reduced conflict intersections, and synchronized streets. Figure 1 shows a schematic of a signalized RCUT with four approaches. Ten States have collectively installed at least 50 RCUTs since the late 1980s.(1) At least five States have installed signalized RCUTs where the major street crossover(s) and U-turn crossover(s) are controlled by traffic signals. Studies have shown RCUTs to have advantages over traditional intersections in terms of travel time and delay, signal progression, pedestrian crossing, and transit service.(1)



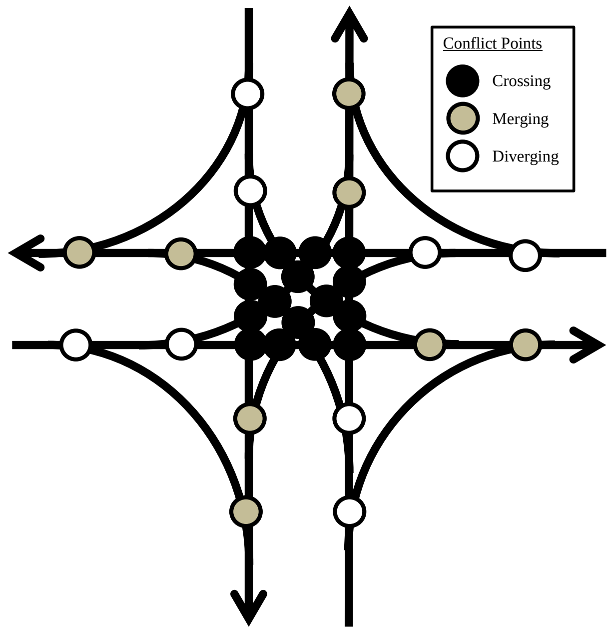
Source: FHWA.

Figure 1. Illustration. Schematic of signalized RCUT.[(1)]

There are several theoretical reasons to believe that RCUTs have the potential to reduce crash frequency and severity compared to conventional intersections. First and foremost, RCUTs reduce the number of conflict points, as shown in table 1 (and illustrated in figure 2 and figure 3). The number of conflict points at an intersection is commonly thought to be related to the number of crashes, and the RCUT design reduces the number of decision points for drivers. This is also true for pedestrian movements. At signalized four-approach RCUTs, pedestrians should experience conflicts when crossing a major street only if a driver violates a red signal or if the pedestrian jaywalks. In addition, the types of vehicle-to-vehicle conflicts change at an RCUT compared to conventional intersections. This includes fewer right-angle conflicts, which generally result in more severe crashes. There is also more distance between conflict points at an RCUT compared to conventional intersections, which provides drivers more space and time to perceive and react to potential safety issues.

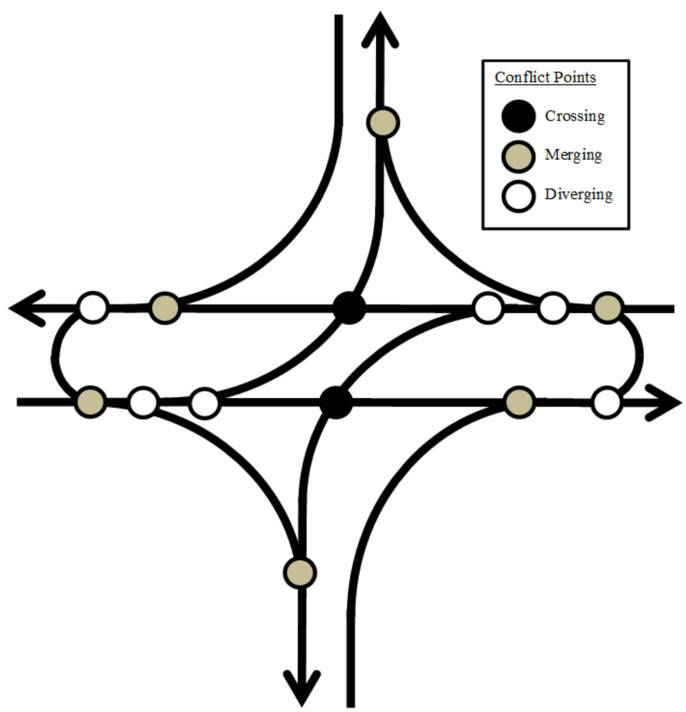
Table 1. Conflict points at conventional intersections and RCUTs.

Number of Approaches	Type of Conflict	Conventional Intersection Conflict Points	RCUT Conflict Points
3	Vehicle-to-vehicle	9	7
3	Vehicle-to-pedestrian	12	5
4	Vehicle-to-vehicle	32	14
4	Vehicle-to-pedestrian	24	8



Source: FHWA.

Figure 2. Illustration. Conventional intersection conflict points (four-approach).



Source: FHWA.

Figure 3. Illustration. RCUT conflict points (four-approach).

There are several unique elements of signalized RCUTs that are expected to improve intersection safety.[1] For example, the signal progression possible along an RCUT corridor can help manage speed and decrease stops, which may produce safety benefits. RCUT signals may function using as few as two phases, simplifying related decisionmaking and reducing opportunities for signal violations and traps. Additionally, most RCUTs feature medians to divide directions of traffic along the major road, potentially resulting in fewer opposite direction head-on and driveway-related crashes sometimes associated with these types of corridors.

Conversely, the following RCUT elements could negate or outweigh the expected safety benefits as compared to a traditional intersection:[1]

- Left-turn and through vehicles from the minor street travel longer overall distances at an RCUT—to the downstream U-turn crossover and back—which could lead to an increase in the number of crashes related to distance traveled (e.g., animal crashes). U-turn crossovers at signalized RCUTs are typically 500 to 800 ft from the main intersection, so total added distances traveled are not insignificant.

- The movements from the minor street—where a right-turn/U-turn combination replaces a direct left-turn left or straight through—may be counterintuitive to unfamiliar drivers and may lead to maneuvers that could result in crashes.

- Signalized RCUTs with two or more lanes in the crossovers or from minor streets involve side-by-side turns, which could lead to sideswipe crashes.

- RCUTs have more signals (two at a three-legged intersection and four at a four-legged intersection) than a conventional intersection with one signal, which may contribute to rear-end crashes.

Three major studies with relatively large crash samples and accepted analysis methods have been published in recent years analyzing the installation of unsignalized RCUTs at sites that previously were conventional unsignalized intersections.[1] The percentage decreases in crashes, shown in table 2, were statistically different from 0 at the 95-percent level or greater. These studies suggest that unsignalized RCUTs can be effective safety countermeasures and offer promise that signalized RCUTs may also be effective safety countermeasures.

Table 2. Results of major safety studies of unsignalized RCUTs.[1]

Parameter	North Carolina	Maryland	Missouri
Number of RCUT sites	13	9	5
Type of traffic control	Stop	Merge	Stop
Decrease in total crashes	27%	44%	35%
Decrease in injury crashes	51%	42%	54%

More recently, RCUTs were featured in the FHWA Every Day Counts 2 program, as well as in projects to develop informational videos, capacity models for the *Highway Capacity Manual*, and informational guides for planners and designers.[2] Some States have also sponsored meaningful research on RCUT operations, and, as previously discussed, thoroughly researched the safety of unsignalized RCUTs. Although research and experience support the implementation of signalized RCUTs to improve traffic operations, research was needed on the safety effectiveness.

The objective of this evaluation was to develop a crash modification factor (CMF) for the replacement of a traditional signalized intersection with a signalized RCUT. The evaluation was also intended to conduct a qualitative analysis of crash data at signalized RCUTs to provide information to designers on expected crash patterns and trends. The evaluation considered 28 signalized RCUT sites across 5 States to understand its safety effectiveness. Finally, the evaluation provided a range of B/C ratios for signalized RCUT installation. Achieving these objectives should help transportation agencies select appropriate locations to install signalized RCUTs to improve intersection safety and operations.

CHAPTER 2. LITERATURE REVIEW

Kramer first developed RCUT intersections in the mid-1980s.(1) A similar concept, called a J-turn intersection, was developed independently in Maryland in the late 1980s. Since the development of the concept, there has been a steady stream of published literature on the design. Recently, FHWA commissioned an exhaustive review of this literature for its *Restricted Crossing U-Turn Intersection Informational Guide*.(1) The Guide summarized the literature in nine chapters, including the following:

- Multimodal considerations.
- Safety.
- Operational characteristics.
- Operational analysis.
- Geometric design.
- Traffic control devices.
- Construction and maintenance.

The Guide posits that, while there is still much unknown about RCUTs, significant knowledge has been gained in the past 25 years that highway agencies can use to design and operate RCUTs.

The Guide found no previous papers making substantial contributions on the safety of signalized RCUTs. However, and as previously noted, the Guide did review three papers that made substantial contributions to the knowledgebase on the topic of the safety of unsignalized RCUT intersections.(1) The first of these three major studies was completed in North Carolina in 2010.(1) The authors examined 13 rural sites where a two-lane minor road met a four-lane divided major road. Before the conversion to an RCUT, the intersection used two-way stop control. STOP signs controlled the RCUT crossovers. The authors used comparison groups to account for other changes from the before to the after periods and used an empirical Bayesian (EB) method to account for potential regression to the mean. Total crashes decreased between 27 and 74 percent, depending on the analysis method employed. The number of fatal and injury, angle, and left-turn crashes decreased substantially with conversion to the RCUT design, while the number of sideswipe, rear-end, and other crashes decreased slightly or increased.

The second major study to examine the safety of unsignalized RCUTs was completed in Maryland in 2012.(3) The nine sites were like those in the North Carolina study, except the U-turn crossovers and minor street right turns had merges, while the left-turn crossovers had YIELD signs. The authors reported results from several types of analyses, but they considered an EB analysis with a calibrated safety performance function that produced a 44-percent decrease in total crashes from the before to the after period to be the most reliable.

Edara et al. produced the third major study to examine the safety of unsignalized RCUT intersections.(4) The five rural sites had STOP signs on the minor street approaches and crossovers before and after conversion to the RCUT design. The EB analysis procedure accounted for regression-to-the-mean bias using the crash prediction model from the *Highway Safety Manual*. The results from the Missouri study showed a 35-percent reduction in total crashes and a 54-percent reduction in injury crashes. Similar to the research conducted in North Carolina, researchers in Missouri observed a large reduction in angle crashes with RCUT installation.

CHAPTER 3. METHODOLOGY

OVERVIEW OF STUDY DESIGNS

Before–after and cross-sectional regression analyses are the two most common methodologies for developing CMFs for installed countermeasures using crash data. The preferred before–after method relies on recent countermeasure installations. This method uses the safety performance at a treatment site before countermeasure installation to predict what would have happened at the site without the countermeasure. Hauer's *Observational Before–After Studies in Road Safety* on before–after evaluations is still the primary guidance for those types of studies.[5] A cross-sectional analysis develops an equation to predict the number of crashes at highway locations, where the equation contains a term for the countermeasure of interest. Before–after studies have an advantage in that using the before-period data to predict what would have happened reduces much of the site-to-site variation that must be accounted for with cross-sectional regression analysis. Thus, before–after studies can provide powerful results with relatively low sample sizes when data are available from the specific timeframe and certain biases are mitigated.

The project team selected a before–after analysis for this evaluation due to the availability of RCUT treatment sites.

BEFORE–AFTER STUDY METHODS

Hauer describes four primary before–after analysis methods, each accounting for a different type of bias.[5] The following provides an overview of the four methods.

Naive Analysis

Naive analyses only adjust for a difference in the number of years of crash data from the before period to the after period.[5] Naive analyses are not trustworthy when more serious biases may be present. Therefore, the naive analysis results are not presented.

Adjustment for Traffic Volume

Adjustments for changes in traffic volume are a standard feature of many crash studies, as traffic volume is highly related to crash frequency. The method is described in Chapter 8 of Hauer.[5] Adjusting for traffic volume accounts for some threats to study validity; however, this method does not account for other events that would cause a bias in study results. Therefore, the project team relied more heavily on the results from other methods in drawing conclusions.

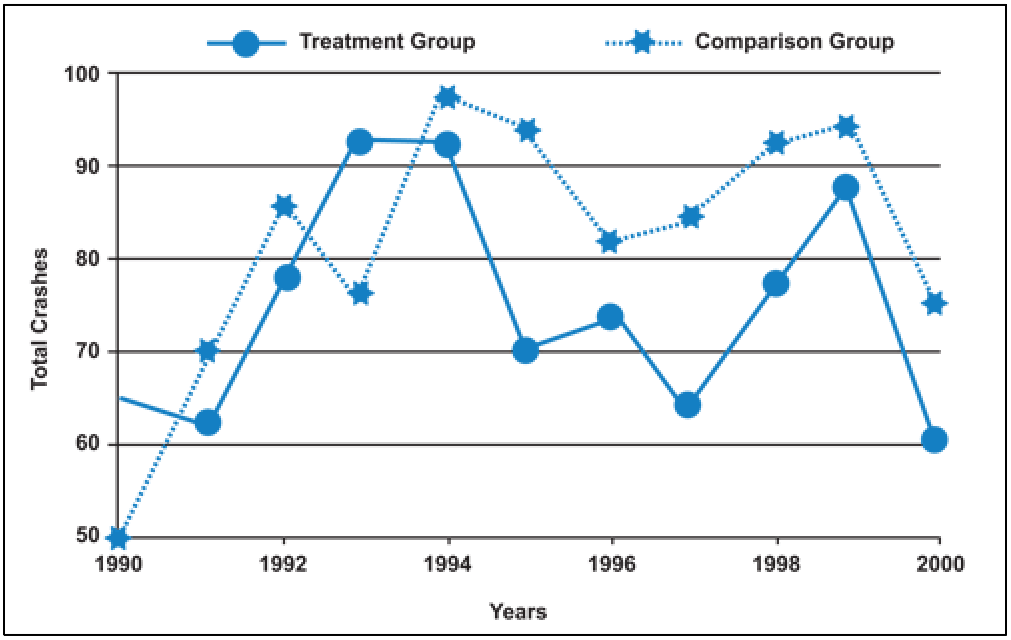
Many CMF studies do not report the results from an analysis adjusting for traffic volume. However, it is an important step when using comparison groups to account for simultaneous event bias (detailed in the following section) does not include an adjustment for changing traffic volumes. Hauer does not provide a method for estimating the CMF and the standard deviation (SD) of the CMF while adjusting for both comparison groups and changing traffic volume.[5] For the purpose of this study, the project team analyzed the adjustment for traffic flow and the adjustment for comparison groups separately.

As detailed in the following chapters, traffic volumes in the dataset were fairly constant and experienced small changes across years at most sites over the study period. This may be due to stable volumes at the sites or a result of traffic volume estimates based on interpolations from relatively rare field counts. Due to the small changes in traffic volume from year to year and a lack of calibrated safety performance functions for signalized intersections in each of the four studied States, the project team assumed a proportional relationship between crashes and volume for this evaluation. Additionally, the traffic volume adjustment method should properly consider a coefficient of variation in the traffic volume data, which is a measure of how much traffic volumes at the site vary from day to day. Coefficients of variation were not available for the treatment sites in this evaluation, so the project team used a middle range value of 0.1 for the calculations.(5)

Comparison Group

One of the most important potential biases to a before–after crash study are events that occur during the study periods at the treatment sites that change the predicted number of crashes regardless of the treatment. Common simultaneous event biases include significant weather events like hurricanes or ice storms and changes in vehicle and crash reporting characteristics. To account for simultaneous event biases, the project team used comparison sites as described by Hauer.(5) The team identified four potential comparison sites for each treatment site. Potential comparison sites were large surface street intersections (to ensure adequate sample sizes) near the treatment site (to ensure that the same events occurred at both places). Aerial photographs were reviewed to ensure the sites did not undergo any discernible treatment during the study period.

Hauer recommends testing potential comparison sites prior to an analysis.(5) The test consists of calculations of odds ratios of the changes in crash frequency at the treatment sites and potential comparison sites from one year to the next before the countermeasure was installed. If this calculation is performed over a series of years before the treatment was installed, a look at the mean of the odds ratios and the SD of the mean will be revealing. The mean should be close to 1.0—and the SD close to 0—for successful comparison sites that are tracking closely to the treatment sites in the years before countermeasure installation. This concept is illustrated in figure 4.



Source: FHWA.

Figure 4. Chart. Hypothetical time series plot of treatment and comparison group.[(6)]

Figure 5 illustrates how the CMF is estimated using the comparison group method.[(5)]

$$\pi = \mathrm{K} \times \left(\frac{N}{M}\right)$$

Figure 5. Equation. Comparison group method.

Where:

π = predicted crashes in the treatment group in the after period had the treatment not been implemented.
M = crashes in the comparison group before the implementation of the treatment.
N = crashes in the comparison group after the implementation of the treatment.
K = crashes in the treatment group before the implementation of the treatment.

Figure 6 illustrates the next step in the process.

$$Var(\pi) = \pi^2 \left(\frac{1}{K} + \frac{1}{M} + \frac{1}{N} + Var(\omega)\right)$$

Figure 6. Equation. Computing the variance of the sequence of sample odds ratios.

Where $Var(\omega)$ is variance of the sequence of sample odds ratios that are calculated based on the time series of crash counts from the treatment and comparison sites.

As mentioned by Hauer, for an ideal comparison group, the mean of the odds ratios is very close to 1, and $Var(\omega)$ is very close to 0.[5] Figure 7 and figure 8 show how to estimate the CMF and variance.

$$CMF = \frac{\frac{\lambda}{\pi}}{\left(1 + \frac{Var(\pi)}{\pi^2}\right)}$$

Figure 7. Equation. CMF estimate.

$$Var(CMF) = \frac{CMF^2\left(\frac{Var(\lambda)}{\lambda^2} + \frac{Var(\pi)}{\pi^2}\right)}{\left(1 + \frac{Var(\pi)}{\pi^2}\right)^2}$$

Figure 8. Equation. Variance estimate.

Where:

λ = crashes in the treatment group after the implementation of the treatment.

Var (λ) = λ assuming reasonably that the crash frequency follows a Poisson distribution.

The project team used a before–after analysis with comparison sites for this evaluation. The method accounts for simultaneous event biases, which the project team thought to be the most threatening potential bias to the evaluation. The method relies on high-quality comparison sites, but, as mentioned, the quality of the comparison sites is testable and is provided later in this report.

Empirical Bayesian

Before–after studies most commonly use the EB method to account for regression-to-the-mean bias. Regression to the mean is the tendency of an abnormally high or low value recorded in one time period to return to a value much closer to the long-run average in the next time period. This is important in most safety studies because transportation agencies typically install countermeasures at high-crash locations and must account for regression to the mean in the after period. Fortunately, regression to the mean was not an important threat to the validity of this evaluation because the treatment sites were not chosen on the basis of any type of hazardous site identification process. Instead, the agencies selected the sites for RCUT installation primarily to relieve congestion. Therefore, the project team did not employ the popular EB method described in Chapter 11 of Hauer.[5] With complex intersections spread over four States, an EB analysis would have been very complicated for this evaluation. The comparison site method proposed herein efficiently accounted for the most important potential study bias—simultaneous events—using comparison sites that passed a quality test. Chapter 4 describes this comparison site method in detail.

CHAPTER 4. SELECTION OF BEST COMPARISON SITES

The quality of the result from the comparison group method relies on the selection of high-quality comparison sites. The project team collected data from four States: Alabama, North Carolina, Ohio, and Texas. To ensure high quality, the project team undertook the following steps during comparison site selection:

1. Identified large intersections near the treatment sites using aerial photographs to serve as possible comparison sites. They identified four potential comparison sites for each RCUT. The project team examined the available time series of aerial photos to ensure there were no major changes to the roadways or surroundings near the potential comparison sites during the study periods.

2. Contacted the respective State agencies to confirm the comparison sites were appropriate in terms of the trends in traffic volumes and the surrounding environment.

3. Obtained crash data for the comparison sites and the RCUTs from the State agencies.

4. Employed the odds ratio test (previously discussed) to determine the appropriate set of comparison sites for each treatment site. The project team tested each potential comparison site separately and all combinations of comparison sites.

5. In cases where odds ratio tests showed that all four potential comparison sites—and all combinations of those four—were unfit for use, computed odds ratios for the comparison sites associated with other treatment sites in the same metropolitan area.

After identifying the best comparison sites and computing CMFs for each individual treatment site, the project team analyzed groups of sites. Analyzing groups of sites boosted sample sizes and generally decreased the SDs of the estimates of the CMFs. The project team analyzed the following:

- Groups of treatment sites from the same State.

- Groups of treatment sites with the longest available before periods (Alabama, North Carolina, and Ohio).

- All sites together.

In all group analyses, the project team used all years of available data at each site. This meant that the group results are somewhat biased in favor of the sites with more data.

A difficulty in analyzing groups of sites was determining the best set of comparison sites. The project team again used odds ratio tests to identify the best set of comparison sites, starting its search with the best comparison sites identified during the individual site analyses.

A group analysis built the sample size and averaged the different sites to overcome the physical or data shortcomings present at each site. The group analyses resulted in the overall signalized

RCUT CMF that is considered a predictor of future general signalized RCUT safety performance.

SUPPLEMENTAL ANALYSIS

In addition to the before–after analyses of all reported crashes previously discussed, the project team conducted a before–after analysis of fatal and injury crashes. The sample of fatal and injury crashes was much smaller than the sample of all crashes, which further emphasized the importance of the group analyses.

The project team analyzed other key crash variables at the individual site and group levels, including day/night and crash type, to determine any changes between the before and after periods. The variable analyses help signalized RCUT designers identify any issues with early installations.

After the project team estimated the CMF for signalized RCUT installation, they developed a B/C ratio for the improvement. Participating States provided information on the cost of the RCUT installation at each study site. The project team based the benefit on the estimated crash reduction (if any) and on an estimate of the travel time savings experienced by motorists using the RCUT. They derived the B/C ratio employing similar methods used in CMF research and development.

CHAPTER 5. RESULTS

SITES

The project team identified 28 signalized RCUTs from 5 States (Alabama, Michigan, North Carolina, Ohio, and Texas). After some investigation, they eliminated two sites in Michigan because the RCUTs were installed in the mid-1990s, and crash data were no longer available from the before period. The project team obtained aerial photos of the remaining 26 sites to review for substantial changes in the roadways or surrounding land uses between the before period and after period. Such changes would likely confound the RCUT installation and make determination of the effects of the RCUT installation impossible. On this basis, the project team eliminated 15 sites. The most common confounding change resulting in site elimination was that the RCUT was installed at the same time the intersection traffic control changed from unsignalized to signalized. Table 3 identifies the final sites selected for evaluation, which included 11 sites in 4 States where signalized RCUTs were installed during years lending themselves to evaluation, and the RCUT installation was the only substantial change at the location.

Table 3. RCUT treatment sites.

State	County	Intersection
Alabama	Houston	US-231 NW of Dothan at Plum Rd.
Alabama	Houston	US-231 NW of Dothan at Retail Dr.
North Carolina	New Hanover	US-421 south of Piner Rd., Wilmington
Ohio	Butler	OH-4 in Hamilton at Symmes Rd.
Ohio	Butler	OH-4 in Hamilton at Tylersville Rd.
Ohio	Butler	OH-4 in Hamilton at Hamilton-Mason Rd.
Texas	Bexar	US-281 north of San Antonio at Evans Rd.
Texas	Bexar	US-281 north of San Antonio at Stone Oak Pkwy./TPC Pkwy.
Texas	Bexar	Loop-1604 west of San Antonio at New Guibeau
Texas	Bexar	Loop-1604 west of San Antonio at Shaenfield
Texas	Travis	TX-71 in Del Valle east of Austin at FM-973/Fallwell Ln.

Table 4 shows the major geometric characteristics of the treatment sites after RCUT construction. Two numbers in a cell means that two approaches to the intersection had those two different values for the parameter. The treatment sites have much in common besides having signalized RCUTs. They are all in suburban areas, on four-lane or six-lane divided arterials, and characterized by high-speed traffic and minimal crossing pedestrians; as a result, the CMFs emerging from this effort will apply to this type of site. Most of the signalized RCUT installations of which the project team is aware that are planned for the next few years share these characteristics.

Table 4. Important design features of sites after RCUT installation.

Parameter	1	2	3	4	5	6	7	8	9	10	11
Intersection angle (degrees)	90	70 80	70 80	80	60	80	90	90	70	90	70 80
Main street speed limit (mph)	45	40	45	50	50	55	60	60	60	60	60 65
Minor street speed limit (mph)	30	20	25	40	40	40	40	40	35	40	35 55
Main street number of through lanes each direction	3	3	2	3	3	2	2 3	2	2 3	3	3
Minor street number of lanes entering intersection each direction	2	1 2	2	3	2 3	2 3	3	3	2	3	1 2
North or west left-turn crossover number of lanes	2	2	1	1	1	1	2	2	2	N/A	1
South or east left-turn crossover number of lanes	2	1	1	1	1	1	2	2	N/A	2	1
North or west U-turn crossover number of lanes	1	1	1	2	2	1	2	2	2	N/A	2
South or east U-turn crossover number of lanes	1	1	1	2	1	2	2	2	N/A	2	2
Distance center of intersection to north or west U-turn crossover (ft)	870	930	890	850	950	950	1,080	1,100	1,560	N/A	1,720

Parameter	1	2	3	4	5	6	7	8	9	10	11
Distance center of intersection to south or east U-turn crossover (ft)	750	620	1,290	830	1,000	1,060	1,080	1,310	N/A	1,340	1,180
Major street channelized right turns	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Minor street channelized right turns	No	No	No	No	No	No	Yes	Yes	No	Yes	No
Crosswalks at main intersection	Yes	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes
Major street median width (ft)	40	40	26	46	34	46	52	52	73	71	58
Minor street median width (ft)	14	12	12	12	12	12	21	2–42	15	4	4
Other interesting design features	None	North U-turn at signal-ized inter-section	Sharp curve on west leg	None	None	None	None	None	3-legged	3-legged	Signal-ized left-turn cross-over west of main inter-section

N/A = not applicable; 1 = Alabama-Plum; 2 = Alabama-Retail; 3 = North Carolina; 4 = Ohio-Symmes; 5 = Ohio-Tylersville; 6 = Ohio-Hamilton-Mason; 7 = Texas-Evans; 8 = Texas-Stone Oak; 9 = Texas-New Guibeau; 10 = Texas-Shaenfield; 11 = Texas-71.

After identifying treatment sites and potential comparison sites, the project team contacted officials in each of the four States for the necessary data. State officials provided information on the RCUTs' construction dates and crash data for the most recent 5 full years before the start of construction, through the construction year(s), up to the most recent available data. The project team decided 5 years of before data was desirable to boost the sample size and to provide the longest possible test of the quality of the comparison sites. The project team also reviewed the available aerial photos for each treatment site to ensure that no substantive changes had occurred during the 5-year before period.

States also provided data on all reported crashes that occurred within 1,500 ft of the main intersection along the major street and within 500 ft along the minor street for treatment sites. These distances ensured that all crashes related to the RCUT—especially those at the U-turn crossovers—were included in the dataset, while midblock crashes were excluded. The project team adjusted the data collection boundary in several instances due to geometric design differences. Two sites in Texas had longer distances to crossovers, so the boundary was extended. Two Alabama sites—US-231 northwest of Dothan at Plum Road and Retail Drive—had other intersections 1,200 ft and 1,000 ft from the main intersections. Thus, the team set the data collection boundary at 1,000 ft at Plum Road and 800 ft at Retail Drive.

Additionally, States provided traffic volume data at and around each treatment site and information on changes to the intersection geometry accompanying the RCUT construction. The States also provided the following crash reporting thresholds:

- Alabama: By law, there is no crash reporting threshold.
- North Carolina: $1,000 total crash damage or a reportable injury.
- Ohio: Fatality, injury, or $1,000 or more in property damage.
- Texas: Fatality, injury, or $1,000 or more in property damage to any one person's property.

The thresholds did not change in any State during the study period. It is important to note the difference between Alabama's threshold and the other three States' threshold.

In the course of contacting officials in the 4 States for crash and other data for the 11 RCUT treatment sites and associated potential comparison sites, the project team also asked the officials why the RCUTs were installed. This information was important when selecting the analysis methodology. If treatments were installed as the result of a high-crash site identification process, regression to the mean is likely to result in a natural decrease in the number of crashes in the after period; methods to adjust for this threat should be used. On the other hand, if the treatments were installed for reasons other than to mitigate safety concerns, regression to the mean is not a potential bias to the study. Regression to the mean may occur from the before period to the after period, but it is just as likely to result in an increase as a decrease in the number of crashes. In this case, methods to adjust for regression to the mean are not needed and may be harmful if they are not executed appropriately. The responding officials in all four participating States indicated that all RCUTs were chosen for operational reasons, including to accommodate future growth in traffic, not due to a high number of crashes. All officials indicated safety was considered and that RCUTs were expected to perform well on the safety dimension but was not a case of selecting the design as a safety treatment for an identified high-crash site.

Table 5 summarizes the crash data provided for the treatment sites. There were some deviations from the desired 5 years of before-period data at some sites due to data availability, most prominently at the Texas sites where no crash data were available before 2009. Also, before-period data from 2003 to 2006 were collected at the Hamilton-Mason Road site in Ohio because crash data from 2007 to 2009 had reporting inconsistencies. The project team collected the oldest 5 years of after-period data available for the North Carolina site.

One way to confirm whether regression to the mean is a serious threat to the validity of an analysis is to look for a significant drop in crashes on average in the year before treatment compared to previous years. The decision to install the countermeasure is likely made without benefit of the crash data from that last year before construction, so if regression to the mean were to manifest in the time series, it would likely do so starting in that year. The project team was able to examine this trait at 8 of the 11 treatment sites, since data for Ohio-Hamilton-Mason were not available in the year before construction, and only 1 year of before-period data was available at the Texas-Evans and Texas-Stone Oak sites. Table 6 shows a summary of the year before construction data and reveals that only two of the eight sites—Alabama-Retail and Texas-Shaenfield—had a significant drop in crashes during the year before construction. At the other six sites, the number of crashes either matched the average from the previous years or rose. It appears that regression to the mean was indeed not a serious threat to the validity of this analysis.

Table 5. Reported crashes by year for the RCUT treatment sites.

Site	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
AL-Plum	--	--	38	31	19	45	35	*	*	*	14	26	--
AL-Retail	--	--	13	12	10	6	3	*	*	*	0	3	--
NC	44	32	46	38	40	*	36	25	36	26	36	--	--
OH-Symmes	--	--	--	24	24	19	24	22	*	*	27	43	--
OH-Tylersville	--	--	--	22	24	16	16	26	*	*	16	8	--
OH-Hamilton-Mason	--	16	12	19	33	--	--	--	*	*	2	7	--
TX-Evans	--	--	--	--	--	--	--	103	*	97	93	135	--
TX-Stone Oak	--	--	--	--	--	--	--	42	*	40	44	85	--
TX-New Guibeau	--	--	--	--	--	--	--	52	51	*	32	30	--
TX-Shaenfield	--	--	--	--	--	--	--	50	31	*	36	46	--
TX-71	--	--	--	--	--	--	--	41	40	30	45	*	16

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.
*Construction years.
--No data.

Table 6. Crash frequency at RCUT treatment sites in the year before construction compared to previous years.

Site	Average Number of Crashes per Year in Years Before the Last Year Prior to Construction	Number of Crashes in the Last Year Prior to Construction
AL-Plum	33	35
AL-Retail	10	3
NC	40	40
OH-Symmes	23	22
OH-Tylersville	20	26
TX-New Guibeau	52	51
TX-Shaenfield	50	31
TX-71	37	45

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.

Adjustment for Traffic Volume

This section reports the results from the analysis that adjusted for an estimated change in traffic volume between the before and after periods. Traffic volume may change due to development in the area, economic changes that affect travel, or changes in overall levels of motorization. Except for the Texas-71 site, the project team obtained traffic volume data from at least one official count or estimate by the responsible agency for at least one station near each site in the before period and the after period. If the responsible agency provided a count or estimate at more than one station and/or year in a before or after period at a particular site, the project team averaged all available counts. Table 7 summarizes the traffic volume data. The data for the Texas-Evans and Texas-Stone Oak sites are from counts on the major and minor streets, while count data for the other sites are from the major street only.

Table 7. Traffic volume data for each site (in thousands of vehicles per day).

Site	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
AL-Plum	26	26	27	27	25	25	25*	26*	25*	27	27
AL-Retail	36	36	36	36	36	35	36*	37*	36*	39	37
NC	35	--	37	--	38*	--	36	--	38	--	--
OH-Symmes	20	--	--	--	19	--	--	*	*	25	--
OH-Tylersville	20	--	--	--	19	--	--	*	*	17	--
OH-Hamilton-Mason	12	--	--	--	12	--	--	*	16*	17	--
TX-Evans	--	--	93	102	112	102	104	133*	110	110	110
TX-Stone Oak	--	--	84	80	78	80	80	80*	89	89	89
TX-New Guibeau	--	--	61	71	69	71	71	65	80*	83	83
TX-Shaenfield	--	--	61	66	69	67	66	50	70*	79	79
TX-71	10	9	9	10	11	--	10	10	10	10	12*

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.
*Construction years.
--No data.

Table 8 shows the results from the analysis of all crashes after accounting for changes in traffic volumes from the before period to the after period. The safety effect is represented by a CMF. The crash reduction factor (CRF) is calculated as 1 minus the CMF value, converted from a proportion to a percentage. As discussed in the methodology section, a CMF equal to 1.0 implies that the treatment is not expected to change the number of crashes, while a CMF below 1 implies that the treatment is expected to reduce crashes. There was no available traffic volume estimate for the Texas-71 site; therefore, the project team could not compute CMF with this method.

Table 8 also shows the estimated SD of each CMF, which can be used to produce an approximate confidence interval for the CMF and determine whether it is significantly different from 1.0 at a particular significance level. If a CMF is 1 SD from 1.0, that corresponds to a 68-percent confidence level that the actual value is different from 1.0. If a CMF is 1.96 SDs from 1.0, that corresponds to a 95-percent confidence level. Among other things, the SD of a CMF is a useful indicator of the adequacy of the sample size, with small SDs usually associated with large samples of crashes.

As shown in table 8, eight sites had a CMF less than 1.0, and two sites had CMF values greater than 1.0. The North Carolina site, both Alabama sites grouped together, and all three Ohio sites grouped together had CMF values well under 1.0, while the Texas sites as a group had a CMF close to 1.0. All 10 sites grouped together had a CMF of more than 1.0, due to the influence of the large sample size from the Texas-Stone Oak site sample size. SDs were reasonable, ranging from 0.09 to 0.25.

The results in table 8 are based on the sums of the traffic volumes from the individual sites. This gives rise to the possibility that the results were skewed by higher volume sites. To account for this possibility, the project team reanalyzed the last five rows in table 8 using volume indices rather than totals (i.e., normalizing the volume at each site in the before period to a value of 1.0). The reanalysis provided only minor changes in the CMFs and the SDs of the CMFs, suggesting that summing the volumes was an acceptable technique for this evaluation.

Table 8. Results from traffic volume analysis of each site and groups of sites.

Site	Before-Period Crashes	Before-Period Traffic Volume (Vehicle/Day)	After-Period Crashes	After-Period Traffic Volume (Vehicle/Day)	Percent Change in Traffic Volume	CMF	SD of CMF
AL-Plum	168	26,000	40	27,000	3	0.56	0.12
AL-Retail	44	36,000	3	38,000	6	0.15	0.09
NC	200	36,000	159	37,000	3	0.76	0.13
OH-Symmes	113	20,000	70	25,000	25	1.20	0.24
OH-Tylersville	104	20,000	24	17,000	−13	0.64	0.17
OH-Hamilton-Mason	80	12,000	9	17,000	48	0.15	0.05
TX-Evans	103	104,000	325	110,000	6	0.97	0.17
TX-Stone Oak	42	80,000	169	89,000	11	1.16	0.25
TX-New Guibeau	103	68,000	62	83,000	22	0.48	0.10
TX-Shaenfield	81	58,000	82	79,000	36	0.72	0.15
All AL	212	62,000	43	65,000	5	0.47	0.10
All OH	297	50,000	103	59,000	19	0.67	0.12
All TX except TX-71	329	310,000	638	361,000	16	0.98	0.15
AL, NC, and OH	709	148,000	305	161,000	9	0.75	0.12
All except TX-71	1,038	458,000	943	522,000	14	1.09	0.16

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.

Comparison Groups

The primary analysis method in this evaluation used comparison sites to adjust for the possibility of changes during the study period, such as development patterns, significant weather events, driver behavior, vehicle fleets, and crash reporting tendencies. As discussed in the methodology section, the key to a successful comparison site analysis is to find comparison sites that match the crash patterns of the treatment sites year by year in the before period. It is believed that the comparison sites change year by year in the after period, reflecting what would have happened at the treatment sites if the treatment had not been installed.

The project team selected comparison sites using the following criteria:

- Geographically located in proximity to the treatment site to be affected by the same trends.
- Geographically located far enough from the treatment site so as not to be affected by the treatment itself.
- Suitable crash sample.
- No obvious changes (e.g., large development or construction projects) between the before and after periods that would affect the crash pattern at a comparison site.
- Sites similar to the treatment sites in terms of design, such as large signalized intersections.

The project team narrowed the list of potential comparison sites using the time series of aerial photos available via the Internet. This review revealed construction or development at many of the potential comparison sites during the time periods of interest, thus disqualifying those sites from further analysis. The project team consulted with local or State transportation officials responsible for the remaining potential sites to gather additional input on high-quality sites.

Table 9 provides a list of potential comparison sites that met the criteria to warrant the collection of crash data. The before and after periods of crash data collected at all comparison sites were equal to the periods for the corresponding treatment site. There were four potential comparison sites for each treatment site.

Table 9. Potential comparison sites.

RCUT Treatment Site	Potential Comparison Site 1	Potential Comparison Site 2	Potential Comparison Site 3	Potential Comparison Site 4
US-231 NW of Dothan at Plum Rd.	US-231 NW of Dothan at Redmond Rd.	US-231 NW of Dothan at John D. Odom Rd.	US-231 NW of Dothan at University Dr.	US-231 NW of Dothan at County Road 59 and Midtown Ave.
US-231 NW of Dothan at Retail Dr.	US-231 SE of Dothan at Ross Clark Cir.	US-231 NW of Dothan at Murphy Mill Rd.	US-231 NW of Dothan at Napier Field Rd.	US-231 NW of Dothan at North Cherokee Ave.
US-421 south of Piner Rd., Wilmington	US-421 at Sanders Rd., Wilmington	US-421 at Silva Terra Dr., Wilmington	US-421 at Myrtle Grove Rd., Wilmington	US-421 at Sea Breeze, Wilmington
OH-4 at Symmes Rd., Hamilton	OH-4 Dixie Hwy. and Ross Rd. in Fairfield	OH-4 Dixie Hwy. and Seward Rd., Fairfield	OH-4 Port Union Rd., Hamilton	South Gilmore Rd. and Mack Rd., Fairfield
OH-4 at Tylersville Rd., Hamilton	OH-747 Princeton Glendale Rd. and Tylersville Rd., West Chester Twp.	South Ross Rd. and Mack Rd., Fairfield	OH-747 Princeton Glendale Rd. and Union Centre Blvd., West Chester Twp.	OH-747 Princeton Glendale Rd. and Port Union Rialto, West Chester Twp.
OH-4 at Hamilton-Mason Rd., Hamilton	OH-747 Princeton Glendale Rd. and Hamilton-Mason Rd., West Chester Twp.	OH-4 and Hamilton Princeton Rd., Hamilton	OH-4 Hamilton-Middletown Rd. at Indian Meadows Dr., Hamilton	Princeton Rd. and Morris Rd., Hamilton
US-281 and Evans Rd. north of San Antonio	North of San Antonio at Brook Hollow Blvd. and Hemier Rd.	North of San Antonio at Bitters Rd. and Hemier Rd.	North of San Antonio at South Tower Dr. and West Bitters Rd.	North of San Antonio at West Ave. and West Blanco Rd.
US-281 north of San Antonio at Stone Oak Pkwy./TPC Pkwy.	US-281 north of San Antonio at Bulverde Rd.	US-281 north of San Antonio at Overlook Pkwy.	North of San Antonio at TPC Pkwy. and Bulverde Rd.	North of San Antonio at Stone Oak Pkwy. and Canyon Golf Rd.

RCUT Treatment Site	Potential Comparison Site 1	Potential Comparison Site 2	Potential Comparison Site 3	Potential Comparison Site 4
Loop-1604 west of San Antonio at New Guibeau	TX-16 Bandera Rd. at Tezel Rd. and Prue Rd., San Antonio	NW of San Antonio at Scenic Loop Rd. and Bandera Rd.	NW of San Antonio at Leslie and Bandera	NW of San Antonio at West Hausman Rd. and Babcock Rd.
Loop-1604 west of San Antonio at Shaenfield Rd.	TX-16 Bandera Rd. at Mainland Dr.	Loop-1604 west of San Antonio at Wiseman Blvd.	West of San Antonio at Alamo Pkwy. and Culebra Rd.	Loop-1604 west of San Antonio at Military Dr. West
TX-71, Del Valle, east of Austin at FM-973/Fallwell Ln.	TX-973 at Webberville Rd., Austin	TX-973, Del Valle, east of Austin at Pearce Ln.	TX-973, Del Valle, east of Austin at Burleson Rd.	TX-973 at Clinger Rd., Austin

OH = Ohio; TX = Texas.

The project team employed the odds ratio test, as Hauer described, to determine the best comparison site(s) for each treatment site or group of treatment sites.(5) The odds ratio test measured the change in crash frequency at a comparison site from one year to the next relative to the change in crash frequency at the treatment site. The project team employed the odds ratio test for each available pair of years in the before period at each site and group of sites. Thus, the project team calculated four odds ratios at most at each site, with 5 years of crash data at most in the before period. An odds ratio of 1.0 meant that the comparison and treatment datasets moved together in complete harmony. The project team examined the mean of the odds ratios calculated, as well as the SD of that mean, with desired values of 1.0 for the mean and 0 for the SD. For each individual treatment site, the project team conducted the odds ratio test on each of its potential comparison sites, on potential comparison sites identified for nearby treatment sites, and on each combination of potential comparison sites. The project team used a combination of the best comparison sites found for each individual treatment site for each group of treatment sites.

In this dataset, the project team conducted tests of comparison sites for 9 of the 11 sites where at least 2 years of before-period data were available. They did not test Texas-Evans Road and Texas-Stone Oak comparison sites because only 1 year of before data were available at those sites. Rather, the project team conducted an analysis using all four comparison sites.

Table 10 displays the test results for the best comparison site or sites with each of the nine other treatment sites. To illustrate the quality of the comparison sites, figure 9 and figure 10 show the correspondence between the numbers of crashes per year in the before period at treatment and chosen comparison sites for the Ohio-Symmes site and for the set of all treatment sites, respectively. Most of the nine treatment sites had good to excellent comparison site(s), with means of the odds ratios within 0.1 of 1.0, SDs of the means less than 0.4, and relatively high sample sizes. The sites with the strongest comparison sites included the following:

- Alabama-Plum: Retail 2 and 4.
- Alabama-Retail: 1.

- North Carolina: 1 and 3.
- Ohio-Symmes: 1 and 3.
- Ohio-Tylersville: 1.
- Ohio-Hamilton-Mason: 2.
- Texas-New Guibeau: 1, 2, 3, and 4.
- Texas-Shaenfield: 1, 2, 3, and 4.
- Texas-71: 1, 3, and 4.

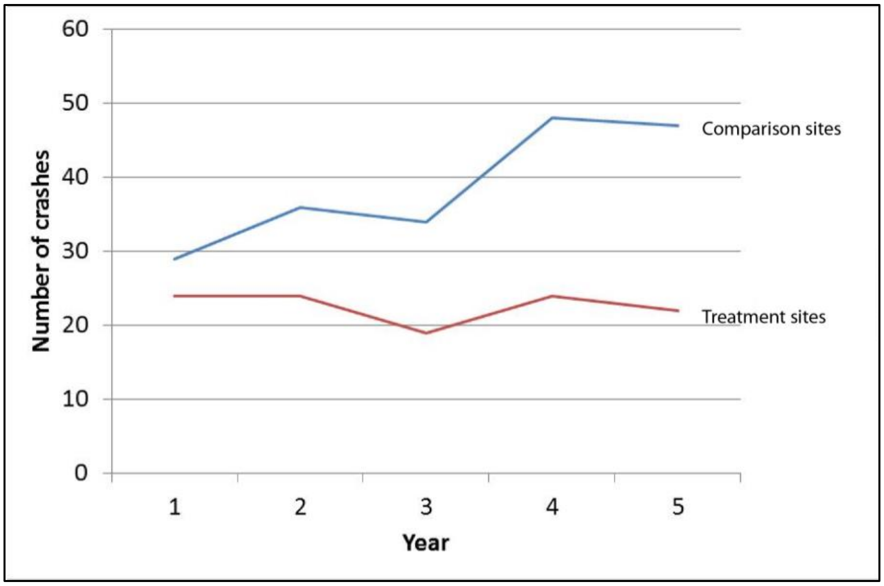
Note that, at the Alabama-Plum Road site, the best comparison site was from the Retail Drive set of potential sites. This is due to the proximity of those two treatment sites.

Table 10. Comparison site test results.

Site	Parameter	Year 1	Year 2	Year 3	Year 4	Year 5	Mean of Odds Ratio	SD of Mean
AL-Plum	Treat crashes	38	31	19	45	35	--	--
AL-Plum	Comp. crashes	48	46	33	49	52	--	--
AL-Plum	Odds ratio	--	1.12	1.09	0.60	1.30	1.03	0.30
AL-Retail	Treat crashes	13	12	10	6	3	--	--
AL-Retail	Comp. crashes	52	57	55	47	42	--	--
AL-Retail	Odds ratio	--	1.08	1.04	1.20	1.32	1.16	0.13
NC	Treat crashes	44	32	46	38	40	--	--
NC	Comp. crashes	43	46	37	45	61	--	--
NC	Odds ratio	--	1.40	0.54	1.40	1.23	1.14	0.41
OH-Symmes	Treat crashes	24	24	19	24	22	--	--
OH-Symmes	Comp. crashes	29	36	34	48	47	--	--
OH-Symmes	Odds ratio	--	1.15	1.10	1.04	1.00	1.08	0.07
OH-Tylersville	Treat crashes	22	24	16	16	26	--	--
OH-Tylersville	Comp. crashes	31	27	18	23	30	--	--
OH-Tylersville	Odds ratio	--	0.74	0.91	1.14	0.74	0.88	0.19
OH-Hamilton-Mason	Treat crashes	16	12	19	33	--	--	--
OH-Hamilton-Mason	Comp. crashes	17	15	21	20	--	--	--
OH-Hamilton-Mason	Odds ratio	--	1.03	0.79	0.51	--	0.78	0.26
TX-New Guibeau	Treat crashes	52	51	--	--	--	--	--
TX-New Guibeau	Comp. crashes	79	79	--	--	--	--	--
TX-New Guibeau	Odds ratio	--	0.99	--	--	--	0.99	--
TX-Shaenfield	Treat crashes	81	82	--	--	--	--	--
TX-Shaenfield	Comp. crashes	24	13	--	--	--	--	--
TX-Shaenfield	Odds ratio	--	0.81	--	--	--	0.81	--
TX-71	Treat crashes	41	40	30	45	--	--	--
TX-71	Comp. crashes	25	19	18	31	--	--	--
TX-71	Odds ratio	--	0.73	1.16	1.07	--	0.99	0.23
All AL	Treat crashes	51	43	29	51	38	--	--
All AL	Comp. crashes	100	103	88	96	94	--	--

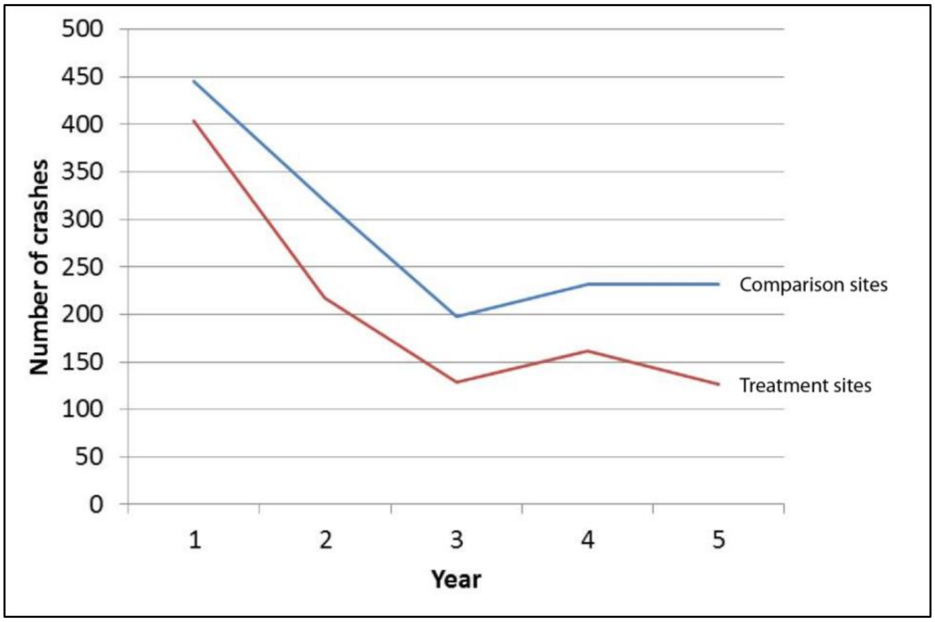
Site	Parameter	Year 1	Year 2	Year 3	Year 4	Year 5	Mean of Odds Ratio	SD of Mean
All AL	Odds ratio	--	1.18	1.21	0.60	1.27	1.07	0.31
All OH	Treat crashes	62	60	54	73	48	--	--
All OH	Comp. crashes	77	78	73	91	77	--	--
All OH	Odds ratio	--	1.02	1.01	0.90	1.25	1.04	0.15
All TX	Treat crashes	288	122	30	45	--	--	--
All TX	Comp. crashes	250	111	18	31	--	--	--
All TX	Odds ratio	--	1.04	0.63	1.06	--	0.91	0.24
AL, NC, and OH	Treat crashes	157	135	129	162	126	--	--
AL, NC, and OH	Comp. crashes	220	227	198	232	232	--	--
AL, NC, and OH	Odds ratio	--	1.19	0.90	0.92	1.27	1.07	0.19
All	Treat crashes	445	257	159	207	126	--	--
All	Comp. crashes	470	338	216	263	232	--	--
All	Odds ratio	--	1.24	1.02	0.93	1.43	1.16	0.23

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.
--No data.
Comp. crashes = comparison crashes.



Source: FHWA.

Figure 9. Graph. Crash frequency in the before period for the Ohio-Symmes treatment site and its recommended comparison sites.



Source: FHWA.

Figure 10. Graph. Crash frequency in the before period for all treatment sites and the recommended set of comparison sites.

The most important results from the evaluation—the results for all crashes using comparison sites to adjust for potential simultaneous event biases—are shown in table 11. This includes a statistic called Var{w}, which is an intermediate step in the calculation of the CMF and the SD of the CMF.(5) Anyone attempting to replicate the calculations will need Var{w}. For cases in which the Hauer formula suggested a negative value for Var{w}, the project team used a value of 0.0055, which is an intermediate value in the range suggested by Hauer.[5] Table 11 shows that eight sites had CMF values less than 1.0, and three sites had CMF values greater than 1.0. For nine sites, the CMF estimate was more than 1 SD away from 1.0. The group results showed CMF values less than 1.0. The CMF for all sites was 0.85 with an SD of 0.16, so the CMF was less than 1 SD away from 1.

Injury Crashes

The results in table 11 are based on all reported crashes. This subsection provides the results of the analysis on fatal and injury crashes. There were not enough fatal crashes in either the before or after periods to analyze in any detail. In the before period, the following was the fatal crash history at the treatment sites:

- Ohio-Hamilton-Mason: 1.
- Texas-Evans: 1.
- Texas-71: 3.

There were no fatal crashes at any treatment site after converting it to an RCUT.

The sample of injury crashes was large enough to allow for the same analyses as for all crashes, namely, traffic volume adjustment and comparison site adjustment.

Table 12 contains the results for the analysis of injury crashes adjusting for changes in traffic volume. The analysis again did not use data from the Texas-71 site because no after-period volume data were available. The results are very similar to the results of the traffic volume adjustment analysis on all crash data, with seven sites having a CMF less than 1.0 and two sites having a CMF greater than 1.0. The overall CMF from this analysis was 1.07 with an SD of 0.17.

Table 13 shows the results from odds ratio tests on the best comparison site or sites for each treatment site or group of treatment sites for injury crashes. The odds ratios and SDs were not as strong for injury crashes as all crashes because the sample sizes were smaller. Nonetheless, the odds ratios were mostly at 0.85 or above, and most SDs were below 0.3.

Table 11. Results from comparison site analysis of each site and groups of sites.

Site	Before-Period Treatment Crashes	Before-Period Comp. Crashes	After-Period Treatment Crashes	After-Period Comp. Crashes	Var{w}	CMF	SD of CMF
AL-Plum	168	228	40	104	0.0055	0.51	0.11
AL-Retail	44	253	3	97	0.0055	0.17	0.10
NC	200	232	159	264	0.075	0.64	0.18
OH-Symmes	113	194	70	78	0.0055	1.49	0.31
OH-Tylersville	104	129	24	50	0.0055	0.57	0.16
OH-Hamilton-Mason	80	79	9	17	0.02	0.47	0.20
TX-Evans	103	69	325	175	0.0055	1.20	0.23
TX-Stone Oak	42	53	169	168	0.0055	1.20	0.28
TX-New Guibeau	103	158	62	185	0.0055	0.50	0.10
TX-Shaenfield	81	37	82	49	0.0055	0.72	0.19
TX-71	156	93	16	23	0.0055	0.39	0.13
All AL	212	481	43	201	0.029	0.44	0.11
All OH	297	396	103	199	0.0055	0.98	0.16
All TX	485	410	654	600	0.022	0.88	0.15
AL, NC, and OH	709	1,109	305	664	0.011	0.71	0.09
All	1,194	1,519	959	1,264	0.036	0.85	0.16

Comp. crashes = comparison crashes.; AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.

Table 12. Results from traffic volume analysis of each site and groups of sites for injury crashes.

Site	Before-Period Crashes	Before-Period Traffic Volume (Vehicle/Day)	After-Period Crashes	After-Period Traffic Volume (Vehicle/Day)	Percent Change in Traffic Volume	CMF	SD of CMF
AL-Plum	25	26,000	6	27,000	3	0.55	0.25
AL-Retail	8	36,000	1	38,000	6	0.26	0.24
NC	91	36,000	33	37,000	3	0.34	0.08
OH-Symmes	48	20,000	31	25,000	25	1.24	0.32
OH-Tylersville	35	20,000	9	17,000	-13	0.69	0.26
OH-Hamilton-Mason	22	12,000	3	17,000	48	0.17	0.10
TX-Evans	29	104,000	116	110,000	6	1.20	0.28
TX-Stone Oak	17	80,000	61	89,000	11	1.00	0.28
TX-New Guibeau	40	68,000	17	83,000	22	0.33	0.10
TX-Shaenfield	27	58,000	27	79,000	36	0.70	0.20
All AL	33	62,000	7	65,000	5	0.48	0.20
All OH	105	50,000	43	59,000	19	0.78	0.18
All TX (except TX-71)	113	310,000	221	361,000	16	0.98	0.17
AL, NC, and OH	229	148,000	83	161,000	9	0.63	0.12
All (except TX-71)	342	458,000	304	522,000	14	1.07	0.17

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.

Table 13. Comparison site test results for injury crashes.

Site	Parameter	Year 1	Year 2	Year 3	Year 4	Year 5	Mean of Odds Ratio	SD of Mean
AL-Plum	Treat crashes	5	4	4	7	5	--	--
AL-Plum	Comp. crashes	5	4	5	8	6	--	--
AL-Plum	Odds ratio	--	0.69	0.83	0.68	0.79	0.75	0.08
AL-Retail	Treat crashes	4	1	2	1	0	--	--
AL-Retail	Comp. crashes	3	2	3	3	4	--	--
AL-Retail	Odds ratio	--	1.14	0.38	0.86	1.18	0.89	0.37
NC	Treat crashes	21	14	23	17	16	--	--
NC	Comp. crashes	12	9	5	6	7	--	--
NC	Odds ratio	--	0.97	0.29	1.29	1.01	0.89	0.42
OH-Symmes	Treat crashes	9	12	7	11	9	--	--
OH-Symmes	Comp. crashes	4	5	4	9	6	--	--
OH-Symmes	Odds ratio	--	0.70	1.02	1.07	0.67	0.86	0.21
OH-Tylersville	Treat crashes	6	10	9	4	6	--	--
OH-Tylersville	Comp. crashes	24	16	11	12	20	--	--
OH-Tylersville	Odds ratio	--	0.35	0.65	1.83	0.89	0.93	0.64
OH-Hamilton-Mason	Treat crashes	4	3	5	10	--	--	--
OH-Hamilton-Mason	Comp. crashes	11	11	20	16	--	--	--
OH-Hamilton-Mason	Odds ratio	--	0.94	0.85	0.35	--	0.71	0.32
TX-New Guibeau	Treat crashes	19	21	--	--	--	--	--
TX-New Guibeau	Comp. crashes	14	17	--	--	--	--	--
TX-New Guibeau	Odds ratio	--	0.98	--	--	--	0.98	--
TX-Shaenfield	Treat crashes	19	8	--	--	--	--	--
TX-Shaenfield	Comp. crashes	11	5	--	--	--	--	--
TX-Shaenfield	Odds ratio	--	0.89	--	--	--	0.89	--
TX-71	Treat crashes	21	17	10	23	--	--	--
TX-71	Comp. crashes	5	5	3	5	--	--	--
TX-71	Odds ratio	--	0.98	0.79	0.53	--	0.76	0.23
All AL	Treat crashes	9	5	6	8	5	--	--

Site	Parameter	Year 1	Year 2	Year 3	Year 4	Year 5	Mean of Odds Ratio	SD of Mean
All AL	Comp. crashes	5	4	5	8	6	--	--
All AL	Odds ratio	--	1.03	0.74	0.91	0.91	0.89	0.12
All OH	Treat crashes	19	25	21	25	15	--	--
All OH	Comp. crashes	39	32	35	37	26	--	--
All OH	Odds ratio	--	0.58	1.21	0.83	1.07	0.92	0.27
All TX	Treat crashes	100	46	10	23	--	--	--
All TX	Comp. crashes	146	27	3	5	--	--	--
All TX	Odds ratio	--	0.39	0.45	0.53	--	0.46	0.07
AL, NC, and OH	Treat crashes	45	43	48	49	36	--	--
AL, NC, and OH	Comp. crashes	56	45	45	51	39	--	--
AL, NC, and OH	Odds ratio	--	0.81	0.86	1.06	0.99	0.93	0.12
All	Treat crashes	149	90	60	73	36	--	--
All	Comp. crashes	205	74	51	59	43	--	--
All	Odds ratio	--	0.59	1.00	0.92	1.42	0.98	0.34

AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.
--No data.
Comp. crashes = comparison crashes.

The strongest comparison sites included the following:

- Alabama-Plum: Retail 3 and 4.
- Alabama-Retail: 3.
- North Carolina: 3 and 4.
- Ohio-Symmes: 3.
- Ohio-Tylersville: 1 and 3.
- Ohio-Hamilton-Mason: 1, 2, 3, and 4.
- Texas-New Guibeau: 2, 3, and 4.
- Texas-Shaenfield: New Guibeau 1 and 2.
- Texas-71: 3 and 4.

Note that, at the Alabama-Plum and Texas-Shaenfield sites, the best comparison sites were from the Retail Drive and New Guibeau sets of potential sites, respectively. This is due to the proximity of those treatment sites to each other.

Table 14 shows the results from the analysis of injury crashes using comparison sites. Note that some of the crash counts for groups of comparison sites do not match the sums of the component individual sites because comparison site data were not double-counted. The CMF values were much like those in the previous table of results, with eight sites having CMF values less than 1.0 and three sites having CMF values greater than 1.0. The CMF for all sites, 0.78, was lower than that for all crashes. This result suggests that signalized RCUTs have a larger positive effect on injury crashes than on property-damage-only crashes. The CMF for injury crashes at all sites was greater than 1 SD from a value of 1.0.

Table 14. Results from comparison site analysis of sites and groups of sites for injury crashes.

Site	Before-Period Treatment Crashes	Before-Period Comp. Crashes	After-Period Treatment Crashes	After-Period Comp. Crashes	Var{w}	CMF	SD of CMF
AL-Plum	25	28	6	13	0.0055	0.45	0.22
AL-Retail	8	15	1	6	0.0055	0.23	0.20
NC	91	39	33	32	0.0055	0.41	0.12
OH-Symmes	48	28	31	8	0.0055	1.90	0.75
OH-Tylersville	35	83	9	32	0.0055	0.62	0.25
OH-Hamilton-Mason	22	58	3	32	0.0055	0.22	0.13
TX-Evans	29	21	116	60	0.0055	1.27	0.39
TX-Stone Oak	17	20	61	56	0.0055	1.13	0.39
TX-New Guibeau	40	31	17	32	0.0055	0.38	0.13
TX-Shaenfield	27	16	27	28	0.0055	0.50	0.19
TX-71	71	18	11	7	0.0055	0.33	0.15
All AL	33	28	7	13	0.0055	0.41	0.19
All OH	105	169	43	72	0.0055	1.06	0.25
All TX	184	106	232	183	0.0055	0.88	0.15
AL, NC, and OH	229	236	83	117	0.0055	0.63	0.11
All	413	357	315	306	0.068	0.78	0.20

Comp. crashes = comparison crashes.; AL = Alabama; NC = North Carolina; OH = Ohio; TX = Texas.

Spatial Patterns

The crash data obtained for this evaluation specified location well enough to allow for a spatial patterns analysis. Notable clusters of crashes included the following:

- Alabama-Plum: Clusters of rear-end crashes southbound on the major street.
- North Carolina: Large clusters of rear-end crashes in both directions of the major street.
- Ohio-Symmes: A cluster of rear-end crashes northbound on the major street and a cluster of rear-end crashes eastbound on the minor street.
- Ohio-Tylersville: Smaller clusters of rear-end and sideswipe crashes in both directions on the major street.
- Texas-Evans: Large clusters of rear-end crashes in both directions of the major street, a cluster of sideswipe crashes northbound on the major street, and a cluster of crashes involving northbound left-turn vehicles.
- Texas-Stone Oak: Large clusters of rear-end crashes on the major street southbound.
- Texas-New Guibeau: Clusters of rear-end crashes northbound on the major street on the side with the stem of the T-intersection.
- Texas-Shaenfield: Clusters of rear-end crashes in both directions on the major street and notable clusters of sideswipe and fixed object crashes southbound on the major street on the side with the stem of the T-intersection.

Thus, with a few exceptions, the crash data mostly showed clusters of rear-end crashes occurring at the RCUT sites. These patterns are somewhat different from those seen at typical conventional intersections, which would tend to feature more prominent clusters of turning and angle crashes.

Other Variables

The collected data allowed for examination of other variables besides severity and location. The appendix provides more information on the changes to crash type, light, weather, road condition, and occasionally other variables (when available) from the before period to the after period at each site. The Alabama-Retail, Ohio-Hamilton-Mason, and Texas-71 sites did not have enough crashes in the after period to detect any important changes. Despite the available data at the Texas-Stone Oak site, no significant changes in the variables occurred at this site. Several important changes occurred at the remaining sites between the before and after periods, including the following:

- Alabama-Plum: The crash type changed drastically, from 68.5 percent right rear angle crashes in the before period to 52.5 percent rear-end center in the after period.
- Alabama-Plum: The percentage of daylight crashes decreased from 74.4 to 60.

- Alabama-Plum: The percentage of crashes in the rain decreased from 20.2 to 7.5.
- North Carolina: The percentage of left-turn, same roadway crashes decreased from 29 to 10.7.
- Ohio-Symmes: The percentage of fixed object crashes increased from 0 to 10.
- Ohio-Symmes: The percentage of wet crashes increased from 32.7 to 45.7.
- Ohio-Tylersville: The percentage of angle crashes decreased from 15.4 to 4.2.
- Ohio-Tylersville: The percentage of wet crashes decreased from 26 to 12.5.
- Texas-Evans: The percentage of same direction, both going straight, rear-end crashes increased from 11.7 to 22.8.
- Texas-Evans: The percentage of dark, no light crashes decreased from 15.5 to 4.9.
- Texas-New Guibeau: The percentage of same direction, both going straight, sideswipe crashes increased from 2.9 to 16.1, while the percentage of same direction, one straight, one stopped crashes decreased from 57.3 to 38.7.
- Texas-Shaenfield: The percentage of same direction, both going straight, sideswipe crashes increased from 2.5 to 19.5, while the percentage of same direction, one straight, one stopped crashes decreased from 60.5 to 24.4.
- Texas-Shaenfield: The percentage of dark, lighted crashes increased from 13.6 to 29.3.

The most prominent changes with RCUT installation appear to be decreases in angle crashes and increases in sideswipe crashes.

CHAPTER 6. ECONOMIC ANALYSIS

This evaluation included an economic analysis on the installation of a signalized RCUT. The results of this analysis can help inform transportation agencies on the benefits and costs of this countermeasure.

To conduct the analysis, the project team employed annualized benefits and costs. Benefits included fewer crashes and shorter travel times. The costs included construction of the RCUT and maintenance of the extra traffic signals required by the RCUT. These benefits and costs should entail the majority of all quantifiable impacts of RCUT installation. The analysis essentially estimated the effects of signalized RCUT installation at a site that has characteristics that are average compared to the 11 test sites in this research.

The project team obtained construction cost data for 9 of the 11 test sites, as shown in table 15. Officials in Alabama emphasized that cost estimates were for RCUT-related items only, while officials in Ohio stated that cost estimates included items that were indirectly related to the RCUT. In that regard, underestimates from Alabama might balance overestimates from Ohio and still provide what looks to be a reasonable average.

Table 15. Estimated construction cost by site.

Site	Estimated Construction Cost
AL-Plum	$500,000
AL-Retail	$500,000
OH-Symmes	$6,500,000
OH-Tylersville	$10,700,000
OH-Hamilton-Mason	$4,700,000
TX-Evans	$2,580,000
TX-Stone Oak	$2,580,000
TX-New Guibeau	$2,850,000
TX-Shaenfield	$2,850,000
Average	$3,750,000

AL = Alabama; OH = Ohio; TX = Texas.

The following assumptions were made during the analysis:

- All benefits and costs were in 2014 dollars.
- Inflation was not relevant to bring the construction costs in table 15 to 2014 dollars or to annualize other benefits and costs into the future.
- RCUTs have a 20-year useful life, like other intersection improvements.[(7)]
- There is a 7-percent-per-year discount rate.
- On average, the RCUT major street carries 52,000 vehicles per day.

- On average, the RCUT minor street carries 10,000 vehicles per day.
- There is no traffic growth during the analysis period.
- Thirty percent of daily traffic occurs during the 4 peak hours of the day.
- The RCUT saves 20 seconds per vehicle during the 4 peak hours of the day and has no net operational effect at other times of the day, in line with previous estimates of the effects signalized RCUTs.[1]
- Time savings are valued at $15 per hour, in line with typical economic analyses.
- There are 250 working days per year that experience time savings.
- Each extra traffic signal costs $5,000 per year to maintain and provide electricity.[8]
- Without the RCUT, crashes would have occurred at the same annual frequency as in the before period at the 11 test sites during the whole analysis period.
- The property-damage-only CMF was 0.85, equivalent to the total CMF in table 11.
- The injury and fatal CMF was 0.78, per table 14.
- The property-damage-only crash cost in 2014 was $18,000.[9,10]
- The injury and fatal crash cost in 2014 was $384,000.[9,10]

The analysis resulted in a $354,000 annualized construction cost. When added to the annual maintenance cost for three extra signals at $15,000, this yielded a total annualized RCUT cost of $369,000. For benefits, using several of the assumptions above, the project team estimated the operations to save 103 hours of motorist time per workday, which equates to $388,000 per year. The safety benefit was a savings of 3.0 property-damage-only crashes per year and 2.3 injury and fatal crashes per year, which results in an annual monetary savings of $948,000. Thus, the B/C ratio was 2.6 to 1.0 considering the safety benefits only and 3.6 to 1.0 considering the safety and operational benefits.

The U.S. Department of Transportation (USDOT) recommends testing the sensitivity of economic analysis results to differences in crash costs by examining the results with 0.57 and 1.41 times the recommended crash costs.[10] Table 16 provides the results from that test. Even at the low levels of crash cost, considering safety only, installing a signalized RCUT at sites like those tested under the assumptions previously listed will be beneficial, and at high crash cost levels, the effort is very beneficial.

Table 16. Sensitivity of B/C ratios.

Parameter	Recommended Crash Cost	Lower Crash Cost	Higher Crash Cost
2014 cost per property-damage-only crash	$18,000	$10,000	$25,000
2014 cost per injury crash	$384,000	$219,000	$541,000
B/C ratio including safety only	2.6	1.5	3.6
B/C ratio including safety and operations	3.6	2.5	4.7

CHAPTER 7. CONCLUSIONS

There are theoretical reasons to believe that signalized RCUT intersections would be safer than similar conventional signalized intersections, and previous research has shown that unsignalized RCUTs are generally safer than conventional unsignalized options. However, there has never been a study of the safety of signalized RCUT intersections. Therefore, the objective of this evaluation was to develop a CMF for signalized RCUT intersections and examine injury crashes, spatial patterns, and other crash variables.

This evaluation collected and analyzed crash data before and after conversion of 11 intersections from conventional to RCUT design. The intersections were in suburban areas along four-lane or six-lane arterials. Available data included more than 2,000 crash reports at the treatment sites over 65 years of intersection operation, including more than 700 injury crashes. Analyses adjusted for changes in traffic volumes. The project team also collected data at 44 potential comparison sites for use in adjusting for simultaneous event and maturation biases.

For most individual sites and groups of sites examined, odds ratio tests showed that there were high-quality comparison sites available, which enhanced the strength of the analyses. Therefore, this evaluation determined the following as the best general estimates of CMFs for conversion of a conventional intersection to an RCUT intersection:

- Overall crashes: CMF = 0.85 (CRF = 15 percent).
- Injury crashes: CMF = 0.78 (CRF = 22 percent).

The SDs of the CMFs were 0.16 and 0.20, respectively. This indicates that the CMF for overall crashes was not significantly different from a neutral value of 1.0 at a 68-percent confidence level but that the CMF for injury crashes was significantly different from a neutral value of 1.0 at a 68-percent confidence level. Regardless, the results support the assumption that a signalized RCUT will generally produce a crash reduction. Also, the fact that RCUTs likely save more injury crashes than overall crashes should not be surprising, since they generally reduce the more severe angle and turning crashes.

The evaluation also produced an estimated B/C ratio for installing an RCUT at the set of test intersections of 3.6 to 1.0 when considering safety and operations or 2.6 to 1.0 considering safety only. When examining the sensitivity of this result to changes in crash costs, the B/C ratio always exceeded 1.0. Installing signalized RCUT intersections at locations similar to those studied should generally lead to positive results in terms of expected crash reductions.

At the individual site level of analysis, 8 of the 11 sites showed decreases in overall and injury crashes after RCUT installation. The three sites with increases (Ohio-Symmes, Texas-Evans, and Texas-Stone Oak) were the only treatment sites with three lanes on both minor street approaches. The only other treatment sites with three lanes on minor street approaches were Texas-Shaenfield, a T-intersection, and the other two Ohio sites with three lanes on one minor street approach and two lanes on the other minor street approach. Therefore, it is likely that signalized RCUTs may be relatively safer when the minor streets are narrower and/or carry lower traffic volumes.

There were clusters of rear-end crashes on the major streets of the RCUTs. An examination of crash types before and after RCUT installation showed that there was generally a conversion from angle crashes to sideswipe crashes.

While this study provided an estimated CMF and B/C ratio for signalized RCUTs, there is still a need for future research to add more knowledge. The project team recommends a followup before–after study with more sites, in more States, over more years, since RCUT installation is accelerating, and such a larger study will be possible in a few years. A larger study may shed more light on the spatial crash patterns and other variables that this study could only touch upon, as well as the circumstances that best favor RCUT installation. A second promising area for future research would be a study with a much larger sample size of sites where a research team could assemble a model of the safety effects of some of the important geometric features of RCUTs. Finally, the project team recommends studies similar to this one for the installation of other types of alternative and conventional intersections. A CMF for signalized RCUTs is only helpful if designers can compare it to CMFs for other intersection forms such as median U-turn, quadrant roadway, and continuous flow intersections, among others.

APPENDIX. ANALYSIS OF OTHER CRASH VARIABLES

Table 17 through table 27 provide more information on the crash variables from the RCUT test sites.

Table 17. Other crash variables at Alabama-Plum site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Right front angle crash	9	5.4	3	7.5
Left front angle crash	1	0.6	1	2.5
Head-on center crash	9	5.4	5	12.5
Undercarriage crash	1	0.6	0	0.0
Broadside right crash	5	3.0	1	2.5
Right rear angle crash	115	68.5	1	2.5
Rear-end center crash	5	3.0	21	52.5
Left rear angle crash	1	0.6	0	0.0
Broadside left crash	1	0.6	0	0.0
No second vehicle crash	10	6.0	1	2.5
No applicable crash type	10	6.0	7	17.5
Missing crash type	1	0.6	0	0.0
Daylight	125	74.4	24	60.0
Dark	39	23.2	13	32.5
Dusk	4	2.4	2	5.0
Dawn	0	0.0	1	2.5
Clear weather	93	55.4	27	67.5
Cloudy weather	40	23.8	10	25.0
Foggy weather	1	0.6	0	0.0
Rainy weather	34	20.2	3	7.5
Dry road condition	118	70.2	33	82.5
Wet road condition	50	29.8	4	10.0
Unknown road condition	0	0.0	2	5.0
Water buildup on road	0	0.0	1	2.5

Table 18. Other crash variables at Alabama-Retail site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Right front angle crash	1	2.3	0	0.0
Left front angle crash	0	0.0	1	33.3
Head-on center crash	4	9.1	0	0.0
Undercarriage crash	2	4.6	0	0.0
Broadside right crash	0	0.0	0	0.0
Right rear angle crash	26	59.1	0	0.0
Rear-end center crash	1	2.3	2	66.7
Left rear angle crash	1	2.3	0	0.0
Broadside left crash	1	2.3	0	0.0
No second vehicle crash	0	0.0	0	0.0
No applicable crash type	6	13.6	0	0.0
Missing crash type	2	4.6	0	0.0
Daylight	34	77.3	2	66.7
Dusk	3	6.8	0	0.0
Dark, roadway lighted	1	2.3	0	0.0
Dark, roadway not lighted	6	13.6	1	33.3
Clear weather	27	74.4	2	66.7
Cloudy weather	7	2.4	0	0.0
Foggy weather	0	5.4	0	0.0
Rainy weather	10	17.9	1	33.3
Dry road condition	33	75.0	2	66.7
Wet road condition	11	25.0	1	33.3

Table 19. Other crash variables at North Carolina site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle crash	4	2.0	2	1.3
Animal crash	1	0.5	4	2.5
Backing-up crash	1	0.5	1	0.6
Fixed object crash	2	1.0	4	2.5
Left-turn, different roadways crash	4	2.0	5	3.1
Left-turn, same roadway crash	58	29.0	17	10.7
Movable object crash	1	0.5	2	1.3
Parked crash	0	0.0	1	0.6
Other crash with vehicle	1	0.5	0	0.0
Pedalcyclist crash	1	0.5	0	0.0
Ran off road, right crash	1	0.5	0	0.0
Rear-end crash	102	51.0	82	51.6
Right-turn, different roadways crash	12	6.0	22	13.8
Right-turn, same roadway crash	1	0.5	2	1.3
Sideswipe, opposite direction crash	1	0.5	1	0.6
Sideswipe, same direction crash	10	5.0	16	10.1
Daylight	139	69.5	112	70.4
Dawn	18	9.0	16	10.1
Dusk	43	21.5	31	19.5
Clear weather	194	97.0	156	98.1
Foggy weather	3	1.5	2	1.3
Rainy weather	3	1.5	1	0.6
Dry road condition	165	82.5	129	81.1
Wet road condition	34	17.0	30	18.9
Icy road condition	1	0.5	0	0.00

Table 20. Other crash variables at Ohio-Symmes site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle crash	10	13.3	7	10.0
Backing-up crash	1	1.3	1	1.4
Fixed object crash	0	0.0	7	10.0
Head-on crash	1	0.9	1	1.4
Left-turn crash	19	16.8	6	8.6
Parked vehicle crash	1	0.9	0	0.0
Other noncrash	0	0.0	2	2.9
Pedestrian crash	0	0.0	1	1.4
Rear-end crash	75	66.4	41	58.6
Sideswipe, meeting crash	2	1.8	0	0.0
Sideswipe, passing crash	4	3.5	4	5.7
Dark, lighted	26	23.0	11	15.7
Dark, no light	7	6.2	2	2.9
Dawn	2	1.8	2	2.9
Daylight	75	66.4	50	71.4
Dusk	2	1.8	1	1.4
Light not stated	1	0.9	4	5.7
No adverse weather condition	87	77.0	51	72.9
Rain	26	23.0	15	21.4
Other weather	0	0.0	2	2.9
Snow	0	0.0	2	2.9
Dry road condition	74	65.5	36	51.4
Snow road condition	1	0.9	2	2.9
Wet road condition	37	32.7	32	45.7
Road condition not stated	1	0.9	0	0.0
Compact causal vehicle	18	15.9	8	11.4
Full-size causal vehicle	10	8.8	16	22.9
Mid-size causal vehicle	35	31.0	18	25.7
Other vehicle	25	22.1	18	25.7
Pickup causal vehicle	17	15.0	8	11.4
School bus causal vehicle	1	0.9	0	0.0
Straight truck causal vehicle	2	1.8	1	1.4
Subcompact causal vehicle	1	0.9	0	0.0
Tractor semitrailer causal vehicle	2	1.8	1	1.4
Vehicle not stated	2	1.8	0	0.0

Table 21. Other crash variables at Ohio-Tylersville site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle crash	16	15.4	1	4.2
Backing-up crash	3	2.9	0	0.0
Fixed object crash	5	4.8	1	4.2
Head-on crash	0	0.0	0	0.0
Left-turn crash	6	5.8	1	4.2
Other non-collision	1	1.0	0	0.0
Rear-end crash	66	63.5	14	58.3
Sideswipe, meeting crash	1	1.0	0	0.0
Overturning crash	1	1.0	0	0.0
Sideswipe, passing crash	5	4.8	7	29.2
Dark, lighted	19	18.3	4	16.7
Dark, no light	7	6.7	1	4.2
Dawn	5	4.8	1	4.2
Daylight	71	68.3	18	75.0
Dusk	2	1.9	0	0.0
No adverse weather condition	82	78.8	21	87.5
Rain	18	17.3	2	8.3
Other weather condition	0	0.0	1	4.2
Snow	3	2.9	0	0.0
Fog	1	1.0	0	0.0
Dry	75	72.1	21	87.5
Snow	1	1.0	0	0.0
Wet	27	26.0	3	12.5
Ice	1	1.0	0	0.0
Compact causal vehicle	14	13.5	3	12.5
Full-size causal vehicle	14	13.5	3	12.5
Mid-size causal vehicle	30	28.8	9	37.5
Motorcycle causal vehicle	1	1.0	0	0.0
Panel truck causal vehicle	5	4.8	0	0.0
Other causal vehicle	22	21.2	6	25.0
Pickup causal vehicle	13	12.5	3	12.5
School bus causal vehicle	1	1.0	0	0.0
Straight truck causal vehicle	1	1.0	0	0.0
Subcompact causal vehicle	1	1.0	0	0.0
Tractor semitrailer causal vehicle	1	1.0	0	0.0
Causal vehicle not stated	1	1.0	0	0.0

Table 22. Other crash variables at Ohio-Hamilton-Mason site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle crash	8	10.0	0	0.0
Backing-up crash	2	2.5	0	0.0
Fixed object crash	4	5.0	0	0.0
Left-turn crash	2	2.5	0	0.0
Other noncrash	0	0.0	1	11.1
Rear-end crash	61	76.3	7	77.8
Sideswipe, passing	3	3.8	1	11.1
Dark, lighted	6	7.5	0	0.0
Dark, no light	8	10.0	2	22.2
Dawn	3	3.8	1	11.1
Daylight	62	77.5	6	66.7
Dusk	1	1.3	0	0.0
No adverse weather condition	64	80.0	8	88.9
Rain	10	12.5	1	11.1
Snow	6	7.5	0	0.0
Dry road condition	60	75.0	7	77.8
Snow road condition	4	5.0	0	0.0
Wet road condition	15	18.8	2	22.2
Ice road condition	1	1.3	0	0.0
Compact causal vehicle	16	20.0	3	33.3
Full-size causal vehicle	6	7.5	0	0.0
Mid-size causal vehicle	23	28.8	3	33.3
Panel truck causal vehicle	2	2.5	0	0.0
Other causal vehicle	17	21.3	3	33.3
Pickup truck causal vehicle	13	16.3	0	0.0
Straight truck causal vehicle	1	1.3	0	0.0
Subcompact causal vehicle	2	2.5	0	0.0

Table 23. Other crash variables at Texas-Evans site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle, both going straight crash	25	24.3	64	19.7
Opposite direction, both going straight crash	0	0.0	1	0.3
Od, one straight, one left-turn crash	9	8.7	21	6.5
One mv other crash	1	1.0	0	0.0
One mv going straight crash	4	3.9	22	6.8
One mv turning left crash	1	1.0	3	0.9
One mv turning right crash	1	1.0	1	0.3
Sd, both going straight, rear-end crash	12	11.7	74	22.8
Sd, both going straight, sideswipe crash	9	8.7	22	6.8
Sd, both left-turn crash	0	0.0	3	0.9
Sd, both right-turn crash	2	1.9	7	2.2
Sd, one straight, one left-turn crash	1	1.0	1	0.3
Sd, one straight, one right-turn crash	1	1.0	1	0.3
Sd, one straight, one stopped crash	37	35.9	105	32.3
Dark, lighted	20	19.4	70	21.5
Dark, no light	16	15.5	16	4.9
Dawn	0	0.0	3	0.9
Daylight	64	62.1	235	72.3
Dusk	0	0.0	1	0.3
Dark, unknown lighting	3	2.9	0	0.0
Clear/cloudy weather	91	88.3	297	91.4
No weather data	2	1.9	0	0.0
Rain	10	9.7	26	8.0
Fog	0	0.0	2	0.6
Dry road condition	83	80.6	291	89.5
Wet road condition	18	17.5	34	10.5
No road condition data	2	1.9	0	0.0

Od = opposite direction; mv = motor vehicle; Sd = same direction.

Table 24. Other crash variables at Texas-Stone Oak site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle, both going straight crash	5	11.9	21	12.4
Od, both going straight crash	0	0.0	1	0.6
Od, one straight, one left-turn crash	4	9.5	6	3.6
One mv other crash	1	2.4	0	0.0
One mv going straight crash	6	14.3	26	15.4
One mv turning left crash	0	0.0	1	0.6
One mv turning right crash	0	0.0	2	1.2
Sd, both going straight, rear-end crash	8	19.0	44	26.0
Sd, both going straight, sideswipe crash	5	11.9	12	7.1
Sd, one straight, one left-turn crash	0	0.0	1	0.6
Sd, one straight, one right-turn crash	0	0.0	1	0.6
Sd, one straight, one stopped crash	13	31.0	54	32.0
Dark, lighted	11	26.2	46	27.2
Dark, no light	2	4.8	12	7.1
Dawn	1	2.4	4	2.4
Daylight	25	59.5	105	62.1
Dusk	0	0.0	2	1.2
Dark, unknown lighting	1	2.4	0	0.0
Unknown lighting	2	4.8	0	0.0
Clear and cloudy weather	37	88.1	116	68.6
Unknown weather	1	2.4	33	19.5
Rain	4	9.5	18	10.7
Fog	0	0.0	2	1.2
Dry road condition	33	78.6	142	84.0
Wet road condition	8	19.0	27	16.0
No road condition data	1	2.4	0	0.0

Od = opposite direction; mv = motor vehicle; Sd = same direction.

Table 25. Other crash variables at Texas-New Guibeau site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle, both going straight crash	4	3.9	6	9.7
Od, both going straight crash	0	0.0	1	1.6
Od, one straight, one left-turn crash	5	4.9	1	1.6
One mv going straight crash	7	6.8	5	8.1
One mv turning right crash	1	1.0	0	0.0
Sd, both going straight, rear-end crash	22	21.4	14	22.6
Sd, both going straight, sideswipe crash	3	2.9	10	16.1
Sd, both left-turn crash	1	1.0	1	1.6
Sd, both right-turn crash	1	1.0	0	0.0
Sd, one straight, one stopped crash	59	57.3	24	38.7
Dark, lighted	24	23.3	10	16.1
Dark, no light	6	5.8	5	8.1
Daylight	71	68.9	43	69.4
Dusk	0	0.0	1	1.6
Dark, unknown lighting	2	1.9	3	4.8
Clear and cloudy weather	90	87.4	56	90.3
Unknown weather	4	3.9	1	1.6
Rain	8	7.8	4	6.5
Fog	1	1.0	1	1.6
Dry road condition	84	81.6	54	87.1
Wet road condition	15	14.6	7	11.3
No road condition data	4	3.9	1	1.6

Od = opposite direction; mv = motor vehicle; Sd = same direction.

Table 26. Other crash variables at Texas-Shaenfield site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle, both going straight crash	9	11.1	13	15.9
Od, one straight, one left-turn crash	1	1.2	0	0.0
One mv going straight crash	6	7.4	7	8.5
One mv turning left crash	0	0.0	1	1.2
One mv turning right crash	0	0.0	1	1.2
Sd, both going straight, rear-end crash	13	16.0	20	24.4
Sd, both going straight, sideswipe crash	2	2.5	16	19.5
Sd, both left-turn crash	0	0.0	2	2.4
Sd, one straight, one left-turn crash	0	0.0	1	1.2
Sd, one right, one stopped crash	1	1.2	1	1.2
Sd, one straight, one stopped crash	49	60.5	20	24.4
Dark, lighted	11	13.6	24	29.3
Dark, no light	7	8.6	3	3.7
Dawn	1	1.2	1	1.2
Daylight	59	72.8	53	64.6
Dark, unknown lighting	3	3.7	1	1.2
Clear and cloudy weather	71	87.6	76	92.7
Rain	9	11.1	5	6.1
Fog	0	0.0	1	1.2
No weather data	1	1.2	0	0.0
Dry road condition	70	86.4	72	87.8
Wet road condition	10	12.3	10	12.2
No road condition data	1	1.2	0	0.0

Od = opposite direction; mv = motor vehicle; Sd = same direction.

Table 27. Other crash variables at Texas-71 site.

Variable Level	Before-Period Number of Crashes	Before-Period Percent of Total Crashes	After-Period Number of Crashes	After-Period Percent of Total Crashes
Angle, both going straight crash	45	28.8	2	12.5
Od, both going straight crash	1	0.6	0	0.0
Od, one straight, one left-turn crash	14	9.0	0	0.0
One mv going straight crash	19	12.2	2	12.5
One mv turning left crash	4	2.6	0	0.0
One mv turning right crash	1	0.6	1	6.2
Sd, both going straight, rear-end crash	21	13.5	4	25.0
Sd, both going straight, sideswipe crash	8	5.1	3	18.8
Sd, one straight, one left-turn crash	0	0.0	1	6.2
Sd, one straight, one right-turn crash	2	1.3	0	0.0
Sd, one straight, one stopped crash	41	26.3	3	18.8
Dark, lighted	22	14.1	4	25.0
Dark, no light	20	12.8	4	25.0
Dawn	4	2.6	0	0.0
Daylight	104	66.7	6	37.5
Dusk	3	1.9	0	0.0
Dark, unknown lighting	3	1.9	2	12.5
Clear and cloudy weather	140	89.7	11	68.8
Unknown weather	1	0.6	0	0.0
Rain	15	9.6	4	25.0
Fog			1	6.2
Dry road condition	136	87.2	11	68.8
Sand, mud, dirt road condition	1	0.6	0	0.0
Wet road condition	18	11.5	5	31.2
No road condition data	1	0.6	0	0.0

Od = opposite direction; mv = motor vehicle; Sd = same direction.

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