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16. Abstract

This report presents the results of research that performed a well-designed before-after evaluation of the safety effects of providing left- and right-turn lanes for at-grade intersections. Geometric design, traffic control, traffic volume, and traffic accident data were gathered for a total of 280 improved intersections, as well as 300 similar intersections that were not improved during the study period. The types of improvement projects evaluated included installation of added left-turn lanes, added right-turn lanes, and extension of the length of existing left- or right-turn lanes. An observational before-after evaluation of these projects was performed using several alternative evaluation approaches. The three contrasting approaches to before-after evaluation used were the yoked comparison or matched-pair approach, the comparison group approach, and the Empirical Bayes approach. The research not only evaluated the safety effectiveness of left- and right-turn lane improvements, but also compared the performance of these three alternative approaches in making such evaluations. The research developed quantitative safety effectiveness measures for installation design improvements involving added left-turn lanes and added right-turn lanes. The research concluded that the Empirical Bayes method provided the most accurate and reliable results. Further use of this method is recommended.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
(none)	mil	25.4	micrometers	µm
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 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 (metric tons)	Mg (or t)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lb	pounds	4.45	Newtons	N
lb/in^2 (psi)	pounds per square inch	6.89	kiloPascals	kPa
k/in^2 (ksi)	kips per square inch	6.89	megaPascals	MPa
		DENSITY		
lb/ft^3 (pcf)	pounds per cubic foot	16.02	kilograms per cubic meter	kg/m^3

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
µm	micrometers	0.039	mil	(none)
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	35.71	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 (metric tons)	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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	pounds	lb
kPa	kiloPascals	0.145	pounds per square inch	lb/in^2 (psi)
MPa	megaPascals	0.145	kips per square inch	k/in^2 (ksi)
		DENSITY		
kg/m^3	pounds per cubic foot	0.062	kilograms per cubic meter	lb/ft^3 (pcf)

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised September 1993)

Table of Contents

Appendices

List of Figures

List of Tables

1. INTRODUCTION

This report presents the results of research on the safety effectiveness of geometric design improvements for at-grade intersections. The objective of the research was to perform a well-designed before-after evaluation of selected types of intersection design improvements. The research was performed as part of a pooled-fund study; a portion of the funding for the research was contributed by highway agencies in the District of Columbia and the states of Iowa, Illinois, Louisiana, Minnesota, Montana, Nebraska, New Jersey, North Carolina, Oregon, and Virginia.

Representatives of the participating highway agencies met on three occasions during the study to assist in guiding the research. In particular, the types of intersection improvements to be evaluated in this study were selected in consultation with the participating state highway agencies. Based on a review of safety literature concerning a broad range of intersection design improvements, presented in section 2 of this report, it was decided that the before-after evaluation should focus on intersection design improvements involving left- and right-turn lanes.

Geometric design, traffic control, traffic volume, and traffic accident data were gathered for a total of 280 improved sites under the jurisdiction of the participating states, as well as 300 similar intersections that were not improved during the study period. The types of improvement projects evaluated included installation of added left-turn lanes, installation of added right-turn lanes, installation of added left- and right-turn lanes as part of the same project, and extension of the length of existing left- or right-turn lanes. An observational before-after evaluation of these projects was performed using evaluation approaches recommended in a recent report by Griffin and Flowers[1] and a recent book by Hauer.[2] Three contrasting approaches to before-after evaluation were used—the yoked comparison or matched-pair approach, the comparison group approach, and the Empirical Bayes approach. The research not only evaluated the safety effectiveness of left- and right-turn lane improvements, but also compared the performance of these three alternative approaches in making such evaluations.

This report presents the research methodology and evaluation approaches used to evaluate left- and right-turn lane projects and presents the results of the evaluations. Section 2 of the report presents a review of the safety literature concerning intersection design improvements; the results of this review were considered in the decision to focus the study of left- and right-turn lane improvements. Section 3 describes the selection of the evaluation sites. The collection of data concerning those evaluation sites is described in section 4. Section 5 presents the evaluation plan for the study, including the three specific evaluation approaches that were used, while section 6 presents and interprets the evaluation results. The conclusions and recommendations of the study are presented in section 7.

Appendix A summarizes the results of safety studies concerning intersection improvements published in the literature. Appendix B presents the results of negative binomial regression modeling on relationships between intersection accident frequency and traffic volumes performed for use with the comparison group and Empirical Bayes approaches. Appendix C presents the detailed results of all before-after evaluations performed in the research; this appendix includes all evaluation results that are discussed in Section 6 of the report, as well as other evaluations whose results were not statistically significant and were, therefore, not used. Finally, appendix D presents the definitions for geometric design and traffic control data items that were collected in the field concerning the study intersections.

2. LITERATURE REVIEW ON SAFETY EFFECTS OF INTERSECTION DESIGN ELEMENTS

This section of the report presents the results of the literature review that was conducted as part of the research. This literature review covered all aspects of intersection safety. Based on this review, a decision was reached to focus the research on the safety effectiveness of left- and right-turn lanes at intersections. Therefore, these issues are addressed in greater detail than most other issues.

Overview

The scope of the literature review includes studies related to the safety effects of a wide variety of geometric design, traffic, and control elements of at-grade intersections. Although the research presented in this report focuses on the safety effectiveness of intersection left- and right-turn lanes, the initial scope of the research was not limited to this topic and could potentially have included the safety evaluation of any type of intersection design improvement. Therefore, this literature review is organized to emphasize studies related to the safety effectiveness of turn lanes, but it also includes a review of all geometric, traffic, and control elements that affect the safety of at-grade intersections.

The review identifies studies that address general intersection geometric design, traffic, and control issues with emphasis on studies that provide a quantitative estimate of the factor of interest. Some studies find a factor to be related to safety, but do not quantify the effect of that factor. With minor exceptions, the review does not address studies that investigated a factor but did not find it to be important or statistically significant. In such cases, it would be difficult without more detailed review of the study to judge whether the lack of an observed effect resulted from the true lack of a relationship of that factor to safety or from a limited sample size or poor study design. The review considers both studies that directly evaluated relationships between the factors of interest and safety and studies that summarized and synthesized past research. The latter were included to take advantage of the judgements made by previous reviewers.

Table 1 presents a list of the intersection features that are discussed in this review. The table is organized into three categories: intersection geometric design features, traffic control and operational features, and traffic characteristics. The specific topics that are most directly related to the safety effectiveness of turn lanes are listed first under each category.

The remainder of this section of the report presents the findings of the literature review of the specific topics identified in table 1. The findings are also presented in an extensive summary table in appendix A.

Table 1. Intersection Features Addressed in the Literature Review.

Intersection geometric design features	Traffic control and operational features	Traffic characteristics
Left-turn lanes – offset left-turn lanes Right-turn lanes Channelization – island design Number of intersection legs (e.g., 3, 4, 5) Intersection type (e.g., cross, T, Y, offset) Roundabouts Angle of intersection (e.g., skew) Curb return radius Sight distance – intersection sight distance – stopping sight distance – sight distance to traffic control device Approach width Number of approach lanes Median width and type Vertical alignment on approaches Horizontal alignment on approaches	Type of traffic control: – uncontrolled – YIELD-controlled – STOP-controlled – signal-controlled – roundabouts Turn prohibitions Presence and type of crosswalks Posted speed limit on approaches Advance warning signs Lighting	Average daily traffic (ADT) – total entering ADT (all approaches) – entering ADTs for major and minor approaches Turning movements Peak hour approach volumes Vehicle mix/percent trucks Distribution of total entering volume by hour of day Distribution of approach volume by hour of day Average approach speed Volume of bicycle traffic Volume of pedestrian traffic

Intersection Geometric Design Features

Left-Turn Lanes

Installation of left-turn lanes has been the focus of many research studies. Various safety-related impacts have been documented depending upon the type of intersection (signalized, unsignalized, four-leg, etc.) where the left-turn treatment was implemented, as well as the different types and/or severity of accidents. Parker[(3)] determined that the addition of left-turn lanes at rural intersections along two-lane highways can reduce the potential for passing-related accidents. On urban four-lane roadways, McCoy and Malone[(4)] found that installation of left-turn lanes reduced rear-end, sideswipe, and left-turn accidents. Foody and Richardson[(5)] found that accident rates decreased by 38 percent with the addition of a left-turn lane at signalized intersections and by 76 percent at unsignalized intersections. Gluck et al.[(6)] reported accident rate reductions ranging from 18 to 77 percent due to the installation of left-turn lanes, based on the review of work by the New Jersey Department of Transportation,[(7,8)] Griewe,[(9)] Agent,[(10)] Ben-Yakov and Craus,[(11)] Craus and Mahalel,[(12)] Tamburri and Hammer,[(13)] and Wilson et al.[(14)]

When implemented with additional safety measures, left-turn lanes have been very effective in increasing safety. Haler reported that left-turn channelization reduced accidents to varying degrees depending upon the intersection configuration.[(15)] Based on a synthesis of work by McFarlane,[(16)] Haler reported that the provision of left-turn lanes at unsignalized intersections, when combined, with installation of curbs or raised medians, reduced accidents by 70, 65, and 60 percent in urban, suburban, and rural areas, respectively. When the channelization was painted rather than raised, accidents decreased only by 15, 30, and 50 percent in urban, suburban, and rural areas, respectively. At signalized intersections, installation of left-turn channelization accompanied by a left-turn signal phase reduced accidents by 36 percent; however, without the left-turn phase, accidents decreased only by 15 percent.[(16)] At unsignalized intersections, findings of a California study indicate greater reductions in accidents with the use of a left-turn lane in a raised median than with painted left-turn lanes.[(17)] Similarly, Lacy[(18)] found that a left-turn lane, when coupled with several other safety improvements, reduced accident frequency by 35 percent and accident severity by 80 percent. Dale[(19)] found that installation of a traffic signal and left-turn channelization at intersections along rural two-lane highways reduced the total number of accidents by 20 percent, while the installation of a traffic signal without any channelization reduced the total number of accidents by only 6 percent.

Not all studies, however, have shown that left-turn lanes reduce accidents. Bauer and Harwood[(20)] found that left-turn lanes were associated with higher frequencies of both total multiple-vehicle accidents and fatal and injury multiple-vehicle accidents. However, this result was not advanced by the authors as a basis for policy because the directions of specific effects in predictive models often represent the surrogate effects of other variables, rather than the true effect of the variable of interest. At unsignalized intersections, McCoy and Malone determined there was a significant increase in right-angle accidents.[(4)]

However, at unsignalized intersections on rural two-lane highways, McCoy et al.[21] found no significant difference in rear-end and left-turn accident rates between intersections with and without left-turn lanes. Poch and Mannering[22] also found some situations in which accidents of specific types increased with installation of left-turn lanes.

Several predictive models and accident modification factors have been developed that indicate left-turn lanes have a positive effect on safety. Maze et al.[23] developed a model that predicted a reduction in left-turn accident rate of 6 percent due to the installation of a left-turn lane with permitted signal phasing and a reduction of approximately 35 percent from installation of a left-turn lane with protected/permitted signal phasing. Vogt[24] developed a model for a four-leg rural intersection of a four-lane major road with STOP-controlled two-lane minor roads which yielded an accident reduction factor for total accidents of 38 percent due to the installation of a left-turn lane along the major road.

In another study, Harwood et al.[25] developed algorithms to predict the expected safety performance of rural two-lane highways. The prediction algorithms combined elements of historical accident data, predictions from statistical models, results of before-after studies, and expert judgements made by experienced engineers. As part of the research, an expert panel of safety researchers developed accident modification factors (AMFs) for specific geometric design and traffic control features. AMFs are used in the accident prediction algorithms to represent the effects of safety of the respective features. The base value of each AMF is 1.0. Any feature associated with a higher accident experience than the base condition has an AMF with a value greater than 1.0, and any feature associated with lower accident experience than the base condition has an AMF with a value less than 1.0.

In developing AMFs for the installation of left-turn lanes on the major-road approaches to intersections on two-lane rural highways, the expert panel conducted an extensive review of past research on the safety effectiveness of left-turn lanes, including most of the studies discussed above. The panel was charged with defining the safety effectiveness of intersection left-turn lanes based on the best study of this issue or based on results from a combination of studies. The panel concluded that there have been no well-designed before-after evaluations of intersection left-turn lanes and no single study that was considered more reliable than others. Therefore, the panel combined results from several studies and developed AMFs for left-turn lanes, which are presented in Table 2. The AMFs represent a judgement by the panel. The panel estimated that installation of a left-turn lane along one major approach reduces intersection-related accidents by 18 to 24 percent, depending upon the type of traffic control and the number of legs, and installation of left-turn lanes along both major approaches to a four-leg intersection reduces intersection-related accidents by 33 to 42 percent, depending upon the type of traffic control. These results are presented in table 2 in the form of AMFs, as defined above.

No research was found that quantifies the safety effectiveness of extending the length of existing left-turn lanes to eliminate traffic overflows into through travel lanes and to allow a greater proportion of vehicle deceleration to occur in the turn lane rather than in the through travel lanes.

Table 2. Accident Modification Factors for Installation of Left-Turn Lanes on the Major-Road Approaches to Intersection on Two-Lane Rural Highways[25].

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign[a]	0.78	—
	Traffic signal	0.85	—
Four-leg intersection	STOP sign[a]	0.76	0.58
	Traffic signal	0.82	0.67

[a] STOP signs on minor-road approach(es)

An emerging issue in the design of left-turn channelization is the restriction in sight distance that opposing left-turn vehicles cause one another. As an indication of this safety problem, David and Norman[26] determined that for average daily traffic (ADT) volumes between 10,000 and 20,000 veh/day, four-leg intersections with opposing left-turn lanes had more accidents than those without. A potentially effective countermeasure for safety problems where opposing left-turn lanes are present is to eliminate the sight restrictions by offsetting the left-turn lanes. Harwood et al.[27] reviewed the safety performance of a limited set of tapered and parallel offset left-turn lanes and found no safety problems. Both McCoy et al.[28] and Joshua and Saka[29] developed procedures to compute the amount of offset required for clear sight lines. However, no evaluations of the accident reduction effectiveness of offset left-turn lanes have been found.

Table 3 summarizes the results of those studies that provided quantitative estimates of the effectiveness of installing left-turn lanes at intersections.

Right-Turn Lanes

Compared to left-turn lanes, very few studies have been conducted on the safety effectiveness of right-turn lanes. Bauer and Harwood[20] indicate that right-turn channelization resulted in a decrease in both total multiple-vehicle accidents and fatal and injury multiple-vehicle accidents. However, Vogt and Bared[30] modeled accidents for three-leg unsignalized intersections along rural two-lane highways, and based upon the prediction model, the presence of a right-turn lane increases intersection-related accidents by 27 percent.

The expert panel discussed above also developed estimates of the safety effectiveness of right-turn lanes; these AMFs are presented in table 4.[25] In their review of information, the expert panel did not find any well-designed before-after studies on the accident reduction effectiveness of right-turn lanes. Based on a review of the available studies, the expert panel estimated the presence of a right-turn lane along one approach to a rural STOP-controlled intersection reduces intersection-related accidents by 5 percent, and the

Table 3. Summary of Research Results Concerning the Safety Effectiveness of Installing Left-Turn Lanes.

Source	Reported LTL effectiveness (percent change in accident frequency)		Conditions/comments
	Total intersection accidents	Left-turn accidents	
Harwood et al. [2000][25]	-18 to -24	—	two-lane highway; LTL on one major-road approach
	-32 to -42	—	two-lane highway; LTLs on two major-road approaches
Vogt [1999][24]	-38	—	LTL at four-leg rural intersection with four-lane major road and two-lane minor road
Maze et al [1994][23]	-6	—	signalized intersection; LTL with permitted phasing
	-35	—	signalized intersection; LTL with protected/permitted phasing
New Jersey Department of Transportation [1993][8]	-35 to -51	—	LTL installation on Route 130 in New Jersey
Griewe [1986][9]	-58	-62	eight LTLs added by restriping
Agent [1983][10]	-77	—	unsignalized intersection
	-54	—	signalized intersection
Ben Yahov and Craus [1980][11]/Craus and Mahalel [1980][12]	-38	—	LTL installation
McFarlane [1979][16]	-70	—	LTL with curbed median; urban
	-65	—	LTL with curbed median; suburban
	-60	—	LTL with curbed median; rural
	-15	—	LTL with painted median; urban
	-30	—	LTL with painted median; suburban
	-50	—	LTL with painted median; rural
	-36	—	signalized intersection with LTL and exclusive phase
	-15	—	signalized intersection with LTL but no exclusive phase

Table 3. Summary of Research Results Concerning the Safety Effectiveness of Installing Left-Turn Lanes (Continued).

Source	Reported LTL effectiveness (percent change in accident frequency)		Conditions/comments
	Total intersection accidents	Left-turn accidents	
Foody and Richardson [1973][5]	-38	—	signalized intersections
	-76	—	unsignalized intersections
Dale [1973][19]	-20	—	two-lane highway intersection; installation of signal with LTL
Lacy [1972][18]	-35	—	installation of LTL with other improvements
Tamburri and Hammer [1968][13]/ Wilson et al [1967][14]	-18	—	unsignalized intersection

Table 4. Accident Modification Factors for Installation of Right-Turn Lanes on the Major-Road Approaches to Intersection on Two-Lane Rural Highways.[25]

Intersection traffic control	Number of major-road approaches on which right-turn lanes are installed	
	One approach	Both approaches
STOP sign[a]	0.95	0.90
Traffic signal	0.975	0.95

[a] STOP signs on minor-road approach(es)

presence of a right-turn lane along both major approaches reduces intersection-related accidents by 10 percent. Similarly for rural signalized intersections, the expert panel estimated a reduction of 2.5 percent in total intersection-related accidents due to the presence of a right-turn lane along one major-road approach and 5 percent for right-turn lanes along both major-road approaches.

No research was found that quantifies the safety effectiveness of extending the length of existing right-turn lanes to eliminate traffic overflows into through travel lanes.

Table 5 summarizes the results of available studies on the safety effectiveness of right-turn lanes.

Table 5. Summary of Research Results Concerning the Safety Effectiveness of Installing Right-Turn Lanes.

Source	Reported LTL effectiveness (percent change in accident frequency)		Conditions/comments
	Total intersection accidents	Right-turn accidents	
Harwood et al. [2000][25]	-5	—	two-lane highway; RTL on one major road approach to an unsignalized intersection
	-10	—	two-lane highway; RTLs on two major-road approaches to an unsignalized intersection
	-2.5	—	two-lane highway; RTL on one major-road approach to an unsignalized intersection
	-5	—	two-lane highway; RTLs on two major-road approaches to signalized intersection
Vogt and Bared [1998][30]	27	—	based on multivariate modeling with Minnesota data

Channelization

Four functional objectives form the basis for channelization design concepts:[31,32]

- Limiting the points of conflict.
- Limiting the complexity of the conflict area.
- Limiting the conflict frequency.
- Limiting the conflict severity.

A variety of measures such as designation and arrangement of traffic lanes, traffic islands, median dividers, and various signs, signals, and markings may be used for channelization purposes. Studies on channelization by David and Norman,[26] Exnicios,[33] and Rowan and Williams[34] in general indicate that channelization improves safety. Exnicios[33] found reductions in accidents as high as 100 percent over a 26-month period. Haler[15] also reported that channelization can reduce accidents.

Channelizing islands are defined areas between traffic lanes that control vehicle movements and serve as refuge points for pedestrians.[35] Islands also provide suitable locations to place traffic control devices. Islands vary in both size and shape, as well as the type of surfacing material used.

Washington et al.[36] found that intersection approaches with raised medians had accident rates 40 percent lower than intersection approaches with flush medians. Forrestel[37] found that installation of a raised median island reduced the pedestrian accident rate by 11.5 percent. In another study, Templer[32] found that a raised median reduced the number of conflicts between pedestrians and vehicles, but the difference was not statistically significant.

Number of Intersection Legs

There is broad agreement in the literature that four-leg intersections experience more accidents than comparable three-leg intersections. This finding is logical because four-leg intersections have more conflict points than three-leg intersections and, therefore, present more opportunities for accidents to occur. Four studies have quantified this effect.

Bauer and Harwood[20] found that both rural and urban STOP-controlled intersections with four legs experienced approximately twice as many accidents as three-leg intersections. Specifically, rural four-leg STOP-controlled intersections experienced an average of 1.1 accidents per year, while three-leg intersections experienced 0.6 accidents per year. Urban four-leg STOP-controlled intersections experienced 2.2 accidents per year, while three-leg intersections experienced 1.3 accidents per year.

Predictive models developed by Harwood et al.[27] showed that typical divided highway intersections with four legs had about twice as many accidents as three-leg intersections for narrow medians and more than five times as many accidents as three-leg intersections for wide medians.

Hanna et al.[38] found that, in rural areas, four-leg intersections experience approximately 69 percent more accidents than T intersections. T intersections are three-leg intersections at which the legs meet at a right angle, while Y intersections are three-leg intersections where one or more of the legs are skewed. David and Norman[26] found that for STOP-controlled intersections in urban areas with total entering traffic volumes under 20,000 veh/day, the accident frequencies for three- and four-leg intersections were very similar; however, for intersections with total entering volumes over 20,000 veh/day, four-leg intersections experienced twice as many accidents as three-leg intersections.

Intersection Type

The review of intersection type focused on the differences between conventional and offset four-leg intersections and between T and Y three-leg intersections. Lau and May[39,40] found these differences to be statistically significant in modeling of injury accidents at both signalized and unsignalized intersections, but their classification and regression tree (CART) analysis results are difficult to interpret as a specific effect of these factors. Lau and May also modeled fatal and property-damage-only (PDO) accidents but, for the sake of simplicity, the discussions in this paper focus on the findings of injury accident modeling that are typical of the others.

Hanna et al.[38] found that, for three-leg intersections, Y intersections have accident rates approximately 50 percent higher than T intersections; for four-leg intersections, offset intersections had accident rates that were approximately 43 percent of the accident rate of conventional four-leg intersections. The effect observed by Hanna et al. is interesting. The operating experience of some highway agencies indicates that offset intersections can create operational and safety problems as through vehicles on the crossroad must turn onto and off of the major road rather than making a simple crossing maneuver. A number of projects have been constructed to realign the legs of offset intersections to convert them to conventional four-leg intersections. However, the results of Hanna et al. suggest the opposite—that offset intersections operate more safely than conventional four-leg intersections. This finding may indicate that, where there is little through traffic on the crossroad, two T intersections operate more safely than one conventional four-leg intersection.

Roundabouts

Roundabouts are a unique topic. They can be considered both an intersection geometric design feature and a form of intersection traffic control. Because roundabouts are classified as a form of intersection traffic control in *Roundabouts: An Informational Guide,* the safety effectiveness of roundabouts is discussed in the section on type of traffic control.[41]

Angle of Intersection

The angle between the legs of an intersection, particularly whether the legs intersect at a right or an oblique angle, has long been considered to affect the safety performance of the intersection. McCoy et al.[42] found that accidents at rural two-way STOP-controlled intersections increase with increasing skew angle; this result applies to both three-leg and four-leg intersections. In addition, the previously discussed difference in safety performance between three-leg T and Y intersections found by Hanna et al.[38] represents an effect of the angle of the intersection.

Harwood et al.[25] incorporated AMFs for intersection skew angle when they developed algorithms to predict the expected safety performance of rural two-lane highways. The AMFs for intersection skew angle were derived from statistical modeling and apply to total intersection-related accidents. Thus, the AMFs were formulated from data and do not represent judgements by the expert panel on the accident reduction effectiveness of this design feature. For a three-leg STOP-controlled intersection, the AMF was calculated as:

$$AMF = \exp(0.0040\ SKEW) \tag{1}$$

For a four-leg STOP-controlled intersection, the AMF was calculated as:

$$AMF = \exp(0.0054\ SKEW) \tag{2}$$

where:

SKEW = intersection skew angle (degrees), expressed as the absolute value of the difference between 90 degrees and the actual intersection angle.

Curb Return Radius

The curb return radius of an intersection controls the turning speed for vehicles making right turns. In addition, larger curb return radii make it possible for intersections to better accommodate right turns by large trucks. Haler(15) cited curb return radius as an important factor in safe intersection operations, but apparently no specific evaluations of the effect of curb return radius on safety have been conducted.

Sight Distance

Sight distance is the distance ahead or along an intersecting roadway that a driver can see from any location on the roadway system. Provision of adequate sight distance is fundamental to the design of roadways and intersections for safe operations. Three types of sight distance are particularly critical to the safe operation of at-grade intersections: intersection sight distance, stopping sight distance, and sight distance to traffic control devices.

Three studies have addressed the safety effects of intersection sight distance. David and Norman(26) found that within specific ADT levels the reduction in accident experience from a sight distance improvement was, in most cases, highest for intersection approaches whose initial sight distance was lowest. Hanna et al.(38) found that intersections with "poor" sight distance had an observed accident rate of 1.33 accidents per million entering vehicles, while intersections as a whole had an accident rate of 1.13 accidents per million entering vehicles. Mitchell(43) found that total intersection accidents were reduced by 67 percent when intersection sight obstructions were removed. Unfortunately, none of these studies were specific concerning the magnitude of the sight distance improvements made.

Fambro et al.[44] found that accident rates were high for intersections located on crest vertical curves with limited sight distance. The results of another recent study by Fambro et al.[45] are consistent with that finding.

No evaluations were found of the safety effects of limited sight distance to traffic control devices, such as STOP signs and signals.

The expert panel of safety researchers discussed earlier reviewed several sources of information to evaluate the effects of intersection sight distance on intersection-related accidents. The panel did not find any single evaluation to be the most credible. Therefore, the AMFs established by the panel represent the panel's best judgment on the safety effects of intersection sight distance. The AMFs are as follows for intersection sight distance at intersections with STOP control on the minor leg(s):

- 1.05 if sight distance is limited in one quadrant of the intersection.
- 1.10 if sight distance is limited in two quadrants of the intersection.
- 1.15 if sight distance is limited in three quadrants of the intersection.
- 1.20 if sight distance is limited in four quadrants of the intersection.

In applying these AMFs, sight distance in a quadrant of an intersection is considered limited if the available sight distance is less than the sight distance specified by AASHTO policy for a design speed of 20 km/h (12 mph) less than the major road-design speed and the sight distance restrictions are due to roadway alignment and/or terrain.

Approach Width

The width of an intersection approach includes the combined widths of the approach lanes and, in some cases, the width of the shoulder, as well. Studies by Bauer and Harwood,[20] Neuman,[31] and Lacy[18] found that increasing the approach width to an intersection reduces the accident rate along the approach. Bauer and Harwood[20] found that as lane width decreases on an intersection approach, accidents tended to increase. Similarly, Neuman[31] indicated that accidents may be reduced by widening the shoulder at intersections on narrow two-lane roadways. Widening of the shoulders may reduce accidents by providing space for collision-avoidance maneuvers and by providing better sight lines if sight distance is limited on the approach. Lacy[18] also found that widening the approaches, combined with other safety improvements, decreased accident frequency by 35 percent and accident severity by 80 percent. By contrast, David and Norman[26] did not find any evidence that incremental changes in lane or shoulder width near intersections affects accident rates.

Number of Approach Lanes

The number of lanes on an intersection approach is determined primarily by traffic demand and the desired level of service. Intuitively, one might assume that the number of accidents is proportional to the number of lanes (i.e., as the number of lanes increases so would the total number of accidents, since the potential number of conflicts would appear to increase). However, Bauer and Harwood[20] found that for unsignalized intersections in both rural and urban areas, the number of accidents tended to be higher on facilities with one approach lane and accidents tended to be lower at intersections with two or more approach lanes. The opposite appears to be the case for urban, four-leg, signalized intersections. David and Norman[26] also indicated that accident frequencies can be reduced for intersections with total entering volumes under 10,000 veh/day by adding through lanes. It should be noted that with a demand-related design parameter such as number of lanes, it is difficult to assess directly whether any observed safety effects are due to the number of lanes or to the traffic volume on the approach.

Median Type and Width

The width of a divided highway median influences the safety performance of intersections on that highway. Harwood et al.[27] found that accident frequencies at rural four-leg signalized intersections decrease as median width increases. In contrast, at both signalized and unsignalized intersections in urban and suburban areas, accident frequencies were found to increase with increasing median width. Similar results for rural divided highway intersections were found in an earlier Ohio study by Priest.[46] An Indiana study by Van Maren found no statistically significant relationship between median width and accident rates at divided highway intersections.[47]

Vertical Alignment

Crest and sag vertical curves are used to provide a smooth transition between roadway segments with different grades. From a safety standpoint, it is undesirable to locate intersections on steep grades or on crest vertical curves with limited sight distance. Steep upgrade approaches to intersections cause difficulty because vehicles accelerate more slowly, resulting in increased time during which the vehicle is exposed in the conflict area of the intersection. Steep downgrade approaches to intersections result in longer stopping distances, which may cause potential problems, as well. Surprisingly, however, Hanna et al.[38] found the accident rates for intersections with grades steeper than five percent to be lower than the average accident rate for all intersections. The average accident rates were 0.97 and 1.13 accidents per million entering vehicles for intersections with steep grades and for all intersections, respectively.

As discussed above, vertical curves cause potential problems at intersections where sight distance is limited. In particular, Fambro et al.[44] concluded that accident rates were high at intersections on crest vertical curves where sight distance was limited.[27]

Horizontal Alignment

From a safety standpoint, it is desirable for the alignment of intersecting roadways to be straight as practical. Horizontal curves on the approaches to intersections make it difficult for a driver to discern the proper path of travel and also affect a driver's visual perspective, since the driver's focus is directed tangentially to the travel path.[48] Horizontal curves also add complexity to the driving environment. Past research has shown that the distance from a horizontal curve to the nearest intersection is related to safety.[49] However, no studies were found which indicate that any specific threshold value for degree of curvature adversely affects safety on intersection approaches.

Traffic Control and Operational Features

Type of Traffic Control

A variety of different traffic control types are used for at-grade intersections including no control, YIELD-control, STOP-control, signal control, and roundabouts.

Poch and Mannering[22] indicated that intersections with no control on any of the approaches experience fewer total and angle accidents than intersections with other types of traffic control. However, this effect could have been observed solely because uncontrolled intersections typically have lower traffic volumes than other intersection types.

Hauer,[15] in a synthesis of past research, noted that conversion from no control to YIELD control reduced accidents by 44 to 52 percent in one study and by 23 to 63 percent in another.

Hall et al.[50] found that accidents can be reduced by 20 to 60 percent by proper use of YIELD signs. However, little additional benefit was found if the YIELD signs were replaced by STOP signs. Agent and Deen[51] found that at YIELD-controlled intersections, over half of the accidents were rear-end collisions, while angle collisions made up over half of the accidents at STOP-controlled intersections. Hanna et al.[38] found that accident rates at STOP-controlled intersections were lower than those at intersections having higher traffic flow.

No safety evaluations were found in the literature for intersections where flashing beacons were used in conjunction with STOP signs at either two-way or all-way STOP-controlled intersections.

Research by Hanna et al.[38] indicates that signalization of intersections that are currently unsignalized typically results in a slight increase in accident rate, a substantial increase in rear-end collisions, and a comparable decrease in angle collisions. Poch and Mannering[22] found that total and angle accidents for signal-controlled intersections were lower than for other traffic control types.

Maze et al.[23] developed predictive models which indicate that a protected left-turn signal phase without a left-turn lane has a positive effect on safety. A numerical example developed by the authors indicates an anticipated reduction in left-turn accidents of 50 percent from installation of a left-turn signal phase. David and Norman[26] found that in urban areas, multiphase traffic signals appear to have lower percentages of fatal and injury accidents than two-phase signals. King and Goldblatt[52] found that signalization leads to a reduction in angle collisions and an increase in rear-end collisions; their results also indicate that signalized intersections have higher accident rates, although this is often offset by reduced accident severity.

U.S. experience with roundabouts is rather limited, but interest has increased recently, partially due to the operational and safety benefits being reported in documents such as *Roundabouts: An Informational Guide.*[41] The *Informational Guide* indicates roundabouts may improve the safety of intersections by eliminating or altering conflict types, by reducing speed differentials at intersections, and by decreasing overall speeds into and through intersections. The *Informational Guide* summarizes the overall safety performance of roundabouts in various countries, including the U.S. After converting intersections with conventional traffic control to roundabouts, a reduction in accidents is reported of about 37 percent for all accidents and 51 percent for injury accidents. These values are consistent with experiences in the U.S. and internationally. Persaud et al.[53] found similar results after performing a before-after accident analysis following the conversion of twenty-three intersections from STOP-control and signal-control to roundabouts. Persaud et al. reported a 40 percent reduction in total accidents, an 80 percent reduction for all injury accidents, and about a 90 percent reduction of fatal and incapacitating injury accidents.

Turn Prohibitions

Research by Lau and May[39,40] found that left-turn prohibitions were a significant factor in predicting injury accidents at both signalized and unsignalized intersections. However, the results of this CART analysis are difficult to interpret in order to obtain an explicit estimate of this effect.

Presence and Types of Crosswalk

The purpose of marked crosswalks is to guide pedestrians across a busy roadway, as well as to increase drivers' awareness of pedestrians. Some intersections provide designated crosswalks for pedestrians, while others do not. Research results provide conflicting conclusions as to whether the provision of marked crosswalks actually improves safety for pedestrians. Several studies have concluded that marked crosswalks decrease accident rates, in some cases by as much as 50 percent.(15,54) On the other hand, perhaps the best-known study on crosswalks, conducted by Herms(55) in 1970, concluded that approximately twice as many pedestrian accidents occurred in marked crosswalks as in unmarked crosswalks. Another study found that pedestrian accidents increased by 86 percent after crosswalks were marked.(15) As Herms pointed out, the increase in accident rates resulting from marked crosswalks may "not be due to the crosswalk being marked as much as it is a reflection on the pedestrian's attitude and behavior when using the marked crosswalk." Other factors which may affect the safety of marked crosswalks include visibility, intersection type, and signal timing.

Although crosswalks typically affect pedestrian safety, it is also important to note that vehicular accident rates may also be affected. Hauer(15) noted that rear-end collisions increase after crosswalks are marked. Thus, the need for crosswalks should be examined from the standpoint of both pedestrian safety and vehicular safety.

Posted Speed Limit

It is rational to assume that the likelihood and severity of accidents on an intersection approach increases as the posted speed limit on the approach increases. Higher posted speed limits are generally associated with higher approach speeds, which require longer distances to bring an approaching vehicle to a complete stop. Therefore, drivers must react more quickly to potential conflicts encountered at the intersections. However, no studies were found that quantify the extent to which accidents increase or decrease with changes in posted speed limits or operating speeds on intersection approaches.

Advance Warning Signs

Advance warning signs are intended to increase a driver's awareness of upcoming traffic situations. Studies of specific types of advance warning signs provide varied results. Gattis and Iqbal(56) found that most drivers do not abide by the "Do Not Block Intersection" sign. Washington(36) found that accident rates increased for approaches to skewed intersections where advance warning signs were provided. Pant and Huang(57) found the "Prepare To Stop When Flashing" sign raised conflict rates by 15 percent on curved approaches but had no influence on conflict rates on tangent approaches. Pant and Huang also noted that the flashing symbol "Signal Ahead" sign had no impact on traffic conflict rates.

Research has also shown positive effects for certain supplements to advance warning signs. Washington[36] found that advance warning signs with flashers (AWFs) can reduce approach accident rates at high-speed signalized intersections by as much as 50 percent. He also concluded that right-angle accidents were reduced when route markers and/or advance warning signs were present. Klugman[58] found that total accident rates decreased from 1.22 to 1.09 accidents per million entering vehicles at AWF-equipped intersections; right-angle and rear-end accident rates also decreased from 0.68 to 0.63 accidents per million entering vehicles. In other related work, Styles[59] concluded that the "Red Signal Ahead" warning sign reduced right-angle accident rates by 42 percent on intersection approaches with crest vertical curves and reduced the total accident rate on intersection approaches with horizontal curves and tangent alignments by 14 and 41 percent, respectively. In a separate study, Styles[60] found that flashing red strobe lights are also effective in reducing right-angle accidents.

It is important to note that many of the studies related to advance warning signs stress the importance of factors such as approach alignment, type of sign, and type of accident as influencing the accident reduction effectiveness for such devices.

Lighting

Intersection lighting is potentially effective as a countermeasure to reduce nighttime accidents. Bauer and Harwood[20] found that rural, four-leg, STOP-controlled intersections that were lighted would be expected to experience 21 percent fewer fatal and injury accidents than unlighted intersections. However, for other intersection types, no similar effect was observed and, in some cases, an opposite effect that may represent a surrogate effect of some other variable was observed. It is important to note that this study evaluated total accidents (daytime plus nighttime), rather than nighttime accidents alone.

Box[61] found that improved lighting reduced the proportion of pedestrian/bicycle, fixed-object, sideswipe, and other accidents that occurred at night on a 4.5-km (2.8-mi) section of a suburban arterial in Illinois. Only nighttime head-on accidents increased as a proportion of total (daytime plus nighttime) accidents.

An extensive study in Los Angeles found no statistically significant reduction in nighttime accidents due to lighting improvements at intersections. Statistically significant reductions in nighttime accidents were found for a few intersections.[62]

Traffic Characteristics

Average Daily Traffic (ADT) Volume

Many studies have found approach traffic volumes to have a strong relationship to intersection accidents. A number of studies have used the total entering ADT as an exposure measure in determining intersection accident rates. Bauer and Harwood[(20)] found better results in accident prediction modeling when the major-road and crossroad ADTs were treated as separate independent variables than when they were combined as a product or a sum. Lau and May[(39,40)] represented the relative traffic volumes on the intersecting roadways by the ratio of the crossroad volume to the total entering ADT, expressed as a percentage.

Turning Movements

Hauer et al.[(63)] developed relationships between accident frequency for specific accident types (e.g., left-turn accidents) and the turning movement volumes most specifically related to that accident type.

Other Traffic Characteristics

No studies were found relating the following traffic flow measures to accidents:

- Peak hour approach volumes.
- Vehicle mix/percent trucks.
- Distribution of total entering volume by hour of the day.
- Distribution of approach volume by hour of the day.
- Average approach speed.
- Volume of bicycle traffic.
- Volume of pedestrian traffic.

Summary

The scope of this literature review covers the safety effectiveness of general intersection geometric design features, traffic control elements, and traffic characteristics, focusing on studies that provide a quantitative estimate of the factor of interest. Based upon the review, it is evident that many design features have the capability to improve the safety of an at-grade intersection. It is also evident by the quantity of the studies related to left- and right-turn lanes that there is considerable interest in quantifying their safety effectiveness. This interest has been stimulated by the number of highway agencies that have installed turn lanes and by the results of previous studies that give a strong indication that installation of left- or right-turn lanes improves the safety of at-grade intersections.

Based on these considerations, representatives of the state highway agencies in this pooled-fund study decided to focus this research on the evaluation of the safety effectiveness of intersection left- and right-turn lanes.

3. SELECTION OF EVALUATION SITES

This section of the report describes the process of selecting evaluation sites for the evaluation of left- and right-turn lane projects and summarizes the characteristics of the sites that were used. The first portion of this section documents the types of projects that were evaluated. The next subsection describes the overall process of identifying candidate intersections, including three types of sites: *improved* or *treatment* sites, *comparison* sites, and *reference* sites. These three types of sites are defined later in this section. The identification and screening of each site type is described and the number and characteristics of sites of each type are summarized.

Evaluation Priorities for Intersection Improvement Types

Based on the results of the literature review and, most especially, on the assessments of the participating state highway agencies, a decision was reached to focus the safety evaluation on projects involving intersection left- and right-turn lanes. In particular, a decision was made to focus the evaluation on the following four project types for which it appeared that sufficient improved sites for an evaluation were likely to be available:

- Installation of a left-turn lane on one or more major-road approaches to an existing intersection where no turn lane was present.

- Installation of a right-turn lane or a right-turn channelizing island on one or more major-road approaches to an existing intersection where no turn lane was present. In some cases, there may have been an existing right-turn channelizing island prior to the project.

- Installation of both left- and right-turn lanes on one or more major-road approaches to an intersection.

- Projects that involved extending the length of an existing left- or right-turn lane, without adding a new turn lane.

The following types of improvement projects were not evaluated:

- Projects in which no left- or right-turn lanes were installed. In particular, candidate projects that involved signal modifications only, such as the addition of exclusive turn phases, were not considered.

- Projects in which through lanes were added on the major road. In particular, corridor improvement projects in which the through roadway was widened along an entire corridor, but turn lanes also were added at selected intersections, were not considered. However, a few projects that installed a two-way left-turn lane

(TWLTL) along the major road, thus providing conventional left-turn lanes at one or more intersections, were retained.

- Projects in which existing through lanes were converted to left- or right-turn lanes.

- Projects in which minor-road approaches were realigned to convert two nearby three-leg intersections into a single four-leg intersection.

Identification of Candidate Intersections

Candidate intersections were identified and reviewed as potential evaluation sites in cooperation with the participating state highway agencies. Three types of sites were considered:

- *Improved* or *treatment* sites, which were intersections at which one of the project types described above was implemented.

- *Comparison* sites, which were intersections similar in geometric design, traffic control, and traffic volume characteristics to the improved sites, but were not improved. The objective was to identify matched pairs of improved and comparison sites with similar characteristics.

- *Reference* sites, which were sites that were not improved, but also were not matched to any particular improved site.

The general characteristics that all study sites were expected to meet were as follows:

- Only three- and four-leg intersections were considered. Multileg intersections were excluded because they typically incorporate unique features that are not representative of most intersections.

- Only intersections with two-way STOP control and signal control were considered. A few intersections with other types of control (e.g., four-way STOP control) were suggested by the participating states, but these other types were not present in sufficient numbers for evaluation.

- Only intersections between public roads were considered. Intersections at which the minor-road leg was a driveway to a shopping center or school were eliminated because it was considered unlikely that reliable traffic volume data for the minor leg by hour of the day exist and those data that do exist are likely to be atypical. However, some three-leg intersections between public roads at which the fourth leg of the intersection is a residential or commercial driveway were retained.

The selection process and characteristics for each type of intersection are discussed below in more detail.

Selection of Improved or Treatment Sites

Improved or treatment sites are sites at which an improvement project was constructed at an intersection. The project types considered were adding left-turn lanes, adding right-turn lanes, adding both left- and right-turn lanes, or extending an existing left- or right-turn lane. This following discussion addresses the identification and screening of candidate projects and summarizes the number and characteristics of the selected sites.

Identification and Screening of Candidate Projects

Candidate projects were identified with the assistance of eight of the participating state highway agencies. The participating states were: Illinois, Iowa, Louisiana, Minnesota, Nebraska, North Carolina, Oregon, and Virginia. Each state identified candidate intersection improvement projects that were constructed from 1994 to 1997. A few projects that were constructed in earlier years (1989-93) or in a later year (1998) were also identified.

The participating states initially suggested nearly 800 candidate intersection improvement projects. These projects were subjected to a screening review that involved reviewing construction plans and project memoranda, reviewing photologs, and, in some cases, visiting the site in the field. From these 800 candidates, a total of 280 improved intersections were selected that met all of the criteria for the study. The reasons for eliminating sites were as follows:

- The site was located at a multileg intersection; only three- and four-leg intersections were included in the study.
- The site had a traffic control other than two-way STOP or signal control.
- The site was not located at a public road intersection. Intersections at which the minor-road leg was a driveway to a shopping center or a school were excluded. Every selected study site had at least one minor-road leg that was a public road.
- Left- or right-turn lanes were added only on minor-road approach(es) to two-way STOP-controlled intersections. Where no traffic signals were present, only projects involving major-road turn lanes were considered. However, at signalized intersections, projects involving added turn lanes or any approach were considered.

- The planned project was never constructed.
- The added turn lane served a new intersection, not an intersection that existed before the improvement.
- Multiple improvements were made as part of the same project, such that the safety effects of the turn-lane improvement would be confounded with the effects of other improvement types. As much as possible, "clean" projects in which a single type of improvement was made were sought; complex projects involving multiple improvements at the same intersection were not considered. The one exception to this criterion was that existing unsignalized intersections where traffic signals were added at the same time the turn lanes were built were retained in the study. There were a substantial number of projects of this type for evaluation and it is certainly of potential interest to highway agencies, although it is unlikely that the safety effects of signalizing the intersection and adding turn lanes can be separated.
- Additional improvements were made within two years before or two years after the turn-lane improvement, such that any evaluation of the turn-lane improvement would be confounded by the other improvements.
- The intersection had unusual features that could have confounded the evaluation of the turn-lane improvement. For example, one intersection at which a left-turn lane was added was eliminated from consideration because there was a railroad crossing running diagonally across the intersection.
- Data needed for before-after evaluation of the project were not available. Geometric design and traffic control data were gathered by the research team and, therefore, were potentially available for any intersection of interest. However, traffic accident and traffic volume data were obtained through the assistance of the participating highway agencies. The data needs of the study for traffic accident and traffic volume data are described in Section 4 of this report. If traffic accident or traffic volume data were not available for a particular site, that site was eliminated from consideration.

These screening criteria were applied during the site-selection phase of the study, which reduced the number of candidate sites from approximately 800 to 388. An additional 108 improved sites were eliminated during the data collection process because unexpected features of the intersection or the project were discovered or because needed data were unavailable.

Number and Characteristics of Improved Sites

As stated above, a total of 280 improved or treatment sites were available for evaluation. The distribution of these sites by state, area type (rural/urban), project type, and project year are described below.

Table 6 presents the distribution of improved sites by state and area type. The tables shows that there are nearly equal numbers of projects at rural and urban sites. Approximately 45 percent of the improved sites (126 out of 280) are located in Illinois; the study was very fortunate that the Illinois Department of Transportation had conducted a substantial number of improvement projects that were suitable for the evaluation. No other state contributed more than 12.5 percent of the sites. An evaluation of sites at which left- or right-turn lanes were added found no major differences in site characteristics between the intersections of specific types in Illinois and those of the same type in other states. Thus, it does not appear to be a source of bias that 45 percent of the improved sites were located in a single state.

Sites were classified as rural or urban based on posted and operating speed, character of adjacent development, and location with respect to population centers, with speed being the single most important factor. Sites with posted speed limits and operating speeds of 88 km/h (55 mi/h) or more were generally classified as rural unless there was good reason based on development or location to do otherwise. Sites with posted speed limits and operating speeds less than 88 km/h (55 mi/h) were generally classified as urban unless there was good reason based on development or location to do otherwise. The urban classification included sites in both urban and suburban areas.

Table 7 presents the distribution of the improved sites at rural intersections by traffic control type and project type. The table shows that, in rural areas, the project types with the largest sample sizes are:

- Added left-turn lanes at existing unsignalized intersections (61 projects).
- Added right-turn lanes at existing unsignalized intersections (41 projects).
- Added left- and right-turn lanes at existing unsignalized intersections (27 projects).

Table 8 presents comparable data for improved sites at urban intersections. The table shows that, in urban areas, the project types with the largest sample sizes are:

- Added left-turn lanes at existing unsignalized intersections (20 projects).
- Added left-turn lanes at existing signalized intersections (43 projects).
- Added right-turn lanes at existing signalized intersections (21 projects).
- Added left- and right-turn lanes at existing unsignalized intersections (12 projects).
- Added left-turn lanes at newly signalized intersections (32 projects).

The other project types in Tables 7 and 8, not listed above, may not be present in sufficient numbers to permit a reliable evaluation.

Table 6. Number of Improved Intersection Sites by Area Type and State.

State	Number of improved sites by area type		
	Rural	Urban	Total
Iowa (IA)	15	17	32
Illinois (IL)	61	65	126
Louisiana (LA)	0	12	12
Minnesota (MN)	1	10	11
North Carolina (NC)	18	5	23
Nebraska (NE)	4	9	13
Oregon (OR)	21	14	35
Virginia (VA)	23	5	28
Total	143	137	280

Table 7. Number of Improved Sites at Rural Intersections.

Intersection traffic control	Project type	Number of improved sites by state								
		IA	IL	LA	MN	NC	NE	OR	VA	Total
Existing unsignalized intersections	Added LTLs	0	21	0	1	14	4	14	7	61
	Added RTLs	14	18	0	0	0	0	5	4	41
	Added both LTLs and RTLs	1	21	0	0	1	0	2	2	27
	Extended LTLs	0	0	0	0	0	0	0	2	2
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Existing signalized intersections	Added LTLs	0	0	0	0	0	0	0	0	0
	Added RTLs	0	0	0	0	0	0	0	0	0
	Added both LTLs and RTLs	0	0	0	0	0	0	0	0	0
	Extended LTLs	0	0	0	0	0	0	0	7	7
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	1	1
Newly signalized intersections	Added LTLs	0	0	0	0	0	2	0	0	2
	Added RTLs	0	0	0	0	0	1	0	0	1
	Added both LTLs and RTLs	0	1	0	0	0	0	0	0	1
Total		15	61	0	1	15	7	21	23	143

LTL = Left-turn lane
RTL = Right-turn lane

Table 8. Number of Improved Sites at Urban Intersections.

Intersection traffic control	Project type	Number of improved sites by state								
		IA	IL	LA	MN	NC	NE	OR	VA	Total
Existing unsignalized intersections	Added LTLs	2	6	1	2	0	5	4	0	20
	Added RTLs	1	3	0	0	0	0	0	0	4
	Added both LTLs and RTLs	0	1	0	0	0	0	0	0	1
	Extended LTLs	0	0	0	0	0	0	0	4	4
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Existing signalized intersections	Added LTLs	9	17	5	3	2	3	4	0	43
	Added RTLs	1	17	2	0	0	0	0	1	21
	Added both LTLs and RTLs	3	7	1	1	0	0	0	0	12
	Extended LTLs	0	0	0	0	0	0	0	0	0
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Newly signalized intersections	Added LTLs	1	14	3	4	3	1	6	0	32
	Added RTLs	0	0	0	0	0	0	0	0	0
	Added both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Total		17	65	12	10	5	9	14	5	137

LTL = Left-turn lane
RTL = Right-turn lane

Table 9 presents not only the number of intersections by area type, traffic control type, and project type, but also the number of added or extended left- and right-turn lanes. The added or extended turn lanes include only major-road turn lanes at unsignalized intersections, but may include both major- and minor-road turn lanes at signalized intersections. The table shows that the 280 improved sites include 411 added or extended left-turn lanes and 185 added or extended right-turn lanes.

Table 10 presents the distribution of improved sites by the year in which the project was constructed. The table shows that 268 of the 280 projects (94 percent) were constructed during the years from 1994 to 1997, inclusive. The earliest project was constructed in 1989 and the latest project was constructed in 1998. Virtually all of the projects were simple enough that their construction was begun and completed during a single calendar year.

Selection of Comparison Sites

Evaluation of the safety effectiveness of the projects implemented at the improved sites requires a method for estimating the changes in safety that would have occurred at the improved sites had the improvements not been made. This is normally accomplished with data from sites that are not improved during the study period.

Later sections of this report present three alternative evaluation approaches that were used during the project. One of the alternative approaches considered relies on one-to-one matching between improved and similar unimproved sites, while two others rely on predictive models developed from groups of unimproved sites. The sites selected as similar to the improved sites through a one-to-one matching process are referred to in this report as comparison sites. The identification and selection of these comparison sites and the number and characteristics of such sites are described below. This is followed by a description of other unimproved sites that were included in the development of predictive models, but were not matched to any particular improved site; such sites are referred to in this report as reference sites, and their selection and characteristics are discussed later in this section of the report.

Identification and Screening of Candidate Comparison Sites

Candidate comparison sites were identified by the research team, with assistance from the participating highway agencies. Screening of candidate comparison sites was conducted both from office and photolog data and in field visits. The criteria for a comparison site to match a particular treatment site were as follows:

- Located in the same state as the improved site.

Table 9. Number of Improved Intersections and Number of Turn-Lanes Added or Extended in Intersection Improvement Projects.

Intersection traffic control	Project type	Number of intersections and added or extended turn lanes								
		Rural intersections			Urban intersections			Combined		
		No. of inter-sections	No. of added or extended LTLs	No. of added or extended RTLs	No. of inter-sections	No. of added or extended LTLs	No. of added or extended RTLs	No. of inter-sections	No. of added or extended LTLs	No. of added or extended RTLs
Existing unsignalized intersections	Added LTLs	61	81	–	20	30	–	81	111	–
	Added RTLs	41	–	57	4	–	6	45	–	63
	Added both LTLs and RTLs	27	45	40	1	2	2	28	47	42
	Extended LTLs	7	7	–	4	6	–	11	13	–
	Extended both LTLs and RTLs	1	2	2	0	0	0	1	2	2
Existing signalized intersections	Added LTLs	0	0	–	43	128	–	43	128	–
	Added RTLs	0	–	0	21	–	46	21	–	46
	Added both LTLs and RTLs	0	0	0	12	42	29	12	42	29
	Extended LTLs	2	2	–	0	0	–	2	2	–
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Newly signalized intersections	Added LTLs	2	4	–	32	60	–	34	64	–
	Added RTLs	1	–	2	0	–	0	1	–	2
	Added both LTLs and RTLs	1	2	1	0	0	0	1	2	1
Total		143	143	102	137	268	83	280	411	185

LTL = Left-turn lane
RTL = Right-turn lane

Table 10. Year Completed for Projects at Improved Intersections.

Year completed	No. of projects	Percent of projects
1989	1	0.4
1991	2	0.7
1992	7	2.5
1993	5	1.8
1994	71	25.4
1995	82	29.3
1996	55	19.6
1997	55	19.6
1998	2	0.7
	280	

- Located geographically as close as possible to the improved site. Whenever possible, a matched comparison site was chosen on the same highway or in the same general area as the improved site; however, where a close geographical location was not possible, a similar intersection in a different part of the state was selected.

- Same number of intersection legs as the improved site (i.e., both were either three-leg or four-leg intersections).

- Same traffic control as the improved site (i.e., both were either two-way STOP-controlled or signal-controlled intersections).

- Similar geometrics to the improved site (e.g., if the improved site was a skewed intersection or was located on a multilane highway, then a skewed intersection or an intersection on a multilane highway was selected as the comparison site, if possible).

- Similar ADT to the improved site; however, ADT matching was approximate because some comparison sites were selected before the minor-road ADT was known.

- No major geometric or traffic control changes during the study period (generally 1988 to 1999).

It was the original intention that the geometrics of the matched comparison site should resemble the geometrics of the improved site in the period before the improvement was made; in other words, the comparison sites would be intersections without major-road turn lanes. This criterion proved impractical because, especially for urban signalized intersections, candidate comparison sites with no turn lanes were very hard to find. Therefore, a decision was made that the geometrics of the matched comparison site should resemble the geometrics of the improved site in either its condition before improvement or after improvement, with matching to the condition before improvement being preferred. In all cases, the matched comparison site must have undergone no major geometric or traffic control improvement during the study period. In other words, if the matched comparison site had major-road left-turn lanes, it must have had those lanes in place during the periods both before and after the project at the improved site.

For improved sites at which both signalization and turn lanes were installed, the matched comparison site was a similar unsignalized intersection that remained unsignalized throughout the study period.

Number and Characteristics of Matching Improved and Comparison Sites

Matched comparison sites were identified for 260 of the 280 improved sites (93 percent). The other 20 sites were sufficiently unique that a satisfactory matching comparison site could not be found.

The characteristics of the 260 pairs of matching improved and comparison sites are summarized in tables 11 through 15, which are analogous to tables 5 through 10 presented above for the improved sites. Tables 11 through 15 represent the characteristics of the 260 improved sites (a subset of the 280 improved sites presented earlier). Section 4 of this report presents further data on the characteristics of the matched improved and comparison sites.

Selection of Reference Sites

As described earlier, a portion of the improved sites' evaluation uses predictive models developed with data from unimproved sites. An advantage of this approach is that one-on-one matching of improved and unimproved sites is not required. In fact, the larger the data set of unimproved sites on which predictive models are based the better, so it is desirable to have data for more unimproved sites than improved sites.

To increase the sample of unimproved sites, additional reference sites were selected. The selection of the additional reference sites and the number and characteristics of the combined data set of comparison and reference sites is described below.

Table 11. Number of Matched Pairs of Improved and Comparison Sites by Area Type and State.

State	Number of matched sites by area type		
	Rural	Urban	Total
Iowa (IA)	15	17	32
Illinois (IL)	59	54	113
Louisiana (LA)	0	11	11
Minnesota (MN)	1	10	11
North Carolina (NC)	18	5	23
Nebraska (NE)	4	8	12
Oregon (OR)	17	14	31
Virginia (VA)	22	5	27
Total	136	124	260

Table 12. Number of Matched Pairs of Improved and Comparison Sites at Rural Intersections.

Intersection traffic control	Project type	Number of matched pairs of sites by state								
		IA	IL	LA	MN	NC	NE	OR	VA	Total
Existing unsignalized intersections	Added LTLs	0	20	0	1	14	4	11	7	57
	Added RTLs	14	17	0	0	0	0	4	4	39
	Added both LTLs and RTLs	1	21	0	0	1	0	2	2	27
	Extended LTLs	0	0	0	0	0	0	0	2	2
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Existing signalized intersections	Added LTLs	0	0	0	0	0	0	0	0	0
	Added RTLs	0	0	0	0	0	0	0	0	0
	Added both LTLs and RTLs	0	0	0	0	0	0	0	0	0
	Extended LTLs	0	0	0	0	0	0	0	6	6
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	1	1
Newly signalized intersections	Added LTLs	0	0	0	0	2	0	0	0	2
	Added RTLs	0	0	0	0	1	0	0	0	1
	Added both LTLs and RTLs	0	1	0	0	0	0	0	0	1
Total		15	59	0	1	18	4	17	22	136

LTL = Left-turn lane
RTL = Right-turn lane

Table 13. Number of Matched Pairs of Improved and Comparison Sites at Urban Intersections.

Intersection traffic control	Project type	Number of matched pairs of sites by state								
		IA	IL	LA	MN	NC	NE	OR	VA	Total
Existing unsignalized intersections	Added LTLs	2	4	1	2	0	5	4	0	18
	Added RTLs	1	0	0	0	0	0	0	0	1
	Added both LTLs and RTLs	0	1	0	0	0	0	0	0	1
	Extended LTLs	0	0	0	0	0	0	0	0	0
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Existing signalized intersections	Added LTLs	9	16	4	3	2	2	4	0	40
	Added RTLs	1	15	2	0	0	0	0	1	19
	Added both LTLs and RTLs	3	6	1	1	0	0	0	0	11
	Extended LTLs	0	0	0	0	0	0	0	4	4
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Newly signalized intersections	Added LTLs	1	12	3	4	3	1	6	0	30
	Added RTLs	0	0	0	0	0	0	0	0	0
	Added both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Total		17	54	11	10	5	8	14	5	124

LTL = Left-turn lane
RTL = Right-turn lane

Table 14. Number of Improved Intersections and Number of Turn-Lanes Added in Projects at Improved Sites with Matched Comparison Sites in Candidate Intersection Improvement Projects.

Intersection traffic control	Project type	Number of intersections and added or extended turn lanes								
		Rural intersections			Urban intersections			Combined		
		No. of inter-sections	No. of added or extended		No. of inter-sections	No. of added or extended		No. of inter-sections	No. of added or extended	
			LTLs	RTLs		LTLs	RTLs		LTLs	RTLs
Existing unsignalized intersections	Added LTLs	57	75	–	18	26	–	75	101	–
	Added RTLs	39	–	54	1	–	1	40	–	55
	Added both LTLs and RTLs	27	45	40	1	2	2	28	47	42
	Extended LTLs	6	6	–	4	6	–	10	12	–
	Extended both LTLs and RTLs	1	2	2	0	0	0	1	2	2
Existing signalized intersections	Added LTLs	0	0	–	40	120	–	40	120	–
	Added RTLs	0	–	0	19	–	41	19	–	41
	Added both LTLs and RTLs	0	0	0	11	38	28	11	38	28
	Extended LTLs	2	2	–	0	0	–	2	2	–
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Newly signalized intersections	Added LTLs	2	4	–	30	56	–	32	60	–
	Added RTLs	1	–	2	0	–	0	1	–	2
	Added both LTLs and RTLs	1	2	1	0	0	0	1	2	1
Total		136	136	99	124	248	72	260	384	171

LTL = Left-turn lane
RTL = Right-turn lane

Table 15. Completion Date for Intersection Improvement Projects With Matched Comparison Sites.

Year completed	No. of projects	Percent of projects
1989	1	0.4
1991	1	0.4
1992	7	2.7
1993	4	1.5
1994	67	25.8
1995	73	28.1
1996	54	20.8
1997	51	19.6
1998	2	0.8
	260	

Identification and Screening of Candidate Reference Sites

Reference sites were intersections similar to the sites that were improved, but not matched to any particular improved site. Reference sites were of the same area types and traffic control types as the improved sites, but must have been free of unusual features and undergone no major geometric or traffic control improvements during the study period.

The research team identified candidate reference sites with assistance from participating State highway agencies. Many of the reference sites were candidate comparison sites that did not match any particular improved site. The candidate reference sites were screened both from office and photolog data and in field visits. Reference sites were retained only if traffic volume and traffic accident data for the site were available.

Number and Characteristics of Comparison and Reference Sites

A total of 40 additional reference sites were selected and included in the data collection effort described in Section 4 of this report. Thus, there were a combined total of 300 unimproved sites available for use in comparison groups and for development of predictive models, 260 matched comparison sites and 40 additional reference sites.

Table 16 presents the distribution of the 300 comparison and reference sites by area type, traffic control type, and state. The comparison and reference sites include only 6 rural signalized intersections, but at least 50 rural unsignalized, urban unsignalized, and urban signalized intersections. Approximately 53 percent of the comparison and reference sites are in rural areas, and 47 percent in urban areas. Approximately 69 percent of the comparison and reference sites are at unsignalized intersections, and 31 percent are at signalized intersections. Approximately 33 percent of the comparison and reference sites are at three-leg intersections, and 67 percent are at four-leg intersections.

Section 4 of this report presents data on the traffic volumes and accident experience at the comparison and reference sites.

Table 16. Number of Comparison and Reference Sites by Area Type, Traffic Control Type, and State.

Area type	Traffic control type	Number of intersection legs	State								
			IA	IL	LA	MN	NC	NE	OR	VA	Total
Rural	Unsignalized	3	2	32	0	0	12	0	12	14	72
		4	15	40	0	1	6	8	7	5	82
		Total	17	72	0	1	18	8	19	19	154
Rural	Signalized	3	0	0	0	0	0	0	0	1	1
		4	0	0	0	0	0	0	0	5	5
		Total	0	0	0	0	0	0	0	6	6
Urban	Unsignalized	3	1	9	2	0	0	0	6	0	8
		4	3	12	2	6	3	5	5	0	36
		Total	4	21	4	6	3	5	11	0	54
Urban	Signalized	3	1	4	1	0	0	0	0	1	7
		4	12	42	6	4	2	5	4	4	79
		Total	13	46	7	4	2	5	4	5	86
Both	Both	3	4	45	3	0	12	0	18	16	98
		4	30	94	8	11	11	18	16	14	202
		Total	34	139	11	11	23	18	34	30	300

4. DATA COLLECTION

This section of the report documents the data collection performed for the intersection sites selected for the safety evaluation of left- and right-turn lanes. The types of data collection addressed includes geometric design and traffic control data, traffic volume data, and traffic accident data. Each type of data is addressed below.

Geometric Design and Traffic Control Data

Data were collected on the geometric design and traffic control features of each improved, comparison, and reference site. Nearly all of the study sites were visited in the field by a research team member to obtain geometric design and traffic control data. In addition, geometric design and traffic control data were obtained from the following sources, whenever available:

- Construction or as-built plans.
- Intersection drawings or sketches.
- Project reports.
- Highway agency project memoranda.

These sources were also useful in documenting what specific geometric changes were made as part of a project.

Field Visits

The field visits provided a key opportunity to observe the characteristics of each site and record data of interest. Some intersections were visited twice, once during the selection of improved sites and once during the data collection activities. Time spent in the field in each state was also used to identify or review candidate comparison and reference sites.

The field activities involved visits to both highway agency offices and field sites, and had multiple purposes including:

- Reviewing each intersection in the field.

- Taking photographs and/or making a videotape of site conditions for later reference during the evaluation.

- Obtaining documentation of the geometrics and traffic control of each intersection both before and after the project.

- Obtaining documentation on the reasons why the project was implemented.

- Obtaining documentation on the starting and completion dates for each project.

- Interviewing the engineers most familiar with development of each project and its operational and safety effects.

The vast majority of field visits to improved sites were made after completion of project construction. This provided an opportunity to verify in the field that the project had, in fact, been constructed and that its geometrics in the period after construction matched the data provided in the office. The geometrics before construction were often evident in the field, due to differences in pavement surfaces, but were also documented from office records. Relying on both office and field data, a record was made of the geometric design and traffic control changes made as part of the improvement project (see appendix D).

Geometric Design and Traffic Control Variables

Geometric design and traffic control data were collected for each study intersection. For each individual intersection approach, the geometric design and traffic control variables obtained were:

- Number of through lanes.
- Number of left-turn lanes.
- Number of right-turn lanes.
- Type of left-turn channelization.
- Type of right-turn channelization.
- Horizontal alignment.
- Approach grades.
- Presence of crest/sag vertical curves.
- Total through lane width.
- Right shoulder type.
- Right shoulder width.
- Total left-turn lane width.
- Total left-turn lane length.
- Total right-turn lane width.
- Total right-turn lane length.
- Presence of median (divided/undivided).
- Median width.
- Median type.
- One-way vs. two-way operation.
- Left-turn prohibition.
- Number of driveways within 76 m (250 ft).
- Type of driveways.
- Curb parking within 76 m (250 ft).

- Type of traffic control.
- Type of left-turn phasing (if signalized).
- Presence of pedestrian signals (if signalized).
- Presence of advance warning signs.
- Posted speed limit.

For the intersection as a whole, variables obtained were:

- Number of intersection legs.
- Angle of intersection.
- Area type (rural/urban).
- Character of development.
- Lighting.
- Level of pedestrian activity.

The set of geometric design and traffic control variables obtained was purposely broader than needed for the planned analyses so that issues beyond those planned could be addressed, as needed. It was never envisioned that all of these variables could, or should, be related to traffic accidents, but they were obtained to assure that the documentation of each study intersection was very complete. Appendix D provides definitions of the measurement methods and codes used for each of these geometric design and traffic control variables.

Traffic Volume Data

Traffic volume data were obtained for each study intersection. The desirable traffic volume data set for any study intersection included:

- Major- and minor-road ADTs for each year of the study period.
- Intersection turning movement counts for morning and evening peak periods.

It was found, as a practical matter, that the participating states nearly always had ADT data on file for the major-road in the vicinity of each intersection. Minor-road ADT data were often, but not always, available for the improved sites; ADT data were likely to be available for the improved sites because there had often been a traffic count made at the intersection as part of the design of the project. Minor-road ADT data for comparison and reference sites were available for virtually every intersection of potential interest in some states and only for a very limited number of intersections in other states.

Intersection turning movement counts were of direct interest to the study. In evaluating the safety effectiveness of intersection left- and right-turn lanes, it would be valuable to know the volume of vehicles turning left or right and using the turn lanes of interest. However, turning movement volumes were not available for most of the intersections. In particular, turning movement volumes were only available for less than 10 percent of the improved sites, and an even smaller percentage of the comparison and reference sites. Therefore, as a practical matter, it was not feasible to use intersection turning volumes in the safety evaluation because the sample size for any given type of project would have been substantially reduced.

It was decided that, for a intersection to be used in the evaluation, ADT data should be available for both the major- and minor-road legs of the intersection for at least one year during the study period. If this minimal traffic volume data set was not available, any improved, comparison, or reference site was dropped from the study. For most intersections, major-road ADT data for several years and minor-road ADT data for at least one year were available. These ADT data came from many sources in the participating highway agencies, including state ADT maps and logbooks, county and city ADT maps, traffic volume data bases and manual files, and, in some cases, traffic counts made specifically for this evaluation. However, as stated above, no intersection was used unless major- and minor-road ADT data were available for at least one year.

Some of the analyses performed required separate estimates of intersection ADTs for each year of the study period. These estimates for each individual year were obtained by interpolation and extrapolation from the ADT data obtained from the participating states. All extrapolations were checked very carefully to assure that the rates of ADT growth or decline were reasonable for the site conditions and consistent with ADT growth or decline patterns at nearby sites. Where ADT data were available for only one year, extrapolations to earlier and later years were made using the following data sources for guidance:

- Minor-road ADTs at a given intersection were extrapolated, where possible, using the growth or decline rate for the major road at the same intersection.

- Major- and minor-road ADTs at one intersection were extrapolated based on ADT growth or decline patterns for a nearby intersection, such as the matched comparison site, or a nearby set of intersections.

- Major- and minor-road ADTs at one intersection were extrapolated based on ADT growth or decline rates from a nearby continuous count station, if available.

Table 17 presents the distribution of ADTs for the improved and comparison/reference sites, including mean, minimum, and maximum values of the ADT for the year 1999, and annualized percentage growth rates in ADT over the period from 1988 to 1999, for major-road ADT, minor-road ADT, and total ADT entering the intersection. Where the ADTs at an intersection differ between the two major-road approaches or the two minor-road approaches, Table 17 is based on the larger of the two major- or minor-road ADT values; for this reason, the mean total entering ADT is not necessarily equal to the sum of the mean major- and minor-road ADTs. Table 18 presents comparable data for the matched improved and comparison sites. The 260 matched improved sites shown in Table 18 are a subset of the 280 total improved sites shown in table 17.

Table 17. ADT Volumes for All Improved and Comparison/Reference Sites.

				Major-road ADT (veh/day)				Minor-road ADT (veh/day)				Total entering ADT (veh/day)			
Area type	Traffic control type	Site type	Number of inter-sections	Mean 1999	Mini-mum 1999	Maxi-mum 1999	Growth rate 1988-1999	Mean 1999	Mini-mum 1999	Maxi-mum 1999	Growth rate 1988-1999	Mean 1999	Mini-mum 1999	Maxi-mum 1999	Growth rate 1988-1999
Rural	Unsignalized	Improved	131	9,100	1,600	32,400	2.6	1,400	50	11,800	2.4	9,700	2,000	32,000	2.6
		Comparison/ Reference	154	8,100	1,100	26,800	2.5	900	25	6,400	2.4	8,500	1,100	26,700	2.5
Rural	Signalized	Improved	8	15,100	10,700	20,000	1.8	5,600	2,500	8,400	2.5	17,800	14,800	22,900	2.3
		Comparison/ Reference	6	20,300	14,500	26,000	3.1	5,900	1,300	11,400	3.7	22,600	19,000	31,700	2.8
Rural	Newly signalized	Improved	4	11,900	4,200	17,700	3.2	5,200	9,200	6,400	3.3	16,400	11,400	21,900	3.1
		Comparison/ Reference	—	—	—	—	—	—	—	—	—	—	—	—	—
Urban	Unsignalized	Improved	25	14,500	1,520	40,600	2.1	1,800	200	8,0001	2.2	15,500	1,800	41,200	2.1
		Comparison/ Reference	54	14,400	2,000	25,600	2.2	2,400	80	6,300	2.2	15,500	2,60	26,500	2.2
Urban	Signalized	Improved	80	21,300	7,200	55,100	1.1	7,900	550	26,000	1.8	26,800	7,500	61,000	1.2
		Comparison/ Reference	86	21,500	5,800	55,100	2.0	7,400	100	25,700	1.9	26,600	6,800	62,300	1.9
Urban	Newly signalized	Improved	32	16,700	4,600	40,300	2.2	4,300	100	13,700	2.2	19,600	5,400	43,800	2.2
		Comparison/ Reference	—	—	—	—	—	—	—	—	—	—	—	—	—

Traffic Accident Data

Traffic accident data for the study intersections were obtained from the computerized accidents records of the participating state highway agencies. In some cases, the computerized data were supplemented with collision diagrams prepared by manual or computer means.

Accident data were obtained for all study intersections in each state for a period of 9 to 13 years. Table 19 shows the specific time periods for which data were available in each state. In most states, the study period began with the calendar year 1988. However, because of limitations on data availability and changes in data formats, data for Minnesota and Virginia were obtained for a period beginning in 1990 and data for North Carolina for a period beginning in 1991. The final year of the study period was 1999 for all states except one; in Oregon, the study was extended to include data for the year 2000 because both accident and ADT data for that period were available.

Data were requested from each state for all accidents during the study period that occurred on any intersection leg within 300 meters (1,000 feet) of each intersection. The 300-meter (1,000-foot) distance was not selected because accidents that far from the intersection are necessarily related to the intersection, but simply to assure that all accidents of potential interest were available and that no request for supplementary data would need to be available.

After evaluation of the available data, a criterion for identifying intersection-related accidents of interest to the evaluation was established. Intersection-related accidents were selected from the available data including accidents assigned mileposts within 75 meters (250 feet) of the study intersection, and had were designated by the investigating officer or accident data coder that they were related to the operation of the intersection. Where closely spaced intersections were present, the 75-meter (250 foot) boundary was decreased to a point half the distance to the adjacent intersection. Accidents indicated as being non-intersection-related or driveway-related were excluded from the evaluation. Table 19 includes data only for accidents that meet this definition of being related to the intersection.

The one exception to this procedure described above was in accident data from Illinois. Illinois codes all intersection-related accidents to the milepost of the intersection. Therefore, the milepost cannot be used to distinguish the distance of a collision from the intersection in question. In Illinois data, all accidents assigned to the intersection milepost are presumed to be related to the operation of the intersection and were included in the analyses.

Table 18. ADT Volumes for Matched Improved and Comparison Sites.

				Major-road ADT (veh/day)				Minor-road ADT (veh/day)				Total entering ADT (veh/day)			
Area type	Traffic control type	Site type	Number of inter- sections	Mean 1999	Mini- mum 1999	Maxi- mum 1999	Growth rate 1988-1999	Mean 1999	Mini- mum 1999	Maxi- mum 1999	Growth rate 1988-1999	Mean 1999	Mini- mum 1999	Maxi- mum 1999	Growth rate 1988-1999
Rural	Unsignalized	Matched Improved	125	9,100	1,600	32,400	2.6	1,300	50	6,800	2.3	9,700	2,000	32,000	2.5
		Matched Comparison	125	7,700	1,100	26,800	2.6	900	25	6,400	2.3	8,100	1,100	26,300	2.6
Rural	Signalized	Matched Improved	7	15,000	10,700	20,000	1.7	5,600	2,500	8,400	2.4	17,700	14,800	22,900	2.3
		Marked Comparison	7	20,300	14,500	26,000	3.1	5,900	1,300	11,400	3.7	22,600	19,000	31,700	2.8
Rural	Newly signalized	Matched Improved	4	11,900	9,200	17,700	3.2	5,200	4,200	6,400	3.3	16,400	11,400	21,900	3.2
		Matched Comparison	4	10,800	7,500	18,000	3.0	1,900	700	2,900	3.1	12,600	8,000	19,600	3.2
Urban	Unsignalized	Matched Improved	20	14,900	1,600	40,600	2.4	1,900	200	8,000	2.3	15,900	1,900	41,200	2.4
		Matched Comparison	20	13,900	2,000	25,600	2.3	1,400	100	4,400	2.0	14,500	2,600	26,500	2.3
Urban	Signalized	Matched Improved	74	21,100	7,200	55,100	1.1	7,800	550	26,000	1.8	26,600	7,500	61,100	1.2
		Matched Comparison	74	21,300	5,800	55,100	1.9	7,200	100	25,700	2.0	26,100	6,800	62,300	1.9
Urban	Newly signalized	Matched Improved	30	15,800	4,600	38,200	2.5	4,200	100	13,700	2.3	18,600	5,400	40,300	2.5
		Matched Comparison	30	14,200	4,000	36,500	2.1	2,800	80	10,200	2.3	15,760	4,800	38,000	2.1

Table 19. Summary of Accident Database.

State	Accident data period			Number of inter-sections	Total No. of accidents	Accidents by severity level			Percentage of accidents by severity level		
	First year	Last year	Total No. of years			Fatal	Injury	PDO	Fatal	Injury	PDO
Iowa (IA)	1988	1999	12	66	3,611	15	1,522	2,074	0.4	42.1	57.5
Illinois (IL)	1988	1999	12	265	12,875	57	4,537	8,281	0.4	35.5	64.1
Louisiana (LA)	1988	1998	11	23	2,668	8	994	1,666	0.3	37.3	62.4
Minnesota (MN)	1990	1999	10	22	890	5	334	551	0.6	37.5	61.9
North Carolina (NC)	1991	1999	9	46	1,055	5	508	542	0.5	48.2	51.3
Nebraska (NE)	1988	1999	12	31	1,681	6	726	949	0.4	43.2	56.4
Oregon (OR)	1988	2000	13	69	1,860	14	946	900	0.8	50.9	48.3
Virginia (VA)	1990	1999	10	58	1,416	13	636	767	0.9	44.9	54.2
Total				580	26,056	123	10,203	15,730	0.5	39.2	60.3

In some states, the accident location milepost or reference point assigned to an intersection may change from year to year. These changes were accounted for so that a consistent set of accident data from year to year were extracted from the available accident data.

The accident data elements obtained from each state varied; in most cases, the accident data provided by the state included more accident descriptors than were needed for the study. Both accident-level and vehicle-level accident descriptors were obtained. The variables that were actually used in preliminary investigations and in the safety evaluation itself were:

- Date of accident (month/day/year).
- Accident location (typically by county, route, and milepost or reference point).
- Accident severity (fatal/injury/property damage only).
- Number of vehicles involved.
- Accident type/manner of collision.
- Direction of travel of involved vehicles.
- Actual or intended movement of involved vehicles (through/left turn/right turn/U turn).
- Relationship to intersection (at intersection/not at intersection but intersection related/not intersection related).
- Vehicle and party types involved (passenger car/truck/bus/pedestrian/bicycle).

The dates for which accident data were obtained are shown in Table 19. The table shows that the periods for which accident data were available varied among the states. In each state, the accident data period extends back to 1988, whenever possible; where a later date is shown for the beginning of the accident data period, data before that date were unavailable. Study periods before and after improvement of each treated site were determined based on criteria described in Section 5 of this report.

Table 19 documents the magnitude of the available accident data base. The table shows that there were a total of 26,056 intersection-related accidents during the study period for all 580 intersections combined. Approximately 49 percent of the accidents occurred in Illinois which, as documented above, included approximately 45 percent of the study intersections. The table also shows the distribution of accident severity, by state and overall; accidents involving fatalities ranged from 0.3 to 0.9 percent of all accidents, and accidents involving non-fatal injuries ranged from 35.5 to 50.9 percent of all accidents.

Table 20 compares the total intersection accident experience, exposure, and accident rate per million entering vehicles, for periods before and after the improvement projects, for the 260 matched improved and comparison sites at rural intersections. Table 21 presents comparable data for urban intersections.

Table 20. Safety Performance of Matched Improved and Comparison Sites at Rural Intersections.

Area type	Traffic control type	Project type	Site type	Before period: No. of acci-dents	Before period: Average ADT (veh/day)	Before period: Exposure (MEV)	Before period: Accident rate (acc/MEV)	After period: No. of accidents	After period: Average ADT (veh/day)	After period: Exposure (MEV)	After period: Accident rate (acc/MEV)
Rural	Unsignalized	Added LTLs	Improved	648	10,000	1288.4	0.50	271	11,400	963.1	0.28
			Comparison	321	7,300	915.6	0.35	346	8,600	730.3	0.47
Rural	Unsignalized	Added RTLs	Improved	240	4,700	445.2	0.54	142	4,750	335.1	0.42
			Comparison	178	5,800	440.2	0.40	108	5,900	354.2	0.30
Rural	Unsignalized	Added both LTLs and RTLs	Improved	234	8,500	568.3	0.41	150	10,400	427.3	0.35
			Comparison	152	7,200	478.2	0.32	94	8,400	344.1	0.27
Rural	Unsignalized	Extended LTLs	Improved	28	12,600	64.3	0.44	14	14,200	20.7	0.68
			Comparison	6	9,400	48.1	0.13	1	11,900	17.4	0.06
Rural	Unsignalized	Extended both LTLs and RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Rural	Signalized	Added LTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Rural	Signalized	Added RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Rural	Signalized	Added both LTLs and RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Rural	Signalized	Extended LTLs	Improved	89	14,600	213.2	0.42	28	17,500	88.2	0.32
			Comparison	139	18,700	267.7	0.52	69	21,700	114.5	0.60
Rural	Signalized	Extended both LTLs and RTLs	Improved	31	13,800	35.2	0.88	8	17,000	12.4	0.65
			Comparison	20	17,200	44.1	0.45	9	20,700	15.1	0.60

MEV = million entering vehicles

Table 20. Safety Performance of Matched Improved and Comparison Sites at Rural Intersections (Continued).

Area type	Traffic control type	Project type	Site type	Before period: No. of accidents	Before period: Average ADT (veh/day)	Before period: Exposure (MEV)	Before period: Accident rate (acc/MEV)	After period: No. of accidents	After period: Average ADT (veh/day)	After period: Exposure (MEV)	After period: Accident rate (acc/MEV)
Rural	Newly signalized	Added LTLs	Improved	40	15,800	39.6	1.01	62	18,400	61.2	1.01
			Comparison	7	13,000	32.0	0.22	31	15,000	50.4	0.62
Rural	Newly signalized	Added RTLs	Improved	27	12,600	18.4	1.47	44	14,900	21.7	2.03
			Comparison	11	9,100	13.3	0.83	20	10,800	15.7	1.27
Rural	Newly signalized	Added both LTLs and RTLs	Improved	23	7,500	22.1	1.04	6	10,700	11.7	0.51
			Comparison	4	5,100	14.8	0.27	1	7,500	8.2	0.12

MEV = million entering vehicles

Table 21. Safety Performance of Matched Improved and Comparison Sites at Urban Intersections.

Area type	Traffic control type	Project type	Site type	Before period: No. of acci-dents	Before period: Average ADT (veh/day)	Before period: Exposure (MEV)	Before period: Accident rate (acc/ MEV)	After period: No. of accidents	After period: Average ADT (veh/day)	After period: Exposure (MEV)	After period: Accident rate (acc/ MEV)
Urban	Unsignalized	Added LTLs	Improved	352	13,500	595.5	0.59	152	16,100	451.5	0.34
			Comparison	216	12,700	567.0	0.38	221	14,900	411.5	0.54
Urban	Unsignalized	Added RTLs	Improved	3	1,700	5.4	0.56	0	2,000	1.5	0.00
			Comparison	8	2,400	7.9	1.03	1	2,700	2.0	0.50
Urban	Unsignalized	Added both LTLs and RTLs	Improved	12	18,400	46.9	0.26	4	18,900	27.6	0.14
			Comparison	17	24,500	62.6	0.27	6	26,500	38.6	0.16
Urban	Unsignalized	Extended LTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Urban	Unsignalized	Extended both LTLs and RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Urban	Signalized	Added LTLs	Improved	2,707	23,700	2,306.7	1.17	1,108	24,800	1,467.0	0.76
			Comparison	2,246	20,500	1,958.1	1.15	1,404	22,900	1,371.9	1.02
Urban	Signalized	Added RTLs	Improved	1,551	24,400	1,298.7	1.19	666	26,400	568.3	1.17
			Comparison	1,502	24,600	1,315.4	1.14	538	27,900	585.8	0.92
Urban	Signalized	Added both LTLs and RTLs	Improved	867	23,700	716.8	1.21	320	28,800	380.7	0.84
			Comparison	796	21,800	662.5	1.20	314	26,700	348.4	0.90
Urban	Signalized	Extended LTLs	Improved	162	32,800	277.7	0.58	133	35,000	159.8	0.83
			Comparison	141	30,600	265.3	0.53	111	36,300	161.7	0.69
Urban	Signalized	Extended both LTLs and RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—

MEV = million entering vehicles

Table 21. Safety Performance of Matched Improved and Comparison Sites at Urban Intersections (Continued).

				Before period				After period			
Area type	Traffic control type	Project type	Site type	No. of acci-dents	Average ADT (veh/day)	Exposure (MEV)	Accident rate (acc/MEV)	No. of accidents	Average ADT (veh/day)	Exposure (MEV)	Accident rate (acc/MEV)
Urban	Newly signalized	Added LTLs	Improved	1,008	15,100	1,155.0	0.87	416	18,100	735.3	0.57
			Comparison	564	13,500	1,029.7	0.55	354	15,500	632.5	0.56
Urban	Newly signalized	Added RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—
Urban	Newly signalized	Added both LTLs and RTLs	Improved	—	—	—	—	—	—	—	—
			Comparison	—	—	—	—	—	—	—	—

MEV = million entering vehicles

5. EVALUATION PLAN

This section of the report presents the evaluation plan for determining the safety effectiveness of intersection improvement projects involving left- and right-turn lanes. The discussion includes the target accident types and locations for the improvement projects to be evaluated and the accident severity levels considered. An overview and comparison of three alternative statistical approaches to before-after evaluation are presented together with a detailed discussion of each of those three approaches. All three alternative statistical approaches were used in the evaluation and the results obtained from each approach are presented in section 6.

Target Accident Types and Locations

As part of the evaluation, data were obtained for each accident that occurred at or near each study intersection in specified time periods both before and after the projects were evaluated. A decision was made concerning which accidents were the “target accidents” to which the evaluation should be applied. Target accidents included all accidents that occurred at or near each intersection during the study period. In addition, it was also considered desirable to limit the evaluation to those accidents of collision types or collision locations that were likely to be affected by the improvements being evaluated. If the accident data for both the before and after periods included accidents of types that could not conceivably be affected by the improvement, then this “noise” would have introduced unnecessary variability into the accident counts that may have prevented the researchers’ ability to observe the effect of the improvement.

Thus, while the effect of the improvement projects on total intersection accidents should be considered, it also is desirable to consider specific subsets of total intersection accidents as the target accidents for the evaluation. On the other hand, the effects of some improvement types may be so pervasive that nearly every intersection accident may be affected. Clearly, the appropriate target accidents depend on the nature of the improvement being evaluated.

Section 3 of this report highlights four key types of intersection improvement projects to be considered in the before-after evaluation:

- Addition of left-turn lanes.
- Addition of right-turn lanes.
- Addition of both left- and right-turn lanes.
- Extension of the length of existing left- and right-turn lanes.

These project types vary in the portions of the intersection and the accident types they potentially affect. The effects of right-turn lanes appear to be the simplest and, therefore, are addressed first. Projects involving left-turn lanes, both left- and right-turn lanes, and extended turn lanes will then be addressed.

Projects Involving Addition of Right-Turn Lanes

The safety effects of adding a right-turn lane on an intersection approach are expected to be limited to only certain types of intersection accidents. For example, it might be supposed that installation of a right-turn lane on a particular approach would affect primarily the following accident types:

- Rear-end collisions between vehicles on the treated approach.
- Sideswipe, same-direction collisions between vehicles on the treated approach.
- Angle or sideswipe collisions between a right-turning vehicle and a vehicle within the intersection or on the departing roadway of the intersecting street.

However, because other collision types could potentially be affected by installation of a right-turn lane, a particular portion of the intersection can be designated as the "target area" rather than designating particular accident types as target accidents. Figure 1 illustrates the portion of the intersection area that would be expected to be affected by installation of a right-turn lane on a major-road approach. Only accidents occurring within the target area would be expected to be affected by the addition of the right-turn lane.

Since only a limited portion of the intersection area is potentially affected by installation of a right-turn lane, it may also be possible to use the accidents that occur in the portions of the intersection outside the target area as a comparison group in the analysis. This idea is explored further below.

Figure 2 illustrates an intersection at which right-turn lanes have been added on both major-road approaches. Here there are separate target areas for the two improvements that touch but do not overlap. Thus, it appears to be possible to evaluate each added right-turn lane separately, and accidents outside the target areas (i.e., on the minor-road approaches and on the departing roadways) could still be considered as part of a comparison group, unaffected by the improvement.

A review of the descriptors of individual accidents available in data from the participating states established that there are no data to explicitly identify accidents within the target areas shown in figures 1 and 2 (essentially accidents that occur on a particular intersection approach). It is possible, however, to identify:

- Accidents that involved vehicles that passed through the approach in question (i.e., vehicles with a particular initial direction of travel). This is very close to the target area definitions shown in figures 1 and 2, but could include collisions involving vehicles on the approach of interest after they have left the shaded areas shown in the figures.

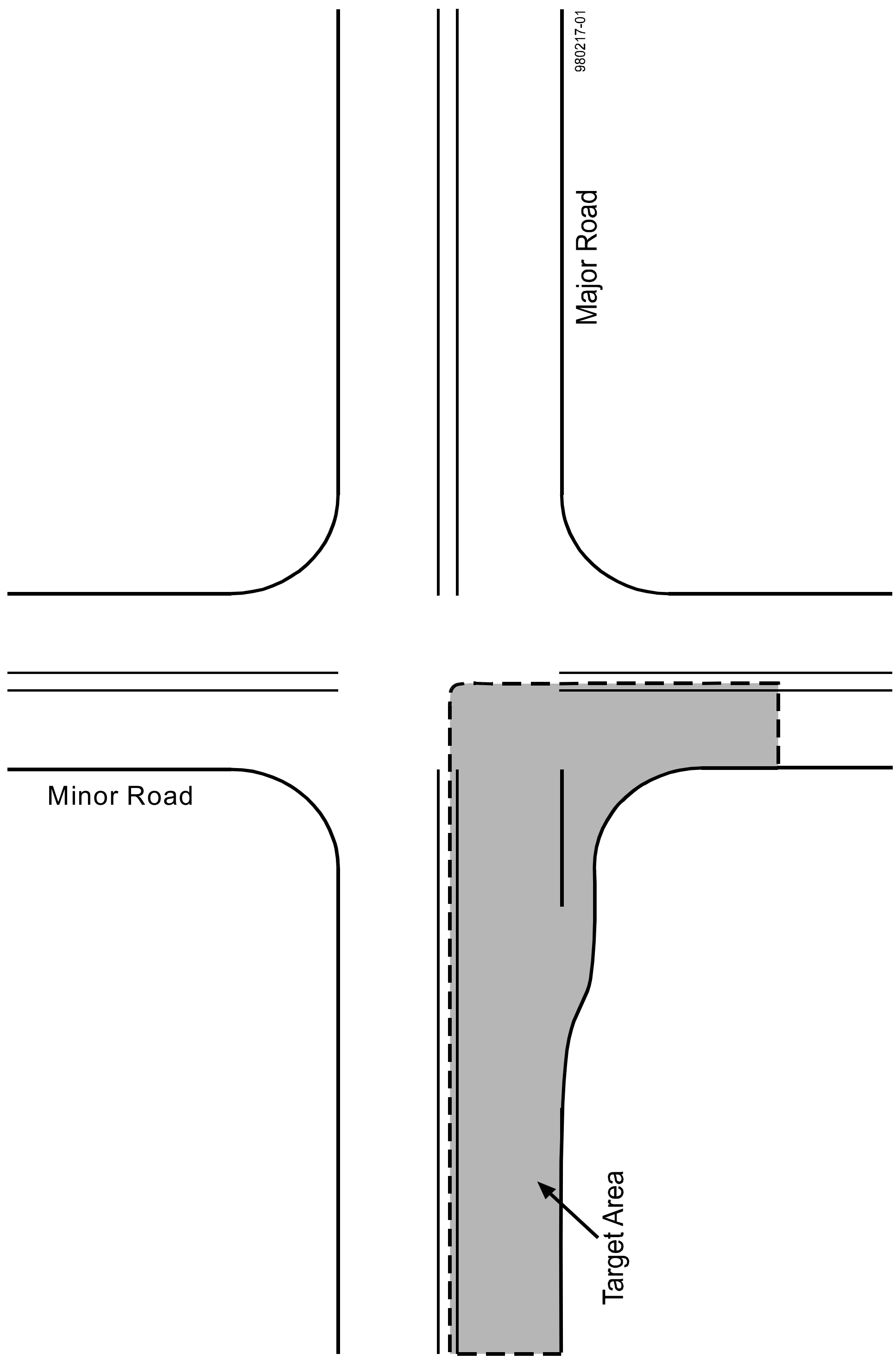

Figure 1. Target Area for Evaluation of an Intersection with a Right-Turn Lane Added on One Approach.

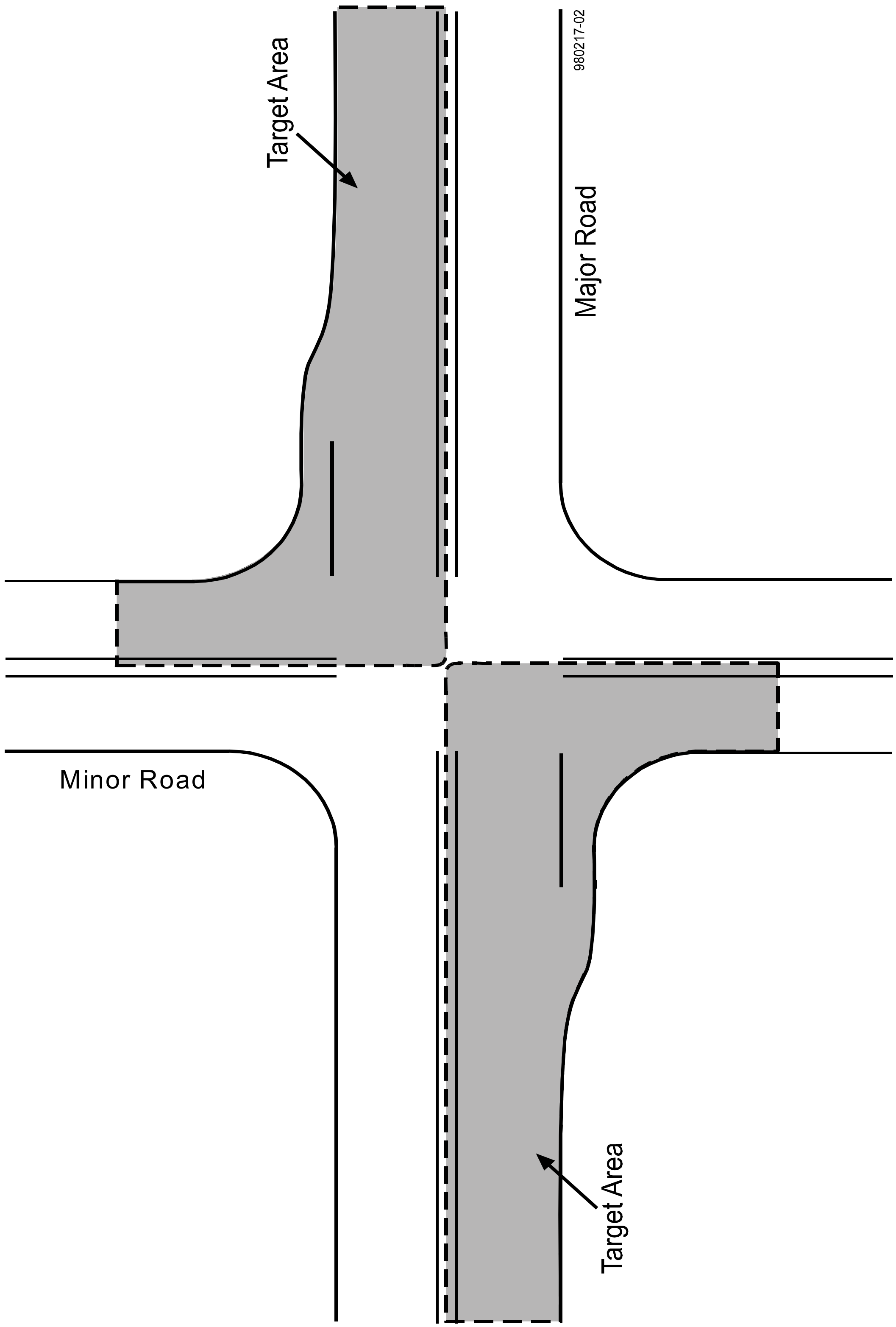

Figure 2. Target Area for Evaluation of an Intersection with Right-Turn lanes Added on Two Approaches.

- Accidents that involved vehicles that passed through the approach in question and were making or intending to make a particular movement (straight ahead, right turn, or left turn). Of these, collisions involving vehicles making the right turn of interest are obviously most relevant to evaluation of a particular right-turn lane.

The preceding discussion leads to definitions of three accident categories that can be used to evaluate added right-turn lanes. These are:

- *Total intersection accidents:* all accidents that occur or are related to the intersection being evaluated.

- *Intersection approach accidents:* all accidents involving one or more vehicles that were on or had passed through the approach(es) on which the right-turn lane(s) being evaluated were installed.

- *Project-related accidents:* all accidents involving one or more vehicles that had made, were making, or intended to make the specific right-turn maneuver(s) for which the right-turn lane(s) being evaluated were installed.

Projects Involving Addition of Left-Turn Lanes

The safety effects of adding a left-turn lane on an intersection approach are also limited to only a portion of the intersection area, but that portion is larger for an added left-turn lane than for an added right-turn lane. Figure 3 illustrates the target area affected by addition of a left-turn lane on one intersection approach. An added left-turn lane affects a primary target area, where collisions may occur between a vehicle turning left and same-direction or opposing-direction vehicles. In addition, collisions could also occur in secondary target areas on the other approaches. Furthermore, at a signalized intersection, accidents on all of the approaches may be indirectly affected if installation of a left-turn lane results in changes in the signal phasing or timing.

Figure 3 illustrates that the primary and secondary target areas for installation of a left-turn lane can include nearly the entire intersection. If left-turn lanes were installed on opposing approaches at the same intersection, the coverage of the intersection area would be even greater.

As in the evaluation of right-turn lanes, the available accident data could not be used to identify explicitly whether any particular collision occurred within the primary or secondary target areas shown in Figure 3. However, the following accident categories can be evaluated:

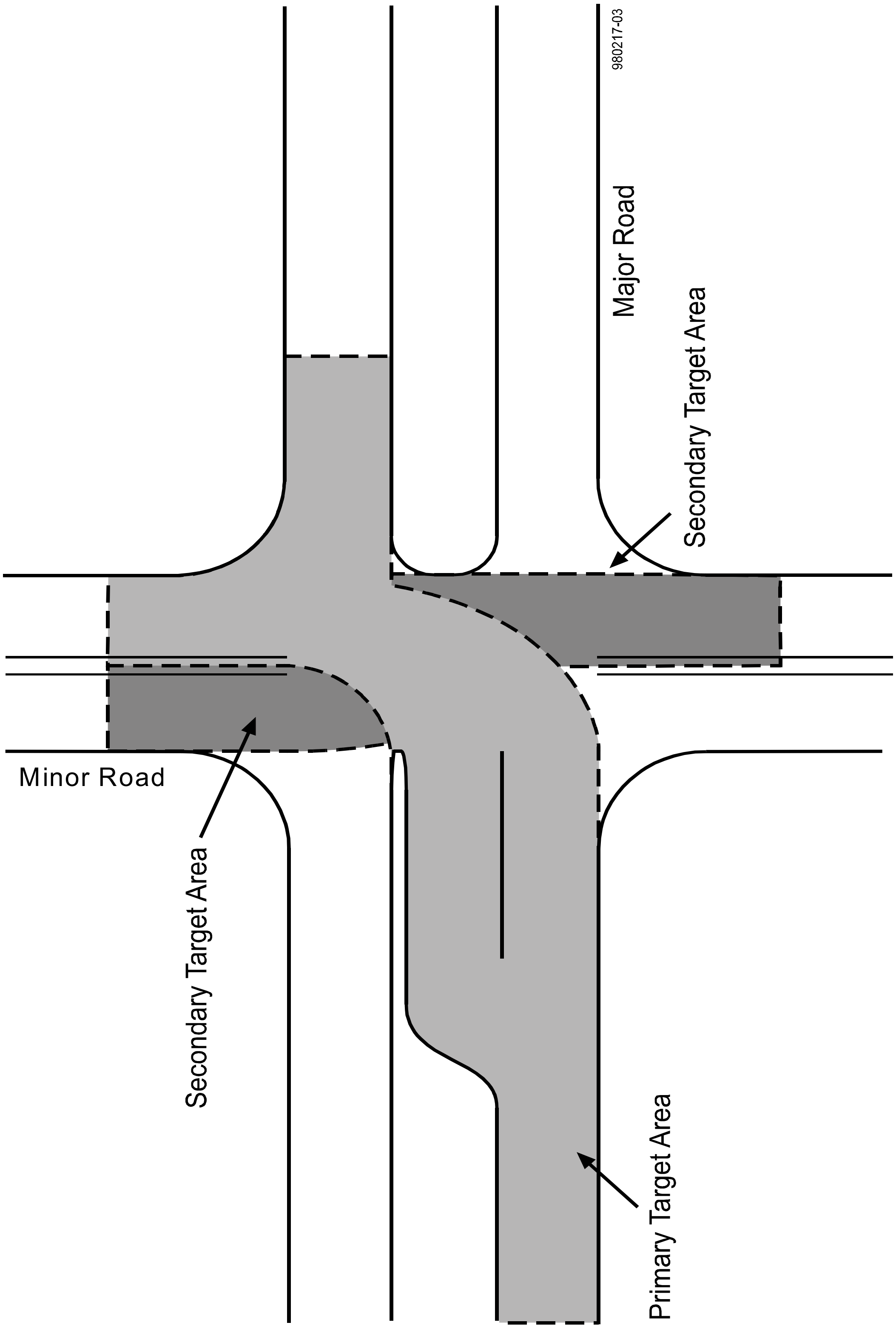

Figure 3. Target Area for Evaluation of an Intersection with a Left-Turn Lane Added on One Approach.

- *Total intersection accidents:* all accidents that occur at or are related to the intersection being evaluated.

- *Approach-related accidents:* all accidents involving one or more vehicles that were on or had passed through the approach(es) on which the left-turn lane(s) being evaluated were installed.

- *Project-related accidents:* all accidents involving one or more vehicle that had made, were making, or intended to make the specific left-turn maneuver(s) for which the left-turn lane(s) being evaluated were installed.

Projects Involving Addition of Both Left- and Right-Turn Lanes

Where both left- and right-turn lanes are added at a single intersection approach, the area of the intersection affected by the project is the combined extent of the shaded areas shown in figures 1 and 3. For such projects, total intersection accidents and intersection approach accidents can be defined as they are for the left- and right-turn lane project types discussed above. However, if both a left- and right-turn lane are installed on the same intersection approach, the definition of project-related accidents must combine the separate definitions for left- and right-turn lane projects given above.

Projects Involving Extension of the Length of Existing Turn Lanes

The target area for projects in which the length of an existing turn lane is extended could potentially be smaller than the target areas for right- and left-turn lanes shown in Figures 1 and 3, respectively. Accidents susceptible to correction by extending a turn lane should probably include only those accidents that occur in the through travel lane in the area upstream of the location where the turn lane begins in the condition before improvement. However, there is no way to identify such accidents explicitly in the available accident data. Therefore, projects involving extension of the length of existing left-turn, right-turn, or left- and right-turn lanes have been evaluated with the same target accident types defined above for addition of those specific types of turn lanes.

Accident Classification by Approach and Movement

The intersection improvement projects being evaluated, by definition, would be expected to directly affect some parts of the intersection and not others. For example, installation of a left-turn lane on one intersection approach would certainly directly affect accidents involving vehicles using that approach, but only indirectly would affect intersection accidents that did not involve that approach. Therefore, researchers developed a method for classifying intersection accidents by the approach and actual or intended turning movement.

Each accident-involved vehicle was classified by its initial direction of travel and intended movement (i.e., by the same data that are normally used to construct a collision diagram). The categories used were as follows:

- 11 - major-road approach 1 - through movement.
- 12 - major-road approach 1 - right-turn movement.
- 13 - major-road approach 1 - left-turn movement.
- 21 - major-road approach 2 - through movement.
- 22 - major-road approach 2 - right-turn movement.
- 23 - major-road approach 2 - left-turn movement.
- 31- minor-road approach 1 - through movement.
- 32 - minor-road approach 1 - right-turn movement.
- 33 - minor-road approach 1 - left-turn movement.
- 41 - minor-road approach 2 - through movement.
- 42 - minor-road approach 2 - right-turn movement.
- 43 - minor-road approach 2 - left-turn movement.

Thus, at four-leg intersections, there are 12 approach/movement combinations. Major-road approach 1 is the northbound or eastbound approach, while major-road approach 2 is the southbound or westbound approach. Similarly, minor-road approach 1 is the northbound or eastbound approach, while minor-road approach 2 is the southbound or westbound approach. At three-leg intersections, 6 of the 12 approach/movement combinations do not exist. In the case of three-leg intersections, the one minor-road approach is designated as minor-road approach 1; approach/movement combinations 31, 41, 42, 43, and either 12 and 23 or 13 and 22 do not exist at a three-leg intersection.

Each two-vehicle accident was classified by the appropriate pair of approach/movement codes for the involved vehicle. For example, a collision between a northbound major-road vehicle turning left and a southbound through vehicle was classified as a 13/21 collision. Accidents involving only a single vehicle were classified by the approach/movement code for that vehicle. Accidents involving more than two vehicles were classified by the approach/movement codes of the first two involved vehicles (whichever vehicles were designated as Vehicle 1 and Vehicle 2 in the accident record).

Accidents were classified by involved approaches using the approach/movement classes shown above. For example, accidents involving the northbound major-road approach to a particular intersection were identified as all accidents for which the approach/movement code for one of the involved vehicles was 11, 12, or 13. Multiple-vehicle accidents involving vehicles from different approaches were counted as approach-related for each of those approaches.

The same concept was used to identify accidents related to particular improvement projects. For example, if the improvement project at a particular intersection involved installing left-turn lanes on both the northbound and southbound major-road approaches, then all accidents for which the approach/movement code of one of the involved vehicles was either 13 or 23 would be considered to be project-related accidents. For sites at which left-turn lanes were added, approximately 11 percent of total intersection accidents before project construction were of accident types related to the project. The comparable percentages of project-related accidents before project construction were 18 percent for installation of right-turn lanes, 28 percent for installation of both left- and right-turn lanes, and 7 percent for extension of the length of existing turn lanes.

This accident classification system was applied to both improved and comparison sites so that when approach-related or project-related accidents were evaluated for an improved site, accidents with comparable approach/movement combinations could be selected for the comparison site.

Accident Severity Levels

Traffic accidents are generally classified into three severity levels—fatal, injury, and property-damage-only—based on the severity of the most serious injury suffered by any party to the accident. Injury accidents are often subdivided further based on the severity of the injury. Property-damage-only accidents are often subdivided further by the amount of property damage sustained in the accident or by whether one or more vehicles are towed from the accident scene.

Accident severity levels are an important consideration in planning a safety evaluation, because the completeness of accident reporting varies by severity level. All accidents involving a fatality or a personal injury are required to be reported to police authorities. Fatal accidents are nearly always reported to police authorities and, therefore, become part of accident databases. Injury accidents are less completely reported. Estimates of the reporting of accidents involving personal injuries vary from 50 to 90 percent and are undoubtedly dependent on the injury severity. The threshold amount at which property-damage accidents are required to be reported to police authorities varies from jurisdiction to jurisdiction. Even those property-damage-only accidents that meet the reporting threshold, and are thus required to be reported, are, in fact, reported in less than 50 percent of cases.

Reporting is presumed to be higher for the most severe property-damage-only accidents in which at least one vehicle is towed from the scene; police authorities are usually aware of cases when a tow truck is summoned. However, not all jurisdictions identify in their accident records whether accident-involved vehicles have been towed from the scene. Unfortunately, most of the eight states that contributed data to this study did not have a code in their data indicating that one or more involved vehicles were towed from the scene. Therefore, data on property-damage-only accidents involving a towaway were not used as a separately category in the study because they could not be consistently identified.

Because of the concerns about incomplete accident reporting, some evaluations have focused exclusively on fatal and injury accidents, excluding property-damage-only accidents because of their low reporting percentage. However, some intersection design improvements are implemented to mitigate patterns of minor accidents that often involve property-damage only. Thus, the evaluation did not focus exclusively on fatal and injury accidents.

The accident severity levels considered in the study were:

- All severity levels combined (fatal, injury, and property-damage-only accidents).
- Fatal and injury accidents only (all property-damage-only accidents excluded).

Evaluation Approaches

This section of the report discusses and compares three alternative approaches to before-after evaluation that were utilized in the research. These are:

- Before-after evaluation with yoked comparisons.
- Before-after evaluation with a comparison group.
- Before-after evaluation with the Empirical Bayes approach.

An overview of each approach is presented below, followed by a discussion of other analysis considerations. A more detailed discussion of the three evaluation approaches is then presented. This later discussion includes a conceptual overview, the statistical analysis approach, and the strengths and weaknesses of the approaches.

The three alternative evaluation approaches combine evaluation concepts recommended in two sources. These are: a recent FHWA report by Griffin and Flowers entitled *A Discussion of Six Procedures for Evaluating Highway Safety Projects*;(1) and the recently published book by Hauer, entitled *Observational Before-After Studies in Road Safety*.(2) These sources share some of the same concepts but use different terminology and notation. To make an appropriate comparison of these concepts, we have introduced a common terminology and notation drawing liberally (but not exclusively) on the terminology and notation used by Hauer.(2)

Before-After Evaluation with Yoked Comparisons

The first of the three analysis approaches is the before-after evaluation with yoked comparisons, or the YC approach. This is a traditional approach to the evaluation of traffic accident countermeasures and involves one-to-one matching between intersections that have been improved by the addition of left- or right-turn lanes and similar intersections that have not been improved. The purpose of the matched or yoked comparison sites is to account for the effects of time trends. This approach has been recommended by Griffin and Flowers.[1] The one-to-one matching of treatment and comparison intersections requires selection of intersections that are similar in key characteristics such as area type (rural/urban), traffic control (signalized/unsignalized), number of legs, and traffic volume. In the YC approach, it is assumed that the change in accidents from before to after the improvement at each treatment site, had the site been left unimproved, would have been in the same proportion as at the matching comparison site. Under this assumption, the accident frequency at each treatment site in the before period would be multiplied by the ratio of "after-to-before" accidents at the comparison site to predict what would have been the expected number of accidents in the after period at the treated site without the improvement.

The specific YC approach that has been employed is one of the designs recommended by Griffin and Flowers.[1] The YC approach is described in more detail later in this section of the report.

Before-After Evaluation with a Comparison Group

The second of the three evaluation approaches that have been utilized in the research is before-after evaluation with a comparison group, which will be termed the CG approach. This is a variation of the YC approach to the evaluation of traffic accident countermeasures and is intended to estimate the safety effectiveness of an improvement, or combination of improvements, while controlling for time-trend effects. This is achieved by careful selection of a suitable comparison group of intersections to match the improved intersections, so that the above-mentioned effects will be manifested equally in the treatment and the comparison groups. The before-after approach with comparison groups differs from the stronger before-after approach with randomized control groups in that the choice of whether or not to improve an intersection was already made by the participating highway agency prior to the study and is therefore not within the control of the research team. In the CG approach, it is assumed that the change in accidents from before to after at the improved intersections, had they been left unimproved, would have been in the same proportion as in the comparison group. Under this assumption, the "before" accident frequency would be multiplied by the ratio of the after-to-before accidents in the comparison group to predict what would have been the expected number of accidents in the "after" period without the improvement. Similar procedures can be used to adjust for differences in traffic volumes (e.g., exposure) at the improved intersections between the before and after periods.

The proper choice of comparison intersections with similar characteristics to those of the improved intersections is, therefore, very important to a valid before-after evaluation. Intersections in the treatment (improved) and comparison groups are matched on their geometric features, traffic control features, and traffic volumes, but not necessarily on their accident experience. Before-period accident frequencies for the treatment and comparison groups do not necessarily need to be similar since the assumption is made in this design that if the improvements were not undertaken, then the change in accidents from before to after conditions for the improved sites would be similar to that for the comparison sites.

The specific CG approach used in the study is a variation of that recommended by Hauer.[2] This approach incorporates a multivariate formula to adjust for the differences in traffic volume between the before and after periods and between treatment and comparison sites. While Hauer develops the CG approach as far as possible within its conceptual limitations, it should be noted that Hauer considers the Empirical Bayes approach, discussed below, to be superior to the CG approach. The CG approach is discussed in more detail later in this section of the report.

Before-After Evaluation with the Empirical Bayes Approach

An alternative analysis approach used in the study is the Empirical Bayes (EB) method. The distinctive features of the EB method are threefold. First, since there is potential for selection bias in the choice of improvement sites, the EB method attempts to account for that bias, which neither the YC nor the CG approach can. Second, the EB method attempts to account explicitly for changes from "before" to "after" in causal factors such as traffic volume. This is particularly important for intersections, since the expected number of accidents at an intersection is a nonlinear combination of the various conflicting flows, and it is often inappropriate to use a simple accident rate to account for the influence of changes in traffic volume.[2,20] Third, in the CG approach, it is common to use only two to three years of "before" accident data for fear that older accident counts are no longer relevant; the EB method can correctly exploit the information in older accident counts, which is particularly important for intersection types that experience only a limited number of accidents per year.

The EB method requires richer data and more effort in analysis. What is referred to above as a comparison group is referred to in the EB method as a sample from a *reference population* or *reference group*. For the reference group, data are required not only about accidents, but also about traffic flow (and perhaps other variables). Using these, one then estimates suitable multivariate models linking accident frequency and causal variables. The result of this modeling then accounts for both selection bias and changes in causal variables. The EB approach has recently been implemented in an evaluation of the safety effects of resurfacing projects by Hauer, Terry, and Griffith[64] and has been used by Persaud et al.[53] to evaluate the safety effects of converting conventional intersections to roundabouts.

The specific EB method used in this study is based on the recently published book by Hauer, entitled *Observational Before-After Studies in Road Safety*.[2] This method is described in more detail later in this section of the report.

Choice Between Alternative Analysis Approaches

The three alternative analysis approaches described above have the same goal but use different methods. In each case, there is a comparison or reference group to provide a means for estimating the accident experience that would have been observed in the after period at the treated sites if no treatment had been made. The YC approach does this by assuming that accidents at each treated site would change between the before and after periods as the accidents did at a similar comparison site. The CG approach replaces the one matched comparison site with a group of similar sites. The EB approach relies on a regression relationship from a group of similar sites (called a reference group rather than a comparison group) to estimate the accident experience in the after period at a treated site if no treatment had been made.

Each of the three approaches described above are valid alternative approaches to the before-after evaluation of intersection design improvements. The EB approach appears to have advantages over the YC and CG methods in its ability to address the effect of regression to the mean, but the EB approach also requires more complete data and greater analysis effort. The CG approach is generally considered to be preferable to the YC approach, because the CG approach relies on multiple sites in a comparison group, while the YC approach relies on a single comparison site. This research has used all three approaches rather than making an *a priori* choice between them. An assessment of the relative performance of the three approaches is presented later in the report.

Dependent Variables

The dependent variable in any statistical analysis is the variable whose value is to be determined or predicted. For all analyses in this study, the single most important dependent variable to assess safety effectiveness as a result of an improvement is the accident frequency at the selected intersections. Yearly accident frequencies, with a minimum of three years (and preferably five years) of "before" data and as much "after" data as possible have been obtained and analyzed. The option of analyzing yearly accident rates (number of accidents per million entering vehicles) is less desirable because accident rates presume a linear relationship between accidents and traffic volume, while most previous studies have shown such relationships to be nonlinear.

Data on all accidents occurring at the intersections during study periods before and after construction of each improvement project have been obtained from the participating states. Accident severity levels that have been used as the dependent variable are:

- Total accidents (fatal, injury, and property-damage-only accidents).
- Fatal and injury accidents (excluding property-damage-only accidents).

The eight specific safety measures considered in the evaluation are:

- Total intersection accidents.
- Fatal and injury intersection accidents.
- Project-related intersection accidents.
- Project-related fatal and injury intersection accidents.
- Total accidents for individual intersection approaches.
- Fatal and injury accidents for individual intersection approaches.
- Project-related accidents for individual intersection approaches.
- Project-related fatal and injury accidents for individual intersection approaches.

Independent Variables

The independent variables in an accident study are those variables whose effects on accidents are to be determined or controlled in the analysis. The primary independent variable is the implementation of the improvement project whose effectiveness is to be determined. Independent variables have been used in several ways in the study:

- To adjust for changes from the before to the after period (e.g., in traffic volume).

- To match an appropriate yoked comparison site to a treatment site in the YC approach (e.g., area type, traffic control, number of legs, and traffic volume).

- To estimate multivariate models from a reference group to adjust for traffic volumes in the CG approach and to determine expected values of accidents in the EB approach.

- To examine how safety may depend on the characteristics of a site (e.g., intersection geometrics or traffic control).

The primary independent variables included in the study are those geometric, traffic control, and traffic volume variables obtained from the participating state highway agencies and in field visits to the study sites.

Before and After Study Periods

Accident data for each site were obtained from the participating state highway agencies for specific time periods. These periods are presented in table 19. Thirteen years of accident data were available for one State, 12 years were available for three States, 11 years were available for one State, 10 years were available for two States, and 9 years were available for one State. As shown in tables 10 and 15, the projects evaluated were constructed on various dates during the period for which these accident data were obtained.

The study periods before and after improvement of each site were selected as follows:

- The *before study period* extended from the beginning of the first year for which accident data for the site were available to the end of the last calendar year before construction of the project.

- The *after study period* extended from the beginning of the year after the project was completed to the end of the last year for which accident data for the site were available.

Both the before and after study periods were composed of complete calendar years. Partial years were not used because they are subject to seasonal effects which could bias the evaluation.

The entire calendar year during which the improvement project was constructed was omitted from the evaluation. This approach avoided the use of partial years of accident data. In addition, because projects in many parts of the country are completed during the summer construction season, exclusion of the entire construction year provides a buffer period of several months between the end of construction and the beginning of the "after" study period. This buffer period provides an opportunity for drivers to become familiar with the improved intersection before the assessment of the project's effectiveness begins.

For the improved or treatment sites as a whole, the "before" study periods ranged from 1 to 10 years in duration, with a mean duration of 6.7 years. The "after" study periods also ranged from 1 to 10 years in duration, with a mean duration of 3.9 years.

Before-After Evaluation with Yoked Comparisons

The first of the three alternative evaluation approaches that will be presented is the before-after evaluation with yoked comparisons, referred to as Design 4 by Griffin and Flowers.[(1)] Of the six evaluation designs presented by Griffin and Flowers, this is the most appropriate for evaluation of intersection design improvements.

Conceptual Overview

The before-after evaluation with yoked comparisons involves a one-to-one matching between treatment and comparison sites. Thus, for each improved or treatment site, a comparison site with similar features was identified. Each selected comparison site was similar to the corresponding treatment site with respect to area type (rural/urban), intersection type (three-leg or four-leg), traffic control (signalized/two-way STOP), geometric design, and traffic volumes. The matched treated and comparison sites were always located in the same state and, usually (but not necessarily) in the same geographic region of the state. The comparison site had to have undergone no geometric design or traffic control improvements (beyond routine maintenance) during the periods for which data were available before and after improvements of the corresponding treatment site. Thus, for any project type of interest, there were *n* pairs of treatment and comparison sites for consideration in the evaluation. The term "yoked comparison" used by Griffin and Flowers refers to the one-to-one matching between the treatment and comparison sites.(1)

Accident data were obtained for periods as long in duration as possible before and after the improvement at each treated site and for the same time periods at the matched comparison site. Griffin and Flowers assume that the durations of the before and after periods are identical at any given treated site, although they may vary from one treated site to another. Despite this assumption, there is no particular reason that the duration of the before and after periods need to be identical, because the adjustment to account for the difference between, for example, a three-year "before" period and a two-year "after" period is obvious.

The key assumption in the YC approach is that the change in accidents between the before and after periods at any comparison sites is representative of the change in accidents that would have occurred at the corresponding treatment site had the improvement at that site not been made. Thus, it is postulated that, if the implementation of the improvement project at any treatment site was beneficial to safety, it resulted in the number of crashes at the treatment site falling more rapidly, or rising less rapidly, than accidents at the comparison site.

The YC approach, as formulated by Griffin and Flowers,(1) does not include a mechanism to account for changes in traffic volume between the before and after periods at the treatment and control sites. Since traffic volume for the before and after periods are available for each site, we have modified the YC approach to adjust for the effects of traffic volume, assuming that those effects are linear (i.e., proportional to the changes in volume).

Table 22 illustrates the accident data that was gathered to employ the before-after design with yoked comparisons for any given type of project. In the table, the values of K, L, M, and N are counts of the number of accidents observed during periods before and after the treatments. The values of π, θ, and E are statistics derived from these data. The analyses employed to derive these measures are described below.

Table 22. Accident Data Layout for a Before-After Evaluation with Yoked Comparisons.

Site number	State	Treatment sites: Number of accidents during before period	Treatment sites: Number of accidents during after period	Comparison sites: Number of accidents during before period	Comparison sites: Number of accidents during after period	Expected number of accidents on treatment site during after period in the absence of treatment	Observed accident reduction effectiveness: Odds ratio	Observed accident reduction effectiveness: Percentage reduction
1	1	K_1	L_1	M_1	N_1	π_1	θ_1	E_1
2	1	K_2	L_2	M_2	N_2	π_2	θ_2	E_2
3	1	K_3	L_3	M_3	N_3	π_3	θ_3	E_3
4	2	K_4	L_4	M_4	N_4	π_4	θ_4	E_4
⋮	2	⋮	⋮	⋮	⋮	⋮	⋮	⋮
i	3	K_i	L_i	M_i	N_i	π_i	θ_i	E_i
⋮	10	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	10	K_n	L_n	M_n	N_n	π_n	θ_n	E_n

Statistical Analysis

For any pair of treatment and comparison sites (designated by subscript *i*), the expected number of accidents at the treated site in the "after" period, had no improvement been made ($\hat{\pi}_i$), is best estimated as:

$$\hat{\pi}_i = K_i \left(\frac{N_i}{M_i} \right) \tag{3}$$

The best estimate of the expected number of accidents after the treatment ($\hat{\lambda}_i$) is the observed accident frequency. In other words:

$$\hat{\lambda}_i = L_i \tag{4}$$

The expected number of accidents without the treatment, π_i, is then compared to the observed number of accidents, $\hat{\lambda}_i$ or L_i, to assess the accident reduction effectiveness of the project at that site. The accident reduction effectiveness of the project can then be assessed as the ratio of what the accident experience was with the treatment to what it would have been without the treatment:

$$\hat{\theta}_i = \hat{\lambda}_i \,/\, \hat{\pi}_i = L_i \,/\, \hat{\pi}_i \tag{5}$$

or, equivalently:

$$\hat{\theta}_i = \hat{\lambda}_i \,/\, \hat{\pi} = \frac{L_i \; M_i}{K_i \; N_i} \tag{6}$$

When $\hat{\theta}_i < 1$, the accident frequency has decreased, and the treatment appears to be effective; when $\hat{\theta}_i > 1$, accident frequency has increased, and the treatment appears to be harmful to safety. The treatment effectiveness can also be expressed as the percentage change in the expected accident frequency, E, estimated as 100 (θ - 1). A negative value of E represents a reduction in accident frequency. If the before and after periods differ in duration, or if traffic volumes have changed between the before and after periods, the proportional changes need to be incorporated in Equations (3) through (5). (More sophisticated methods of accounting for the traffic volume effects will be discussed in conjunction with the CG and EB approaches.)

The first step in the analysis is simply to plot the pairs of observed and expected accident frequencies for the "after" period (known as L_i and $\hat{\Pi}_i$, respectively), as illustrated in Figure 4. If all of the data points were to fall on the diagonal line in the figure, then one would conclude that the treatment had no effect. Points that fall below the diagonal line suggest that the treatment was beneficial, while points that fall above the diagonal line suggest that the treatment was harmful.

Equations (3) through (6) address the estimated treatment effectiveness at a single site. An overall estimate of the treatment effectiveness can be derived from the effectiveness estimates for the individual sites using a weighted average. The weight, w_i, for each site represents the reciprocal of the squared standard error of the log odds ratio, R_i, generated from the data for that site, or:

$$R_i = \ln\left(\frac{L_i \; M_i}{K_i \; N_i}\right) = \ln \hat{\theta}_i \tag{7}$$

The squared standard error for R_i is calculated as:

$$R^2_{i(se)} = \frac{1}{K_i} + \frac{1}{L_i} + \frac{1}{M_i} + \frac{1}{N_i} \tag{8}$$

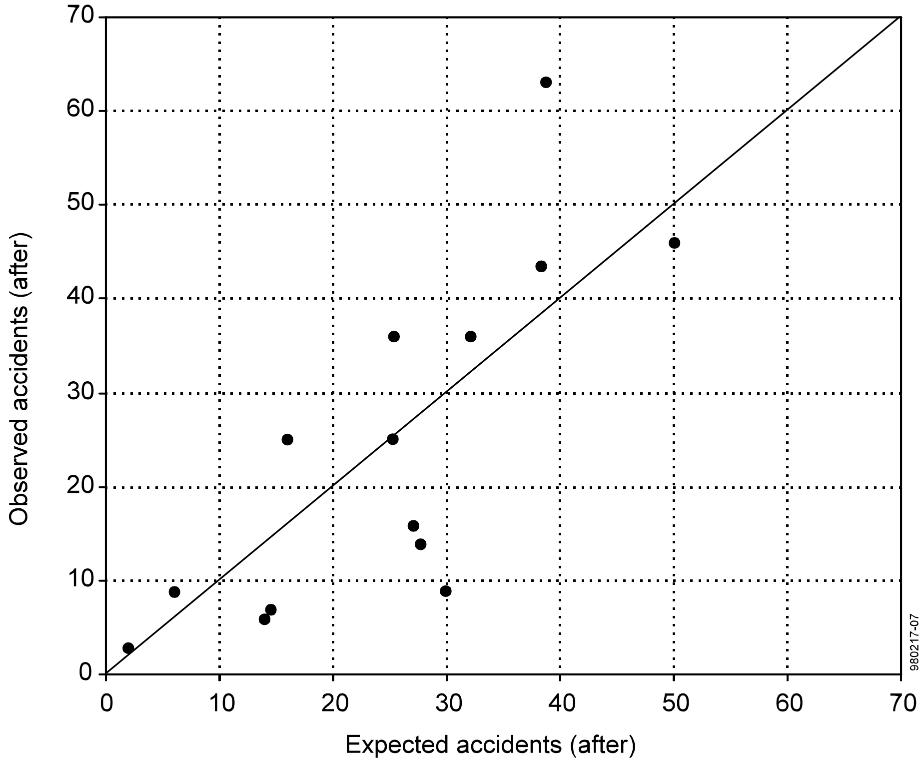

Figure 4. Plot of Observed vs. Expected Accident Frequencies.

from which the weight, w_i, is simply calculated as:

$$w_i = 1 / R_{i(se)}^2 \quad (9)$$

A weighted average (mean) log odds ratio across all n pairs of sites can be determined as:

$$R_{mean} = \frac{\Sigma w_i \; R_i}{\Sigma w_i} \quad (10)$$

By exponentiating Equation (10), an overall average (mean) odds ratio, or project effectiveness, can be obtained for the *n* sites as:

$$\theta_{mean} = e^{R_{mean}} \quad (11)$$

Thus, the overall mean percentage accident reduction effectiveness of a treatment can be estimated as:

$$E_{mean} = 100(\theta_{mean} - 1) \quad (12)$$

The next step in the analysis is to assess whether the estimated effectiveness, θ_{mean}, is statistically significantly different from one, or whether the mean percentage accident reduction effectiveness is statistically significantly different from zero. Since R_{mean} is asymptotically normally distributed, a z-test is used to test for significance, as follows. The standard error of R_{mean} is computed as:

$$R_{mean(se)} = 1 / \sqrt{\Sigma\, w_i} \quad (13)$$

A standard normal z-score can then be obtained as:

$$z = R_{mean} \,/\, R_{mean(se)} \quad (14)$$

If z falls within the interval from -1.96 to +1.96, there is no apparent treatment effect at the 95 percent confidence level. If z falls outside the interval from -1.96 to +1.96, there is a statistically significant treatment effect (beneficial if z is negative, harmful if z is positive).

The approach described above is also used to estimate a 95 percent confidence interval for the estimated treatment effect, θ_{mean}. First, the upper and lower 95 percent confidence limits around R_{mean} would be estimated as:

$$R_{mean\,(upper)} = R_{mean} + 1.96\, R_{mean\,(se)} \quad (15)$$

$$R_{mean\,(lower)} = R_{mean} - 1.96\, R_{mean\,(se)} \quad (16)$$

Next, the upper and lower 95 percent confidence limits for the treatment effect expressed as a weighted average log odds ratio would be determined by exponentiating Equations (15) and (16) as:

$$\theta_{mean\,(upper)} = e^{L_{mean(upper)}} \quad (17)$$

$$\theta_{mean\,(lower)} = e^{L_{mean(lower)}} \quad (18)$$

Finally, substituting $\theta_{mean\ (upper)}$ and $\theta_{mean\ (lower)}$ for θ_{mean} in Equation (12) provides a 95-percent confidence interval for the estimated treatment effect expressed as a percentage accident reduction:

$$E_{mean\,(upper)} = 100\left[\theta_{mean\,(upper)} - 1\right] \tag{19}$$

$$E_{mean\,(lower)} = 100\left[\theta_{mean\,(lower)} - 1\right] \tag{20}$$

Thus, it can be said that the estimated percentage effect of the treatment is, on the average, E_{mean}, with 95-percent confidence that it is in the range from $E_{mean\ (lower)}$ to $E_{mean\ (upper)}$. For example, it might be concluded that the estimated effectiveness of a particular intersection improvement project type in reducing accidents is 25 percent, on the average, with 95-percent confidence that it is in the range from 9 percent to 38 percent.

Using Equations (11), (12), and (13), the standard error of E_{mean} is computed as:

$$E_{mean(se)} = 100\ \theta_{mean} / \sqrt{\sum w_i} \tag{21}$$

To complete the analysis and estimation of the mean measure of effectiveness, the homogeneity of the individual estimated treatment effects, R_i, is tested. The plot of the pairs of observed versus expected accidents in Figure 4 provides a view of the scatter of the data around the diagonal. A chi-square (χ^2) analysis that partitions the total chi-square value into a chi-square for treatment and a chi-square for homogeneity will be performed to determine whether the scatter of the data points about the overall estimate of treatment effectiveness is within expectations. The calculations for the χ^2 analysis are shown in Table 23.

Table 23. Calculations of χ^2 Treatment, χ^2 Homogeneity, and χ^2 Total for Before-After Evaluation with Yoked Comparisons.

Source	Chi-square (χ^2)	Degrees of freedom (df)	Probability
Treatment	$R_{mean}^2\ (\Sigma w_i)$	1	p_T
Homogeneity	$\Sigma w_i\ (R_i - R_{mean})^2$	n–1	p_H
Total	$\Sigma w_i\ (R_i)^2$	n	—

The probability, or significance, levels p_T and p_H, associated with the treatment and homogeneity effects, respectively, provide a measure of statistical significance of these two sources of variability in the data. p_T provides the same test for significance as did Equation (13). If p_H is less than 0.05 (i.e., a significance level of 5 percent), then Griffin and Flowers[1] recommend a conclusion that the data are not homogeneous across pairs of sites and that some other factors besides treatment are affecting the analysis. In such a case, Griffin and Flowers maintain that the data should not be combined into a single measure of effectiveness of the treatment. By contrast, Hauer[2] maintains that variations in treatment effectiveness between sites are to be expected and that otherwise valid effectiveness measures should not necessarily be excluded on the basis of lack of homogeneity. In this research, the test for homogeneity recommended by Griffin and Flowers was performed and the results were documented in appendix C of this report, but no effectiveness measures were excluded due to lack of homogeneity.

The statistical analysis described above has been programmed in the commercially available SAS software package and performed for a variety of intersection and treatment types as described in section 6 of this report.

Adjustment for Traffic Volume and Study Period Duration

The equations presented above are applicable if both the treatment and comparison sites have the same traffic volumes, both before and after the project, and if the duration of the before and after periods for both the treated and comparison sites are equal. In most cases, these assumptions are not appropriate. Typically, the traffic volumes of the treated and matched comparison sites differ and, for both sites, the traffic volumes typically change from the before to the after period; traffic volume growth over time is most common, but in some cases traffic volumes may actually decline from before to after the improvement project. Furthermore, it is not uncommon for the durations of the before and after periods to differ.

An adjustment factor for traffic volume in the yoked comparison analysis can be computed as:

$$Adj_1 = \frac{\left(ADT_{AT} \,/\, ADT_{BT}\right)}{\left(ADT_{AC} \,/\, ADT_{BC}\right)} \tag{22}$$

where: Adj_1 = Traffic volume adjustment factor.
ADT_{BT} = Traffic volume (veh/day) for treated site in the before period.
ADT_{AT} = Traffic volume (veh/day) for treated site in the after period.
ADT_{BC} = Traffic volume (veh/day) for comparison site in the before period.
ADT_{AC} = Traffic volume (veh/day) for comparison site in the after period.

An adjustment factor for duration of study periods in the yoked comparison analysis can be computed as:

$$Adj_2 = \frac{\left(YEARS_{AT} \,/\, YEARS_{BT}\right)}{\left(YEARS_{AC} \,/\, YEARS_{BC}\right)} \tag{23}$$

where: Adj_2 = Duration adjustment factor.
$YEARS_{BT}$ = Duration of before period for treated site (years).
$YEARS_{AT}$ = Duration of after period for treated site (years).
$YEARS_{BC}$ = Duration of before period for comparison site (years).
$YEARS_{AC}$ = Duration of after period for comparison site (years).

Normally, $YEARS_{BT}$ and $YEARS_{BC}$ are equal, as are $YEARS_{AT}$ and $YEARS_{AC}$, so that ADj_2 is usually equal to 1.0.

To apply these adjustments in the YC analysis, Equation (6) must be recast as:

$$\hat{\theta}_i = \frac{L_i\ M_i}{K_i\ N_i\ Adj_1\ Adj_2} \tag{24}$$

The remainder of the analysis proceeds as described above.

Strengths and Weaknesses of This Evaluation Approach

The strength of the YC approach is its simplicity and its conceptual appeal to engineers. Since there is one and only one matching comparison site for each treatment site, care can be taken in assuring that the treatment and comparison sites are similar in a number of engineering factors such as traffic volume, geometric design, and traffic control. Also, the data needs for this approach are readily apparent and known in advance.

The YC approach has three major weaknesses, however. First, by relying on only one comparison site for each treated site, the YC approach relies on very limited data in estimating the values of π_i, the accident experience that would have been observed at particular treatment sites if no treatment had been made. If the treatment and comparison sites are well matched, the values of M_i and N_i will be similar in magnitude to K_i and L_i (i.e., often quite small) and will be highly variable. The YC approach does not utilize data from other similar treatment sites to increase the magnitudes of M_i and N_i and, therefore, the reliability of the estimates that can be made with them. Thus, the YC approach is likely to produce accident reduction effectiveness estimates with relatively wide confidence limits.

Second, the YC approach cannot deal with the well-known phenomenon of "regression to the mean." If the treated sites have been selected for improvement because of high short-term accident experience in the before period, then simple probability theory suggests that accident experience is likely to be lower in the after period even if no improvement is made. Thus, the effect of the treatment is likely to be partially confounded with the expected decrease in accident experience from regression to the mean. Regression to the mean can only be accounted for with knowledge of the "normal" or expected value of before-period accident experience at the treated sites and the YC approach cannot supply such information.

Third, the yoked comparison approach has difficulty dealing with accident frequencies with values equal to zero. Specifically, if either K_i or N_i is zero in Equation (6) or Equation (24), then the effectiveness of the treatment is undefined. This problem is usually resolved by substituting 0.5 for zero as the value of K_i or N_i in these equations, but the existence of this problem represents a conceptual weakness of the YC approach.

Despite these weaknesses, the YC approach has been used in this research because one objective of the study is to assess the performance of alternative analysis approaches. In particular, the YC approach was useful because the matched comparison sites required by the YC approach also served as the foundation for a comparison group for the CG approach and a reference group for the EB approach.

Before-After Evaluation with a Comparison Group

The second of the three alternative evaluation approaches used in the study is before-after evaluation with a comparison group. This approach has been formulated based on recommendations by Hauer,[2] with variations to handle the adjustments for traffic volume, study period duration, and state-to-state differences inherent in this study. The CG approach overcomes one weakness of the YC approach—the limitation to a single comparison site for each treatment site. For each treatment site, the CG approach replaces the yoked or matched comparison site with a group of comparison sites so that the accident experience of the entire comparison group is used in estimating what the accident experience of each treatment site would have been had the improvement not been made. It should be noted that, although Hauer has developed the CG approach as far as its limitations permit, he considers the EB approach, presented below, to be conceptually superior to the CG approach.

Conceptual Overview

In the CG approach, the idea of one-to-one matching of the treatment and comparison sites is discarded and the available comparison sites, taken as a whole, are considered as a *comparison group*. Indeed, the comparison group should preferably include more sites than the treatment group. The purpose of the comparison group is still to estimate the change in accidents that would have occurred at the treated sites if the treatment had not been made.

The CG approach has been implemented as follows. For any particular project type, such as those discussed in section 3 of this report, a certain number of intersections at which improvements of that particular type have been made were available for evaluation. These intersections will be referred to as the treatment group. Researchers identified a second group of intersections at which no geometric design or traffic control changes (other than routine maintenance) were made during the time periods for which data are available for the treated intersections. This second group of intersections constitutes the comparison group. Accident and traffic volume data were generally available for the same time periods for both the comparison group and the treatment group.

The comparison sites would normally be similar to the treatment group in geometric design and traffic control features, although Hauer does not consider close physical similarity between the treatment and comparison sites to be critical. Instead, Hauer maintains that close agreement between the treatment and comparison groups in the monthly or yearly time series of accident frequencies during the period before improvement of the treated sites is more important.(2) In other words, Hauer considers that it is not vital that the comparison sites look like the treatment sites, but it is vital that the comparison sites have accident histories similar to the accident histories for treatment sites for the period before improvement of those sites. Such similarity in accident experience during the period before improvement increases confidence (but cannot assure) that the comparison group will behave as the treatment group would have behaved had the improvement not been made. Hauer suggests a statistical technique to assess analytically the appropriateness of any particular comparison group for the corresponding treatment group.(2) Hauer's approach of matching on the basis of safety rather than physical characteristics was not fully implemented in this study, because researchers had the matched comparison sites that were used in the yoked comparison analysis available for use as a comparison group. The matching comparison sites had been selected to be physically similar to the individual treatment sites, so the matched comparison sites, as a group, were physically similar to the treatment sites as a group. The treatment and comparison sites were also similar in traffic volume levels. Additional reference sites with similar physical characteristics and traffic volumes were added to increase the size of the comparison group.

The key features that distinguish the CG approach from the YC approach are as follows:

- The estimate of the odds ratio, θ_i, for each treated site are based on a comparison group rather than a single yoked comparison site. Even where the same comparison group is used for all intersections of a specific project type, the comparison group data vary because the dates of the before and after periods for specific treated sites vary. Section 9.5 of Hauer's book provides an appropriate procedure for analyzing such data.(2)

- Before-to-after changes in traffic volume at the treated sites are accounted for explicitly using safety performance functions (i.e., multivariate regression relationships) like those used in Chapter 8 of Hauer's book. Figure 5 illustrates the use of a regression relationship between accident frequency and traffic volume as a safety performance function to adjust for a change in traffic volumes between the before and after periods. The adjustment factor for the effect on accidents of a change in traffic volume is r_{tf}, defined as shown in the figure.

- The YC approach incorporates a test for homogeneity of the treatment effects, as illustrated in table 23. If the chi-square value for homogeneity is too large, Griffin recommends that the data from different sites not be combined into a single accident reduction factor.(1) As noted in the preceding discussion of the YC approach, Hauer assumes that it is natural for the effect of the same treatment to vary from site to site.(2) Therefore, in the CG approach, an average effect is determined and its precision is assessed by examining its site-to-site variance.

The CG approach leads to a very similar formulation of the data for the evaluation to that used in the YC approach. Table 24 is analogous to table 22 and differs only in that the columns formerly headed "Comparison sites" are now headed "Comparison group." In each row of table 24, M_i and N_i are based on an entire comparison group and not just on one matching site. However, the values of M_i and N_i in table 24 may vary even among the sites that use the same comparison group if the time periods on which K_i and L_i are based vary. Furthermore, the data for the individual comparison sites that are combined to determine M_i and N_i must first be adjusted for differences in traffic volume between the treatment and comparison sites. An adjustment for state-to-state differences in accident frequency is also needed where a specific comparison state is located in a different state than the treatment site.

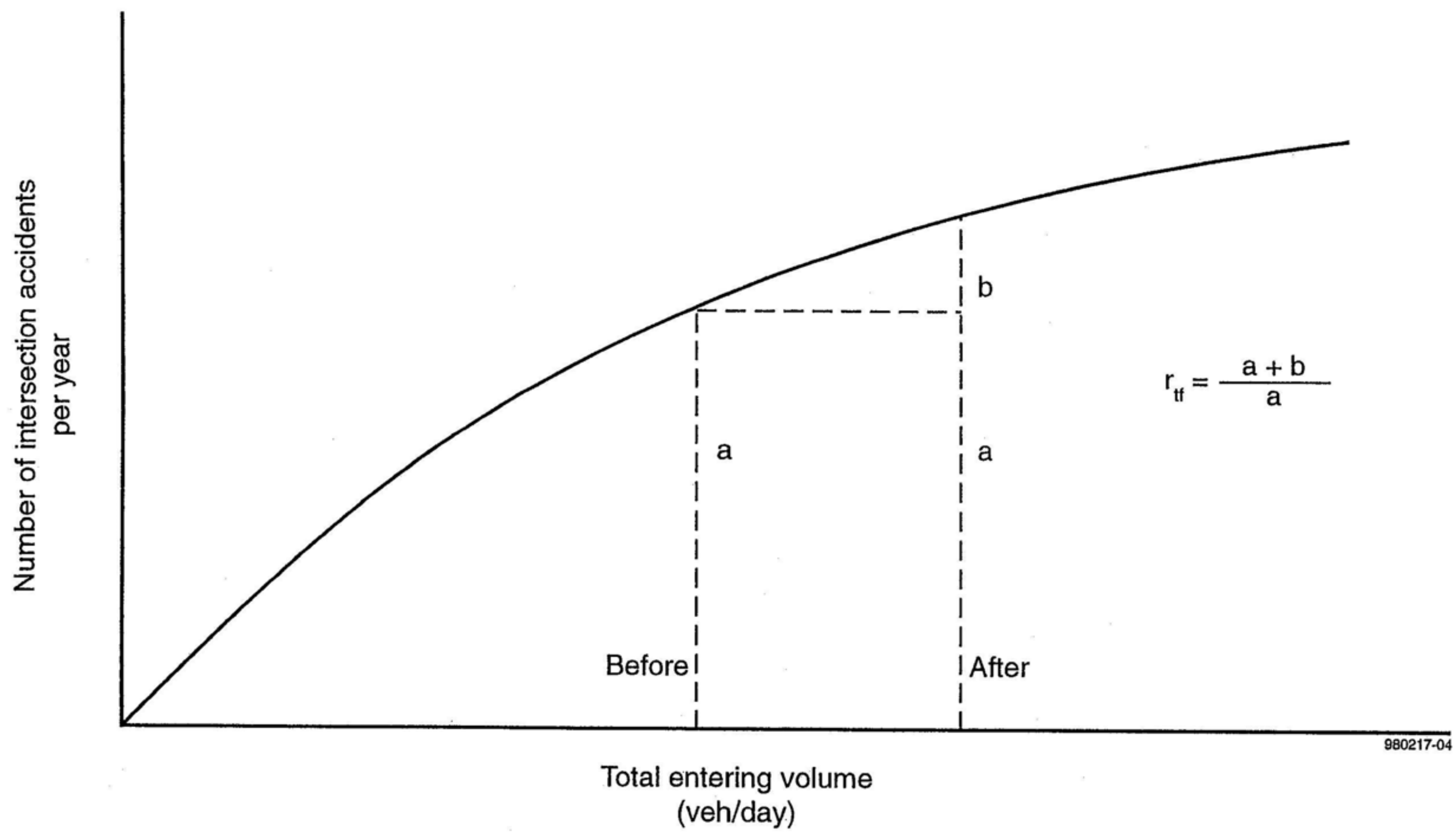

Figure 5. Typical Regression Relationship for Predicting Intersection Accident Frequency as a Function of Entering Traffic Volume.

Table 24. Accident Data Layout for Before-After Evaluation with Comparison Group.

Site number	State	Treatment sites		Comparison group		Expected number of accidents on treatment site during after period in the absence of treatment	Observed accident reduction effectiveness	
		Number of accidents during before period	Number of accidents during after period	Number of accidents during before period	Number of accidents during after period		Odds ratio	Percentage reduction
1	1	K_1	L_1	M_1	N_1	π_1	θ_1	E_1
2	1	K_2	L_2	M_2	N_2	π_2	θ_2	E_2
3	1	K_3	L_3	M_3	N_3	π_3	θ_3	E_3
4	2	K_4	L_4	M_4	N_4	π_4	θ_4	E_4
⋮	2	⋮	⋮	⋮	⋮	⋮	⋮	⋮
i	3	K_i	L_i	M_i	N_i	π_i	θ_i	E_i
⋮	10	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	10	K_n	L_n	M_n	N_n	π_n	θ_n	E_n

The statistical analysis methodology used to determine the values of π, θ, and E in the CG approach is explained below.

Statistical Analysis

The statistical analysis methodology for the CG approach must be explained in terms of both the observed accident counts and their expected values. As shown in Table 25, the observed accident counts that correspond to the row and column headings shown in the table will be referred to as K, L, M, and N, and their expected values, which are unknown, will be referred to by the Greek letters κ, λ, μ, and ν.

Table 25. Observed and Expected Accident Counts.

	Treatment group	Comparison group
Before	K, κ	M, μ
After	L, λ	N, ν

The comparison ratio, r_C, for the comparison group is defined as the ratio of the expected accident count during the after period to the expected accident count in the before period. In other words:

$$r_C = \nu / \mu \tag{25}$$

The CG approach assumes that the expected number of accidents for the treatment group in the after period, had no treatment been implemented, can be predicted as:

$$\pi = r_C \, \kappa \tag{26}$$

Implicit in Equation (25) is the assumption that the corresponding ratio for the treatment group, had no treatment been implemented:

$$r_T = \pi / \kappa \tag{27}$$

is equal to r_C. In other words:

$$r_T = r_C \ \ or, \ equivalently, \ \ r_C / r_T \ = \ 1 \tag{28}$$

The ratio r_C/r_T is also known as the odds ratio, ω_i.

The customary effectiveness of a treatment at a given site is the same as that derived for the YC approach in Equations (3) through (6). However, for the CG approach, the subscript *i* in these equations represents the appropriate data for a particular treatment site. Each treatment site has a corresponding comparison group, and the individual sites in that comparison group will be represented here by the subscript *j*.

The CG analysis proceeds in a manner similar to the YC analysis except that for any given treated site, M_i and N_i in Equation (6) must be determined as the sum of the adjusted accident frequencies for the individual comparison sites within the comparison group. Adjustments to accident frequencies for the individual comparison sites are needed when (1) the treatment and comparison sites have different traffic volume levels, (2) the study periods for the treatment and comparison sites have different durations, or (3) the treatment and comparison sites are located in different states, and the safety performance of the particular intersection type in question differs between those states.

Because of the need to make these adjustments, the computation of the comparison group analysis is more complex than suggested by Equations (6) through (11). Specifically, a set of adjustments were first made to the data for the comparison group sites that correspond to each treatment site. Then, the comparison group sites corresponding to each treatment site were combined to determine pooled accident frequencies for the comparison group as a whole. Finally, an adjustment was made to the combined treatment and comparison site data in determining the treatment site odds ratio.

In the comparison group analysis, the traffic volume adjustment was made using a regression relationship between accident frequency and traffic volume, rather than assuming that the adjustment should be proportional to traffic volumes as shown in Equation (22). These regression relationships were developed with negative binomial regression and involved separate coefficients for major- and minor-road traffic volumes, as described in the next section. These regression relationships also involved a coefficient to represent the differences in accident frequency between states.

For each individual comparison site, its accident frequency was adjusted to be comparable to its equivalent value under the same conditions (traffic volume, duration of study period, and state) as the treatment site. The adjustment factor for the comparison site in the before period is:

$$Adj_B = \frac{f\left(MajADT_{BT}, MinADT_{BT}, STATE_T\right) YEARS_{BT}}{f\left(MajADT_{BC}, MinADT_{BC}, STATE_C\right) YEARS_{BC}} \tag{29}$$

where:

Adj_B	=	Adjustment factor for comparison site accident frequency in the before period.
f(x,y,z)	=	Predicted accident frequency as a function of major-road traffic volume (x), minor-road traffic volume (y), and state (z) from a negative binomial regression relationship (see discussion later in this section).
$MajADT_{BT}$	=	Major-road traffic volume (veh/day) in the before period at the treatment site.
$MajADT_{BC}$	=	Major-road traffic volume (veh/day) in the before period at the comparison site.
$MinADT_{BT}$	=	Minor-road traffic volume (veh/day) in the before period at the treatment site.
$MinADT_{BC}$	=	Minor-road traffic volume (veh/day) in the before period at the comparison site.
$YEARS_{BT}$	=	Duration of before period for treatment site (years).
$YEARS_{BC}$	=	Duration of before period for comparison site (years).

Similarly, the adjustment factor for the comparison site in the after period is:

$$Adj_A = \frac{f\left(MajADT_{AT}, MinADT_{AT}, STATE_T\right) YEARS_{AT}}{f\left(MajADT_{AC}, MinADT_{AC}, STATE_C\right) YEARS_{AC}} \tag{30}$$

where:

Adj_A	=	Adjustment factor for comparison site accident frequency in the after period.
$MajADT_{AT}$	=	Major-road traffic volume (veh/day) in the after period at the treatment site.

$MajADT_{AC}$	=	Major-road traffic volume (veh/day) in the after period at the comparison site.
$MinADT_{AT}$	=	Minor-road traffic volume (veh/day) in the after period at the treatment site.
$MinADT_{AC}$	=	Minor-road traffic volume (veh/day) in the after period at the comparison site.
$YEARS_{AT}$	=	Duration of after period for treatment site (years).
$YEARS_{AC}$	=	Duration of after period for comparison site (years).

With these adjustment factors, the adjusted accident frequencies for an individual comparison site can be determined as:

$$MADJ_j = M_j \ Adj_B \tag{31}$$

and

$$NADJ_j = N_j \ Adj_A \tag{32}$$

Then, the values of the adjusted before period accident frequencies, $MADJ_j$, are summed over all of the comparison sites corresponding to a specific treatment site, *i*, to calculate the total adjusted before-period comparison group accident frequency, M_i. Similarly, the values of the adjusted after-period accident frequencies, $NADJ_j$, are summed over all comparison sites to calculate the total adjusted after-period comparison group accident frequency, N_i.

In combining the treatment site and comparison group accident frequencies, a final adjustment must be made to the after-period accident frequency for the treatment site. This adjustment also uses the negative binomial regression relationships. The adjustment is determined as:

$$Adj_3 = \frac{f\left(MajADT_{AT}, MinADT_{AT}, STATE_T\right)}{f\left(MajADT_{BT}, MinADT_{BT}, STATE_T\right)} \tag{33}$$

where: Adj_3 = Adjustment factor applied to after-period accident frequency [analogous to Adj_1 in Equation (22)].

This adjustment is applied by modifying the value of the observed after-period accident frequency for the treatment site, L_i', as follows:

$$L_i = L_i' \ / \ Adj_3 \tag{34}$$

The odds ratio is then determined as in Equation (6), and the analysis proceeds as in the YC approach.

Appropriateness of Comparison Groups

Hauer [2] states explicitly that the foundation of the CG method rests on the assumption (or the hope) that Equation (28) is correct. While Hauer discusses the importance of agreement in key safety measures between the treatment and comparison groups, no specific statistical methodology for assessing the level of agreement between the treatment and comparison groups is presented. Therefore, such a methodology has been developed for use in the current study.

Confirming the degree of agreement between the group of treatment or improved sites and the comparison group is an important aspect in the before-after analysis. The comparison sites were selected because they were similar in physical characteristics and traffic volumes to the treatment sites, but there was no *a priori* assurance that the treatment and comparison sites were similar in safety performance in the time period before improvement of the treatment sites. A statistical approach to providing this assurance was developed and implemented using groups of treatment and matched comparison sites over the entire period before improvement of the treatment sites. For each combination of area type, traffic control, and project type, a time series of total intersection accidents at the treatment sites was compared to the time series of accidents at the matching comparison sites. An example pair of treatment and comparison time series is illustrated in Figure 6. Each of the two time series shown in the figure represents the series of average accident frequencies per site per year over the entire before period. Each time series is based on the same number of intersections, and the number of intersections included decreases from year to year as more and more treatment sites reach the year during which they were improved.

The evaluation approaches used in this report do not require that the treatment and comparison time series shown in figure 6 coincide. However, if the treatment and comparison groups are well matched, the average annual accident frequency for the comparison group should rise when the average for the treatment group rises, and fall when the average for the treatment groups falls. A perfect match in accident trends between the treatment and comparison groups would exhibit a pair of two jagged but parallel lines in plots like figure 6.

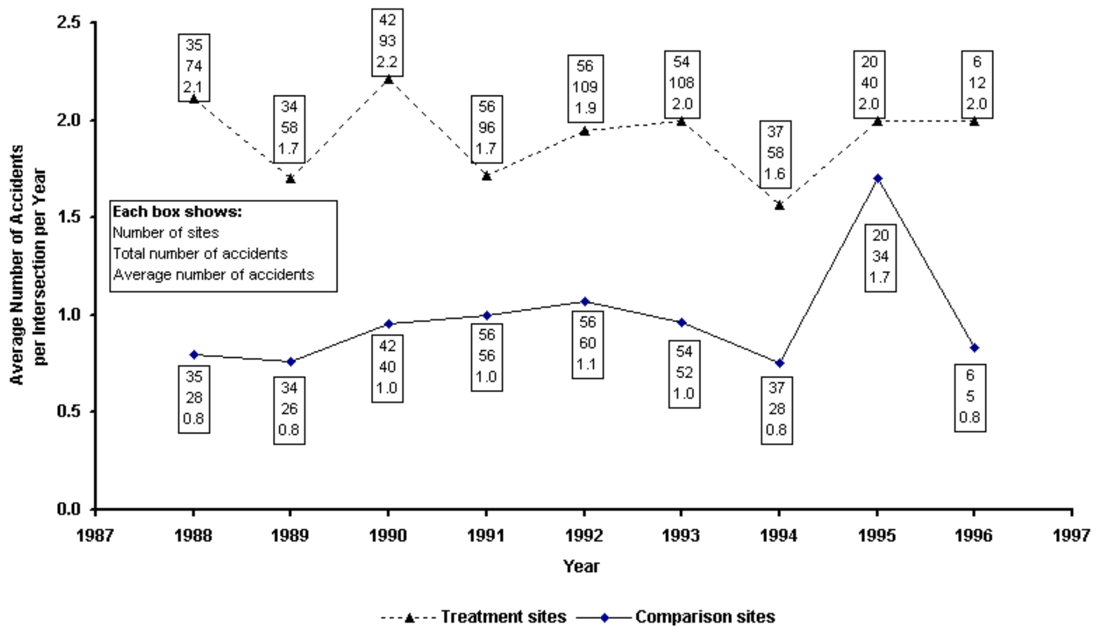

Figure 6. Comparison of Accident Experience for Treatment and Comparison Groups for Rural Unsignalized Intersections at Which Left-Turn Lanes Were Added.

The objective of the statistical assessment of the degree of agreement between treatment and control groups is to test whether the corresponding time series, like those shown in the figure, are parallel. A basic two-way analysis of repeated measures approach with interaction was used to test whether the two time series (treatment and comparison) of yearly accidents deviate significantly from parallelism. The two main factors used in the analysis of variance are the type of site (i.e., treatment vs. comparison) and the year (i.e., the sequence of calendar years as shown in the figure). The various sites were nested within their respective type of site. The repeated measures nature of the design refers to the yearly measurements (observed accident counts) made on the same sites. In addition, a first-order autoregressive covariance structure was assumed for the accidents to reflect the property of correlations being larger for nearby times than for far-apart times. In this approach, the evaluation of the interaction between the two factors, type of site and year, provides a test for parallelism. PROC MIXED of SAS was used to perform the analyses of variance. The 10-percent significance level was used to assess the results of these analyses of variance.

This approach was implemented for selected treatment and comparison groups for two safety performance measures—total intersection accidents and fatal and injury intersection accidents. The results of 20 analyses are shown in table 26. This table presents results for all treatment and comparison groups that included more than 20 site-years of data. For each safety performance measure, site type, and improvement project type, the table shows the number of site-years in the individual treatment or comparison groups and an indication of whether the two time series can be considered to be parallel at the 90 percent confidence level. For the cases shown in the table, there were no significant effects for lack of parallelism. Based on these results, it was concluded that the groups of treatment and comparison sites are comparable in their safety performance.

Table 26. Comparison of Accident Frequency Time Series for Treatment and Control Groups in the Time Period Before Improvement of the Treatment Sites.

Area type	Traffic control type	Project type	Number of improved or treated site-years in before period	Test for lack of parallelism: significant at 10% level?
Total Intersection Accidents				
Rural	Signalized	Extended LTLs	40	No
Rural	Unsignalized	Added LTLs	340	No
Rural	Unsignalized	Added both LTLs and	184	No
Rural	Unsignalized	Added RTLs	266	No
Urban	Newly Signalized	Added LTLs	203	No
Urban	Signalized	Added LTLs	267	No
Urban	Signalized	Added both LTLs and	84	No
Urban	Signalized	Added RTLs	141	No
Urban	Signalized	Extended LTLs	23	No
Urban	Unsignalized	Added LTLs	123	No
Fatal and Injury Intersection Accidents				
Rural	Signalized	Extended LTLs	40	No
Rural	Unsignalized	Added LTLs	340	No
Rural	Unsignalized	Added both LTLs and	184	No
Rural	Unsignalized	Added RTLs	266	No
Urban	Newly Signalized	Added LTLs	203	No
Urban	Signalized	Added LTLs	267	No
Urban	Signalized	Added both LTLs and	84	No
Urban	Signalized	Added RTLs	141	No
Urban	Signalized	Extended LTLs	23	No
Urban	Unsignalized	Added LTLs	123	No

Negative Binomial Regression Relationships for Traffic Volume and State Adjustments

The adjustments for traffic volume and state effects presented above (Adj_A, Adj_B, and Adj_3) are based on negative binomial regression relationships for predicting accident frequency as a function of major-road traffic volume, minor-road traffic volume, and state.

Because the relationship between accident frequency and traffic volume is generally nonlinear (as illustrated in figure 5), the regression relationship can provide a more accurate adjustment for the effect of traffic volume than the proportional adjustment used in the YC approach [see Equation (22)]. State-to-state differences were included in the negative binomial regression models where they were found to be statistically significant.

Regression relationships were developed for complected as many combinations of the following intersection characteristics as possible using the comparison and reference site data:

- Area type (urban/rural).
- Type of traffic control (signalized/unsignalized).
- Number of intersection legs (three or four).
- Number of lanes on major road (two-lane/multilane).

A variety of dependent variables (accident frequency measures) were used in modeling, including:

- Total intersection accidents.
- Total fatal and injury intersection accidents.
- Total project-related intersection accidents.
- Total fatal and injury project-related intersection accidents.
- Total accidents for individual intersection approaches.
- Total fatal and injury accidents for individual intersection accidents.
- Total project-related accidents for individual intersection approaches.
- Total fatal and injury project-related accidents for individual intersection approaches.

These relationships were developed with negative binomial regression because (1) negative binomial regression is well suited to deal with accident frequencies which are frequently zero or very low numbers and (2) negative binomial regression provides an overdispersion parameter that makes it useful in the EB analysis as well as the CG analysis.

The model development process and the specific models developed are presented in Appendix B of this report.

Strengths and Weaknesses of This Evaluation Approach

A strength of the CG approach, in contrast to the YC approach, is that it relies on a group of similar sites, rather than a single site, to determine the values of M_i and N_i. The increased size of the accident sample in the comparison group should decrease the variance of the accident data and, thus, shrink the confidence limits for the accident reduction effectiveness.

On the other hand, some unwanted variability in accidents may be introduced by the inevitable diversity of the sites that make up the comparison group. Even if the comparison group as a whole resembles the treatment group as a whole, some of the comparison sites are bound to be quite different in physical characteristics (and in accident experience) from any given treatment site.

Like the YC approach, the CG approach cannot determine the treatment effectiveness when K_i or N_i is equal to zero. The same approximation used in the YC approach (setting zero values equal to 0.5) is used in the CG approach.

An important weakness of the CG approach is that, like the YC approach, it cannot address the bias created by regression to the mean. This weakness will be addressed by the EB approach.

Before-After Evaluation with the Empirical Bayes Approach

The third of the three alternative evaluation approaches that was used in the research is before-after evaluation with the Empirical Bayes (EB) approach. This approach was formulated by Hauer[(2)] and is the only known approach to before-after evaluation that directly addresses regression to the mean.

Conceptual Overview

In the EB approach, the comparison group discussed in the CG approach is replaced with a reference group that is used to model the relationship between accident frequency and fundamental intersection descriptors such as traffic volume. These models are then used together with the observed accident counts at the treated sites in the before period to estimate the number of accidents that would have occurred at the treated sites in the after period if no improvement had been made.

To accomplish this, the reference group should consist of intersections that are similar to the treated intersections before they were treated (i.e., intersections with left- and right-turn lanes), or intersections whose safety performance is similar to that of such intersections. In this research, the reference groups for the EB approach were drawn from the same sites used as the comparison group for the CG approach, including both matched comparison sites from the YC approach and additional reference sites.

The regression relationships used in the EB approach were the same negative binomial regression relationships used for the CG approach and discussed earlier in this section. A more detailed discussion of the development of these regression relationships is presented in Appendix B of this report. Separate regression relationships were developed for specific combinations of the following intersection characteristics:

- Area type (urban/rural).
- Traffic control type (signalized/unsignalized).
- Number of intersection legs (three or four).
- Number of lanes on major road (two-lane/multilane).

The EB approach leads to another variation of the data layout for the evaluation. Table 27 is analogous to Tables 22 and 24 but is adapted to fit the EB approach. A key difference of Table 27 from Tables 22 and 24 is that the accident experience of the reference group does not appear explicitly. Instead, the reference group is used to develop regression models that are used in estimating the values of π shown in the table. Once the values of π have been determined, the computation of θ and E is much as presented previously.

Table 27. Accident Data Layout for Before-After Evaluation with the Empirical Bayes Approach.

		Treatment sites			Observed accident reduction effectiveness	
Site number	State	Number of accidents during before period	Expected number of accidents during after period in the absence of treatment	Observed number of accidents during after period	Odds ratio	Percentage reduction
1	1	K_1	π_1	L_1	θ_1	E_1
2	1	K_2	π_2	L_2	θ_2	E_2
3	1	K_3	π_3	L_3	θ_3	E_3
4	2	K_4	π_4	L_4	θ_4	E_4
⋮	2	⋮	⋮	⋮	⋮	⋮
i	3	K_i	π_i	L_i	θ_i	E_i
⋮	10	⋮	⋮	⋮	⋮	⋮
n	10	K_n	π_n	L_n	θ_n	E_n

The statistical analysis methodology for the EB approach is explained below.

Statistical Analysis

The statistical analysis methodology for the EB approach revolves around the use of the reference group to develop regression relationships between accident experience and key site characteristics such as traffic volumes. Figure 5, which is presented in the discussion of the CG approach of this report, shows a typical regression relationship of this type. The abscissa in figure 5 is a measure of traffic volume such as the total volume per day entering the intersection. Analogous relationships have been developed using both the major- and minor-road average daily traffic volumes (ADTs) as predictor variables; such relationships have been used in the evaluation, but cannot be illustrated in a two-dimensional graph.

A key change in the EB approach from the YC approach and the CG approach is in the treatment of the observed accident count in the period before improvement of the treated sites. In both the YC and CG approaches, this observed value is used as the best available estimate of safety at the treated site during the before period. The EB approach recognizes that the expected value of the accident count for a site, as indicated by a regression relationship such as that shown in figure 5, has value as well and may, in some cases, be a much more important piece of information than the observed accident count. In other words, the observed accident count in the before period is simply one observation of a random process and better evaluations will result if, in addition to knowing the observed accident count, the process itself is understood.

To illustrate this process, consider the example in figure 7, which utilizes the same regression relationship shown in figure 5. Figure 7 shows the observed accident count for an intersection in the before period as a point above the regression line for the corresponding traffic volume. This indicates that the observed accident count is higher than expected. Such higher-than-expected accident counts are subject to regression to the mean (as are lower-than-expected accident counts). The best estimate of accident experience at this site for the before period, given both the observed accident frequency and that from the regression relationship, is the value corresponding to the x between the observed point and the expected value.

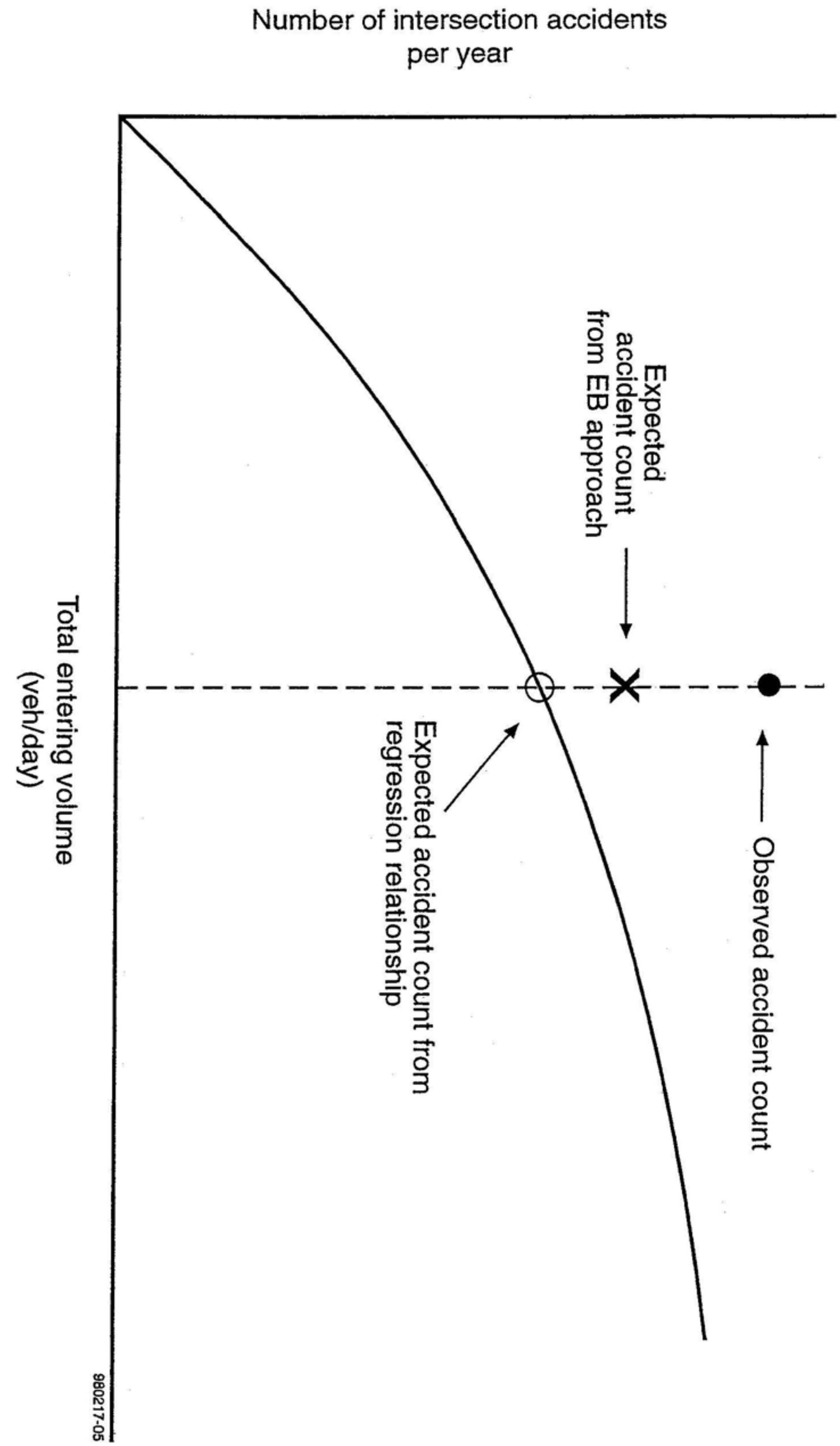

Figure 7. Use of Regression Relationship in the EB Approach.

Hauer provides an analytical procedure to estimate the position of the *x* in figure 7. This analytical procedure involves, in essence, a weighted average of the observed and expected values. This analytical procedure is fundamental to the EB approach. Hauer refers to the observed accident count as K and the expected value of the accident count as E(κ). E(κ) is an expected value that can be estimated from a regression relationship like that shown in figure 7. As noted above, the regression relationships actually used in the EB analysis are the same negative binomial regressions that were described earlier for use in the CG analysis. These negative binomial regressions predict accidents for a one-year period, so the equation for E(κ) also incorporates the duration of the before period:

$$E(\kappa) = f\,(MajADT_{BT}\,, MinADT_{BT}\,, STATE_{T}\,)\,YEARS_{BT} \qquad (35)$$

The *x* in figure 7, denoted as E{κ|K}, is estimated using a weight factor, α, as follows:

$$E\left\{\kappa \middle| K\right\}_i = \alpha E\left\{\kappa\right\}_i + (1-\alpha)\,K_i \qquad (36)$$

The subscript *i* in Equation (34) indicates that the values apply to a specific treatment site. Hauer demonstrates that to estimate $E\{\kappa|K\}_i$ with maximum precision, α must have the value indicated below:

$$\alpha = \frac{1}{1+\dfrac{VAR\{\kappa\}_i}{E\{\kappa\}_i}} \qquad (37)$$

The value of $E\{\kappa\}_i$ in Equation (35) can be obtained from the regression relationship shown in figure 7. The value of $VAR\{\kappa\}_i$ can be obtained from analysis of the residuals from that regression relationship.

It can also be shown that α can be estimated from the overdispersion parameter of the negative binomial regression relationship and the expected before period accident frequency for the treatment site:

$$\alpha = \frac{1}{1+d\;\;E(\kappa)_i} \qquad (38)$$

where: d = overdispersion parameter of the appropriate negative binomial regression relationship

In applying Equation (36), the value of E(κ) for a single year was used so that α would not depend on the duration of the before period. The value of $E\{\kappa|K\}_i$ is determined from Equation (36) using the weight, α, determined from Equation (38).

The variance of $E\{\kappa|K\}_i$ is then determined as:

$$Var\ E\left\{\kappa\middle|K\right\}_i = (1-\alpha)\ E\left\{\kappa\middle|K\right\}_i \tag{39}$$

As in the YC and CG approaches [see Equation (4)], the best estimate of the expected accident frequency after the treatment, $\hat{\lambda}_i$, is the observed accident frequency after the treatment, L_i.

Adjustment factors are now needed to account for differences in traffic volume and duration between the before and after study periods. The traffic volume adjustment, r_{TF}, uses the appropriate negative binomial regression relationship:

$$r_{TF} = \frac{f\left(MajADT_{AT}, MinADT_{AT}, STATE_T\right)}{f\left(MajADT_{BT}, MinADT_{BT}, STATE_T\right)} \tag{40}$$

The adjustment factor for the duration of the study period is:

$$r_d = \frac{YEARS_{AT}}{YEARS_{BT}} \tag{41}$$

The next step is to estimate π_i, the expected value of the accident count that would have occurred during the after period if the improvement had not been made. This value is estimated as:

$$\hat{\pi}_i = E\left\{\kappa\middle|K\right\}_i r_d\ r_{tf} \tag{42}$$

where r_d is the ratio of the durations of the before and after periods and r_{tf} is the ratio of the expected accident counts for the traffic volume levels (or traffic flow rates) at the intersection during the before and after periods, as illustrated in f7igure 5. (NOTE: r_{tf} is *not* equal to the ratio of the before and after traffic volumes unless the regression relationship being used is linear).

The customary estimate of the effectiveness of the treatment is $\hat{\theta}_i$, which can be determined as:

$$\hat{\theta}_i = \hat{\lambda}_i / \hat{\pi}_i \tag{43}$$

The overall effectiveness of a group of treatments at similar sites can be determined by summing and then combining values of $\hat{\lambda}_i$ and $\hat{\pi}_i$. The overall treatment effectiveness is equal to:

$$\hat{\theta} = \frac{\Sigma\ \hat{\lambda}_i}{\Sigma\ \hat{\pi}_i} = \frac{\hat{\lambda}}{\hat{\pi}} \tag{44}$$

However, the use of $\hat{\theta}$ in this form is not recommended because, even if $\hat{\lambda}$ and $\hat{\pi}$ are unbiased estimators of λ and π, the ratio $\hat{\lambda}/\hat{\pi}$ is a biased estimator of $\hat{\theta}$. Although this bias is often small, Hauer(2) recommends that removing it is a worthwhile precaution. An approximately unbiased estimator for $\hat{\theta}$ is given by:

$$\hat{\theta}* \ = \ \hat{\theta} \, / \, \left[1 \ + \ VAR\left\{\hat{\pi}\right\} / \, \hat{\pi}^2\right] \tag{45}$$

Investigation during the current research confirmed that the difference between $\hat{\theta}$ and $\hat{\theta}*$ is very small, usually affecting only the third or fourth significant digit of the treatment effectiveness. Nevertheless, because of the potential bias in $\hat{\theta}$, the value of $\hat{\theta}*$ was used as the treatment effectiveness estimate in this research.

The variance of $\hat{\lambda}$ can be determined as:

$$VAR\left\{\hat{\lambda}\right\} = \Sigma\ \hat{\lambda}_i \tag{46}$$

The variance of $\hat{\pi}$ can be determined as:

$$VAR\{\hat{\pi}\} = \Sigma \ \ VAR\, E\left\{\kappa|K\right\}_i \, r_d^2 \, r_{tf}^2 \tag{47}$$

Finally, the variance of $\hat{\theta}*$ can be estimated as:

$$VAR\left\{\hat{\theta}*\right\} \cong \hat{\theta}^2\left[(VAR\left\{\hat{\lambda}\right\} / \, \lambda^2) + (VAR\left\{\hat{\pi}\right\} / \, \pi^2\right] / \left[1 + VAR\left\{\hat{\pi}\right\} / \, \pi^2\right]^2 \tag{48}$$

As indicated in Equation (12), the effectiveness of the treatment can be expressed as a percentage accident reduction in the form:

$$E \ = \ 100\,(\hat{\theta}* - 1) \tag{49}$$

Typically, Hauer(2) does not estimate a 95 percent confidence interval for θ or E. Rather, Hauer reports the percentage accident reduction effectiveness, E, and its standard deviation, also expressed as a percentage. Hauer also suggests that the estimated effect, E, should not be relied upon unless its estimated standard deviation is two to three times smaller than E. In this research, only results where the standard deviation of E was less than half of E were used. This is nearly equivalent to the Z value of 1.96 used in the YC and CG approaches.

Hauer has also formulated a more sophisticated EB approach in which the prediction of accident frequencies from the appropriate negative binomial regression relationship to determine the value of $E\{\kappa\}_i$ is done on a year-by-year basis, rather than for the before period as a whole. This more sophisticated EB approach was applied to 32 EB analyses, which constitute all of the EB analyses presented in Section 6 of this report that had sample sizes of 20 improved intersections or more. The differences in effectiveness measures between the EB approach described above and Hauer's more sophisticated approach ranged as high as 6 percent, but was typically less than 2 percent. The mean of the differences in effectiveness measures between the two approaches was 1.3 percent. While Hauer's more sophisiticated approach is desirable on theoretical grounds, and can be applied when year-by-year traffic volume data for the before period are available, the actual change in the results obtained in this study was minimal.

Strengths and Weaknesses of This Evaluation Approach

The major strength of the EB approach is that, among the evaluation approaches presented here, only the EB approach can address the potential bias created by regression to the mean. Neither the YC approach nor the CG approach can do this. In his recent book, Hauer presents a strong theoretical case for the advantages of the EB approach.(2)

Another strength of the EB approach is that, since regression modeling makes very efficient use of data, reference groups needed for the EB approach should be smaller than the comparison groups that would be required for the CG approach. This should enable percentage accident reduction for specific projects types to be assessed within the desired precision level in cases where this was not possible with the CG approach.

The EB approach eliminates the difficulty with zero values of accident frequency that is inherent in both the YC and CG approaches. In the EB approach, a value of K_i equal to zero can be treated naturally without arbitrarily substituting a value of 0.5. The weighting provided by Equation (36) will result in a non-zero value of $E\{\kappa|K\}_i$, because $E\{\kappa\}_i$ will be greater than zero even when K_i is not.

Execution of the Evaluation Plan

The evaluation plan is presented in this section of the report. The YC, CG, and EB evaluation approaches were applied to the database discussed in sections 3 and 4 of this report.

Yoked Comparison Evaluations

A total of 214 YC evaluations were performed for specific combinations of:

- Eight safety measures.

- total intersection accidents
  - fatal and injury intersection accidents
  - project-related intersection accidents
  - project-related fatal and injury intersection accidents
  - total accidents for individual intersection approaches
  - fatal and injury accidents for individual intersection approaches
  - project-related accidents for individual intersection approaches
  - project-related fatal and injury accidents for individual intersection approaches

- Two area types.
  - rural
  - urban

- Two intersection types.
  - three-leg intersections
  - four-leg intersections

- Three traffic control types.
  - unsignalized (two-way stop-control)
  - signalized
  - newly signalized (i.e., signalized in conjunction with left-turn installation)

- Five project types.
  - added left-turn lanes
  - added right-turn lanes
  - added left- and right-turn lanes
  - extension of the length of existing left-turn lanes
  - extension of the length of existing left- and right-turn lanes

The YC approach using one-to-one matching of treatment and comparison sites was executed as described above. The sample sizes for the 214 evaluations performed ranged from 1 to 35 intersections and from 1 to 116 intersection approaches. Statistically significant effectiveness measures were found for 37 of the 214 evaluations performed. Obviously, the evaluations with larger sample sizes are more likely to provide statistically significant results.

The results of the YC evaluations are presented in tables C-1 through C-10 in appendix C of this report and are discussed in section 6. The tables in Appendix C show the number of sites included in each evaluation; these are, in some cases, smaller than the total number of sites for that intersection and project type shown in section 4 of this report because of outliers that were omitted from the analysis. Outliers consisted of anomalous sites at which substantial unexplained increases in accident frequency occurred. For example, one site experienced 1 accident in 4 years before the turn lane project and 53 accidents in 6 years after the project. Such large increases in accident frequency suggest problems in accident reporting rather than actual project effects. In all analyses performed in this study, sites were excluded as outliers if the apparent treatment effectiveness was greater than equal to a 100 percent *increase* in accident frequency (i.e., if the odds ratio, $\hat{\theta}_i$, was greater than or equal to 2.0). Sites with less than 5 accidents in the before period were not excluded as outliers, even if $\hat{\theta}_i$ was greater than or equal to 2.0, because such variations in accident frequency over time are not unusual when the accident frequencies are very small.

Comparison Group Evaluations

A total of 150 CG evaluations were performed for specific combinations of:

- Six safety measures.
- Two area types.
- Two intersection types.
- Three traffic control types.
- Five project types.

The CG analysis omitted two safety measures that were considered in the YC analysis. These were:

- Project-related fatal and injury intersection accidents.
- Project-related fatal and injury accidents for individual approaches.

The CG analysis used the negative binomial regression relationships shown in Appendix B to adjust accident frequencies for differences in traffic volume between the before and after study periods and between the treatment and comparison sites. These negative binomial regression relationships also accounted for state-to-state differences in accident frequency in cases where treatment and comparison sites were located in different states. The state-to-state differences in accident frequencies in this multistate database were, in some cases, substantial (see appendix B). In evaluations for which no satisfactory regression models were available, proportional traffic volume adjustments based on Equation (22) were made.

The CG approach, using a comparison group to replace the single comparison site used in the YC analysis, was executed as described above. The sample sizes for the 150 evaluations ranged from 1 to 39 for intersections and from 1 to 155 for intersection approaches. Statistically significant effectiveness measures were found for 47 of the 150 evaluations performed. The resulting CG evaluations are presented in tables C-11 through C-16 in appendix C of this report and are discussed in Section 6.

Empirical Bayes Evaluations

A total of 108 EB evaluations were performed for specific combinations of:

- Six safety measures.
- Two area types.

- Two intersection types.
- Three traffic control types.
- Five project types.

The same six safety measures are used as in the CG evaluation, because negative binomial regression relationships, needed for the CG and EB evaluations, could not be developed for the safety measures based on project-related fatal and injury accidents. Several other cases also had to be omitted from the EB analysis because of unsatisfactory models.

The EB approach, using the negative binomial regression relationship in place of the comparison sites used in the YC and CG approaches, was executed as described above. The sample sizes for the 108 evaluations ranged from 1 to 39 for intersections and from 2 to 148 for intersection approaches. Statistically significant effectiveness measures were found for 48 of the 108 evaluations performed. The results of the EB evaluations are presented in table C-17 through C-22 in appendix C of this report and are discussed in section 6.

6. EVALUATION RESULTS

This section of the report presents and interprets the results of the evaluations conducted using the YC, CG, and EB approaches. Detailed results of all evaluations conducted as part of the study are presented in appendix C. This section focuses on those evaluation results that were found to be statistically significant. All tests of statistical significance in this report were performed at the 5 percent significance level (95 percent confidence level) unless otherwise stated.

The evaluation results are tabulated in several different ways in this section. First, results tables for each dependent variable and target area are presented. Then, the same results are tabulated and reviewed by project type.

Evaluation Results for Specific Safety Measures

Tables 28 through 40 present the evaluation results for specific safety measures. The results for four-leg intersections are presented first. There are more statistically significant analysis results for four-leg intersections than for three-leg intersections because there were more treated sites and more accidents per site for four-leg intersections. The tables and the safety measures presented for four-leg intersections include:

- Table 28—total intersection accidents.
- Table 29—fatal and injury intersection accidents.
- Table 30—project-related intersection accidents.
- Table 31—project-related fatal and injury intersection accidents.
- Table 32—total accidents for individual intersection approaches.
- Table 33—fatal and injury accidents for individual intersection approaches.
- Table 34—project-related accidents for individual intersection approaches.

Each table shows all treatment effectiveness measures that were obtained for the YC, CG, and EB approaches. Only those results that were statistically significant are included. There is no table for project-related fatal and injury accidents on individual intersection approaches because none of the evaluation results for that safety measure were statistically significant for the YC approach and, because of low accident frequencies, appropriate regression models to conduct the CG and EB approaches could not be developed.

The tables and the safety measures presented for three-leg intersections include:

- Table 35—total intersection accidents.
- Table 36—fatal and injury intersection accidents.
- Table 37—project-related intersection accidents.

Table 28. Evaluation Results for Total Intersection Accidents at Four-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
			No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
				for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs	2	-70.3	-35.2						
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	21	-58.8	-32.1	25	-60.6	-33.7	25	-49.6	-27.6
Rural	Unsignalized	Added LTLs and RTLs				15	-25.2	-12.6			
Rural	Unsignalized	Added RTLs				29	-35.1	-22.6	28	-22.0	-14.0
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs	24	-43.8	-22.4	28	-46.4	-24.1	25	-20.0	-10.4
Urban	Signalized	Added LTLs	33	-42.0	-13.0	37	-18.3	-5.8	39	-29.5	-9.5
Urban	Signalized	Added LTLs and RTLs	9	-21.3	-5.5	10	-26.6	-6.8	10	-27.8	-7.1
Urban	Signalized	Added RTLs							18	-9.0	-4.1
Urban	Signalized	Extended LTLs				3	42.3	25.4	3	49.5	29.7
Urban	Unsignalized	Added LTLs	8	-70.5	-35.2	9	-53.4	-26.7			
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs							3	-67.1	-40.3

Note: Only statistically significant evaluation results are shown.

Table 29. Evaluation Results for Fatal and Injury Intersection Accidents at Four-Leg Intersections.

			YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
				Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	Project type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs	2	−82.6	−41.3	2	−57.5	−28.7			
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	22	−70.4	−39.7	25	−73.9	−41.0	24	−63.4	−35.4
Rural	Unsignalized	Added LTLs and RTLs				15	−44.7	−22.3			
Rural	Unsignalized	Added RTLs				29	−37.2	−23.4			
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs	23	−42.7	−21.8	28	−48.7	−25.2	14	−54.2	−28.1
Urban	Signalized	Added LTLs	35	−39.5	−12.4	39	−18.0	−5.8	39	−28.4	−9.2
Urban	Signalized	Added LTLs and RTLs				10	−45.9	−11.8	10	−45.2	−11.6
Urban	Signalized	Added RTLs							17	−20.6	−9.2
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs	8	−79.5	−39.7	9	−58.8	−29.4			

Note: Only statistically significant evaluation results are shown.

Table 30. Evaluation Results for Project-Related Intersection Accidents at Four-Leg Intersections.

			YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
				Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	Project type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs							23	−66.2	−37.2
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs	35	−39.1	−12.6						
Urban	Signalized	Added LTLs and RTLs	7	−59.8	−15.5	9	−40.2	−10.3			
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs	8	−79.0	−39.5	9	−60.4	−30.2	7	−51.2	−25.6
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 31. Evaluation Results for Project-Related Fatal and Injury Accidents at Four-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON			COMPARISON GROUP[a]			EMPIRICAL BAYES[a]		
			No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
				for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs									
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs									
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs	8	−81.5	−40.8						
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

[a] Because of small accident frequencies, regression models could not be developed for this safety measure. Therefore, the CG and EB evaluations could not be performed.

Table 32. Evaluation Results for Total Accidents on Individual Intersection Approaches at Four-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
Rural	Newly Signalized	Added LTLs	4	-67.5	-67.5	4	-44.1	-44.1			
Rural	Newly Signalized	Added LTLs and RTLs				2	-68.8	-34.4	2	-61.4	-30.7
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	40	-47.3	-47.3	50	-61.0	-61.0	50	-54.6	-54.6
Rural	Unsignalized	Added LTLs and RTLs				30	-27.9	-14.0			
Rural	Unsignalized	Added RTLs				58	-31.6	-31.6	57	-26.7	-26.7
Rural	Unsignalized	Extended LTLs							4	-43.0	-43.0
Urban	Newly Signalized	Added LTLs	47	-55.0	-55.0	56	-45.7	-45.7	49	-28.0	-28.0
Urban	Signalized	Added LTLs	106	-42.0	-42.0	147	-28.0	-28.0	148	-34.2	-34.2
Urban	Signalized	Added LTLs and RTLs	32	-30.9	-15.4	39	-34.5	-17.2	38	-32.5	-16.2
Urban	Signalized	Added RTLs	28	-25.7	-25.7				67	-17.6	-17.6
Urban	Signalized	Extended LTLs				12	45.3	45.3	11	57.8	57.8
Urban	Unsignalized	Added LTLs	16	-69.4	-69.4	18	-54.4	-54.4	17	-20.1	-20.1
Urban	Unsignalized	Added LTLs and RTLs							2	-66.3	-33.1
Urban	Unsignalized	Added RTLs							6	-75.8	-75.8

Note: Only statistically significant evaluation results are shown.

Table 33. Evaluation Results for Fatal and Injury Accidents on Individual Intersection Approaches at Four-Leg Intersections.

			YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
				Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	Project type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs				4	-76.4	-76.4	4	-42.1	-42.1
Rural	Newly Signalized	Added LTLs and RTLs							2	-55.4	-27.7
Rural	Newly Signalized	Added RTLs				2	-65.6	-65.6			
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	41	-55.0	-55.0	50	-70.8	-70.8	49	-61.0	-61.0
Rural	Unsignalized	Added LTLs and RTLs				49	-48.1	-24.1			
Rural	Unsignalized	Added RTLs				58	-37.0	-37.0	55	-24.3	-24.3
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs	49	-58.1	-58.1	55	-46.9	-46.9	48	-43.2	-43.2
Urban	Signalized	Added LTLs	114	-40.0	-40.0	154	-22.6	-22.6	122	-35.3	-35.3
Urban	Signalized	Added LTLs and RTLs	34	-35.4	-17.2	39	-49.7	-24.9	35	-53.4	-26.7
Urban	Signalized	Added RTLs							64	-22.2	-22.2
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs	16	-77.8	-77.8	18	-55.4	-55.4			
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 34. Evaluation Results for Project-Related Accidents on Individual Intersection Approaches at Four-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
			No. of improved sites	Percent change in accident frequency for entire project	Percent change in accident frequency for one turn lane	No. of improved sites	Percent change in accident frequency for entire project	Percent change in accident frequency for one turn lane	No. of improved sites	Percent change in accident frequency for entire project	Percent change in accident frequency for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs									
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs	115	-33.9	-33.9				127	-40.4	-40.4
Urban	Signalized	Added LTLs and RTLs	32	-59.7	-29.8	38	-39.1	-19.6	34	-49.5	-24.8
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs	16	-78.1	-78.1	18	-60.5	-60.5	14	-50.5	-50.5
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 35. Evaluation Results for Total Intersection Accidents at Three-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	31	-63.7	-63.7	35	-53.5	-53.5	36	-43.7	-43.7
Rural	Unsignalized	Added LTLs and RTLs							12	-29.4	-23.5
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs									
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs				10	-35.0	-35.0	8	-33.2	-33.2
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 36. Evaluation Results for Fatal and Injury Intersection Accidents at Three-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	34	−58.6	−58.6	35	−54.8	−54.8			
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs									
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs									

Note: Only statistically significant evaluation results are shown.

Table 37. Evaluation Results for Project-Related Intersection Accidents at Three-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs				35	−62.3	−62.3			
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs									
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs									
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

- Table 38—total accidents for individual intersection approaches.
- Table 39—fatal and injury accidents for individual intersection accidents.
- Table 40—project-related accidents for individual intersection approaches.

These tables are comparable to those presented above for four-leg intersections. There is no table for project-related fatal and injury accidents at three-leg intersections because no evaluation results for that accident type were statistically significant.

Evaluation Results for Specific Project Types

The evaluation results for specific project types are presented in tables 41 through 46. Specifically, the evaluation results by project type for four-leg intersections are presented in the following tables:

- Table 41—projects involving added left-turn lanes.
- Table 42—projects involving added right-turn lanes.
- Table 43—projects involving added left- and right-turn lanes.
- Table 44—projects involving extension of the length of existing turn lanes.

The evaluation results by project type for three-leg intersections are presented in:

- Table 45—projects involving added left-turn lanes.
- Table 46—projects involving added right-turn lanes.

There were no statistically significant evaluation results for projects involving addition of both left- and right-turn lanes or extension of the length of existing turn lanes at three-leg intersections, so no tables of evaluation results are presented for these project types.

The results in tables 41 through 46 are drawn from, and are identical to, the results in tables 28 through 40. However, results for the safety measures involving project-related fatal and injury accidents are omitted because only the YC approach could be evaluated for those cases and, even for the YC approach, very few statistically significant results were obtained due to low accident frequencies analyzed.

The next section addresses the choice among the alternative analysis methods presented in these tables. Then, the results for the specific project types can be interpreted.

Table 38. Evaluation Results for Total Accidents on Individual Intersection Approaches at Three-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
			No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
				for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs	4	−67.5	−67.5						
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs	34	−47.5	−47.5	70	−51.9	−51.9	62	−45.2	−45.2
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs							9	−49.3	−49.3
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs							3	−44.5	−44.5
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs	10	−55.4	−55.4	20	−54.4	−54.4	16	−32.3	−32.3
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 39. Evaluation Results for Fatal and Injury Accidents on Individual Intersection Approaches at Three-Leg Intersections.

Area type	Traffic control type	Project type	YOKED COMPARISON No. of improved sites	YOKED COMPARISON Percent change in accident frequency for entire project	YOKED COMPARISON Percent change in accident frequency for one turn lane	COMPARISON GROUP No. of improved sites	COMPARISON GROUP Percent change in accident frequency for entire project	COMPARISON GROUP Percent change in accident frequency for one turn lane	EMPIRICAL BAYES No. of improved sites	EMPIRICAL BAYES Percent change in accident frequency for entire project	EMPIRICAL BAYES Percent change in accident frequency for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs				70	−43.6	−43.6			
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs							9	−47.6	−47.6
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs									
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 40. Evaluation Results for Project-Related Accidents on Individual Intersection Approaches at Three-Leg Intersections.

			YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
				Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	Project type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
Rural	Newly Signalized	Added LTLs									
Rural	Newly Signalized	Added LTLs and RTLs									
Rural	Newly Signalized	Added RTLs									
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Added LTLs				70	−64.3	−64.3			
Rural	Unsignalized	Added LTLs and RTLs									
Rural	Unsignalized	Added RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Newly Signalized	Added LTLs									
Urban	Signalized	Added LTLs									
Urban	Signalized	Added LTLs and RTLs									
Urban	Signalized	Added RTLs									
Urban	Signalized	Extended LTLs									
Urban	Unsignalized	Added LTLs									
Urban	Unsignalized	Added LTLs and RTLs									
Urban	Unsignalized	Added RTLs									

Note: Only statistically significant evaluation results are shown.

Table 41. Evaluation Results for Projects Involving Added Left-Turn Lanes at Four-Leg Intersections.

Area type	Traffic control type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
			for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
TOTAL INTERSECTION ACCIDENTS										
Rural	Newly Signalized	2	-70.3	-35.2						
Rural	Unsignalized	21	-58.8	-32.1	25	-60.6	-33.7	25	-49.6	-27.6
Urban	Newly Signalized	24	-43.8	-22.4	28	-46.4	-24.1			
Urban	Signalized	33	-42.0	-13.0	37	-18.3	-5.8	39	-29.5	-9.5
Urban	Unsignalized	8	-70.5	-35.2	9	-53.4	-26.7			
FATAL AND INJURY INTERSECTION ACCIDENTS										
Rural	Newly Signalized	2	-82.6	-41.3	2	-57.5	-28.7			
Rural	Unsignalized	22	-70.4	-39.7	25	-73.9	-41.0	24	-63.4	-35.4
Urban	Newly Signalized	23	-42.7	-21.8	28	-48.7	-25.2	14	-54.2	-28.1
Urban	Signalized	35	-39.5	-12.4	39	-18.0	-5.8	39	-28.4	-9.2
Urban	Unsignalized	8	-79.5	-39.7	9	-58.8	-29.4			
PROJECT-RELATED INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized							23	-66.2	-37.2
Urban	Newly Signalized									
Urban	Signalized	35	-39.1	-12.6						
Urban	Unsignalized	8	-79.0	-39.5	9	-60.4	-30.2	7	-51.2	-25.6
TOTAL ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized	4	-67.5	-67.5	4	-44.1	-44.1			
Rural	Unsignalized	40	-47.3	-47.3	50	-61.0	-61.0	50	-54.6	-54.6
Urban	Newly Signalized	47	-55.0	-55.0	56	-45.7	-45.7	49	-28.0	-28.0
Urban	Signalized	106	-42.0	-42.0	147	-28.0	-28.0	148	-34.2	-34.2
Urban	Unsignalized	16	-69.4	-69.4	18	-54.4	-54.4	17	-20.1	-20.1

Note: Only statistically significant evaluation results are shown.

Table 41. Evaluation Results for Projects Involving Added Left-Turn Lanes at Four-Leg Intersections (Continued).

Area type	Traffic control type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
			for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
FATAL AND INJURY ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized				4	-76.4	-76.4	4	-42.1	-42.1
Rural	Unsignalized	41	-55.0	-55.0	50	-70.8	-70.8	49	-61.0	-61.0
Urban	Newly Signalized	49	-58.1	-58.1	55	-46.9	-46.9	48	-43.2	-43.2
Urban	Signalized	114	-40.0	-40.0	154	-22.6	-22.6	122	-35.3	-35.3
Urban	Unsignalized	16	-77.8	-77.8	18	-55.4	-55.4			
PROJECT-RELATED ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Newly Signalized									
Urban	Signalized	115	-33.9	-33.9				127	-40.4	-40.4
Urban	Unsignalized	16	-78.1	-78.1	18	-60.5	-60.5	14	-50.5	-50.5

Note: Only statistically significant evaluation results are shown.

Table 42. Evaluation Results for Projects Involving Added Right-Turn Lanes at Four-Leg Intersections

Area type	Traffic control type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
TOTAL INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized				29	−35.1	−22.6	28	−22.0	−14.0
Urban	Signalized							18	−9.0	−4.1
Urban	Unsignalized							3	−67.1	−40.3
FATAL AND INJURY INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized				29	−37.2	−23.4			
Urban	Signalized							17	−20.6	−9.2
Urban	Unsignalized									
PROJECT-RELATED INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									
TOTAL ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized				58	−31.6	−31.6	57	−26.7	−26.7
Urban	Signalized	28	−25.7	−25.7				67	−17.6	−17.6
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Table 42. Evaluation Results for Projects Involving Added Right-Turn Lanes at Four-Leg Intersections (Continued).

		YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
			Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
FATAL AND INJURY ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized				2	−65.6	−65.6			
Rural	Unsignalized				58	−37.0	−37.0	55	−24.3	−24.3
Urban	Signalized							64	−22.2	−22.2
Urban	Unsignalized									
PROJECT-RELATED ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Table 43. Evaluation Results for Projects Involving Added Left- and Right-Turn Lanes at Four-Leg Intersections.

Area type	Traffic control type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
			for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
TOTAL INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized				15	−25.2	−12.6			
Urban	Signalized	9	−21.3	−5.5	10	−26.6	−6.8	10	−27.8	−7.1
Urban	Unsignalized									
FATAL AND INJURY INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized				15	−44.7	−22.3			
Urban	Signalized				10	−45.9	−11.8	10	−45.2	−11.6
Urban	Unsignalized									
PROJECT-RELATED INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized	7	−59.8	−15.5	9	−40.2	−10.3			
Urban	Unsignalized									
TOTAL ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized				2	−68.8	−34.4	2	−61.4	−30.7
Rural	Unsignalized				30	−27.9	−14.0			
Urban	Signalized	32	−30.9	−15.4	39	−34.5	−17.2	38	−32.5	−16.2
Urban	Unsignalized							2	−66.3	−33.1

Note: Only statistically significant evaluation results are shown.

Table 43. Evaluation Results for Projects Involving Added Left- and Right-Turn Lanes at Four-Leg Intersections (Continued).

Area type	Traffic control type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
FATAL AND INJURY ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized							2	-55.4	-27.7
Rural	Unsignalized				49	-48.1	-24.1			
Urban	Signalized	34	-35.4	-17.2	39	-49.7	-24.9	35	-53.4	-26.7
Urban	Unsignalized									
PROJECT-RELATED ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized	32	-59.7	-29.8	38	-39.1	-19.6	34	-49.5	-24.8
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Table 44. Evaluation Results for Projects Involving Extension of the Length of Existing Turn Lanes at Four-Leg Intersections

			YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
				Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	Project type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
TOTAL INTERSECTION ACCIDENTS											
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLS									
Rural	Unsignalized	Extended LTLs									
Urban	Signalized	Extended LTLs				3	42.3	25.4	3	49.5	29.7
FATAL AND INJURY INTERSECTION ACCIDENTS											
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Signalized	Extended LTLs									
PROJECT-RELATED INTERSECTION ACCIDENTS											
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Signalized	Extended LTLs									

Note: Only statistically significant evaluation results are shown.

Table 44. Evaluation Results for Projects Involving Extension of the Length of Existing Turn Lanes at Four-Leg Intersections (Continued).

Area type	Traffic control type	Project type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
			No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
				for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
TOTAL ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES											
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Extended LTLs							4	−43.0	−43.0
Urban	Signalized	Extended LTLs									
FATAL AND INJURY ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES											
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Signalized	Extended LTLs									
PROJECT-RELATED ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES											
Rural	Signalized	Extended LTLs									
Rural	Signalized	Extended LTLs and RTLs									
Rural	Unsignalized	Extended LTLs									
Urban	Signalized	Extended LTLs									

Note: Only statistically significant evaluation results are shown.

Table 45. Evaluation Results for Projects Involving Added Left-Turn Lanes at Three-Leg Intersections

Area type	Traffic control type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
			for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
TOTAL INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized	31	−63.7	−63.7	35	−53.5	−53.5	36	−43.7	−43.7
Urban	Newly Signalized									
Urban	Signalized									
Urban	Unsignalized				10	−35.0	−35.0	8	−33.2	−33.2
FATAL AND INJURY INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized	34	−58.6	−58.6	35	−54.8	−54.8			
Urban	Newly Signalized									
Urban	Signalized									
Urban	Unsignalized									
PROJECT-RELATED INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized				35	−62.3	−62.3			
Urban	Newly Signalized									
Urban	Signalized									
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Table 45. Evaluation Results for Projects Involving Added Left-Turn Lanes at Three-Leg Intersections (Continued).

		YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
			Percent change in accident frequency			Percent change in accident frequency			Percent change in accident frequency	
Area type	Traffic control type	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane	No. of improved sites	for entire project	for one turn lane
TOTAL ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized	4	−67.5	−67.5						
Rural	Unsignalized	34	−47.5	−47.5	70	−51.9	−51.9	62	−45.2	−45.2
Urban	Newly Signalized									
Urban	Signalized							9	−49.3	−49.3
Urban	Unsignalized	10	−55.4	−55.4	20	−54.4	−54.4	16	−32.3	−32.3
FATAL AND INJURY ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized				70	−43.6	−43.6			
Urban	Newly Signalized									
Urban	Signalized							9	−47.6	−47.6
Urban	Unsignalized									
PROJECT-RELATED ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized				70	−64.3	−64.3			
Urban	Newly Signalized									
Urban	Signalized									
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Table 46. Evaluation Results for Projects Involving Added Right-Turn Lanes at Three-Leg Intersections

Area type	Traffic control type	YOKED COMPARISON: No. of improved sites	YOKED COMPARISON: Percent change in accident frequency for entire project	YOKED COMPARISON: Percent change in accident frequency for one turn lane	COMPARISON GROUP: No. of improved sites	COMPARISON GROUP: Percent change in accident frequency for entire project	COMPARISON GROUP: Percent change in accident frequency for one turn lane	EMPIRICAL BAYES: No. of improved sites	EMPIRICAL BAYES: Percent change in accident frequency for entire project	EMPIRICAL BAYES: Percent change in accident frequency for one turn lane
TOTAL INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									
FATAL AND INJURY INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									
PROJECT-RELATED INTERSECTION ACCIDENTS										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									
TOTAL ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized							3	-44.5	-44.5
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Table 46. Evaluation Results for Projects Involving Added Right-Turn Lanes at Three-Leg Intersections (Continued).

Area type	Traffic control type	YOKED COMPARISON			COMPARISON GROUP			EMPIRICAL BAYES		
		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency		No. of improved sites	Percent change in accident frequency	
			for entire project	for one turn lane		for entire project	for one turn lane		for entire project	for one turn lane
FATAL AND INJURY ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									
PROJECT-RELATED ACCIDENTS FOR INDIVIDUAL INTERSECTION APPROACHES										
Rural	Newly Signalized									
Rural	Unsignalized									
Urban	Signalized									
Urban	Unsignalized									

Note: Only statistically significant evaluation results are shown.

Comparison of Alternative Evaluation Approaches

The tables presented above include results from the YC, CG, and EB approaches. For example, table 41 presents the results of 30 before-after evaluations for projects involving added left-turn lanes at four-leg intersections. Of these 30 evaluations, there are:

- Fourteen evaluations for which all three evaluation approaches provided statistically significant results.
- Four evaluations for which only the YC and CG approaches provided statistically significant results.
- One evaluation for which only the YC and EB approaches provided statistically significant results.
- One evaluation for which only the CG and EB approaches provided statistically significant results.
- Two evaluations for which only the YC approach provided statistically significant results.
- One evaluation for which only the EB approach provided statistically significant results.
- Five evaluations for which none of the approaches provided statistically significant results.

In any evaluation for which more than one approach provides statistically significant results, a key issue is to determine which results should be used.

The discussion of the three evaluation methods in section 5 of this report makes clear that, on conceptual and theoretical grounds, the EB approach appears to be the most desirable of the three approaches. The primary reason for this is that, among the three approaches, only EB can account for regression to the mean. When comparing the CG and YC methods, the CG method is most desirable on conceptual and theoretical grounds because it uses a group of comparison sites, rather than a single site, to determine what would have happened at the treatment site had the improvement not been made. The use of multiple comparison sites should reduce the variance of the treatment effect and provide more accurate results. Thus, we began the study with the idea that the three evaluation approaches, in descending order of appropriateness, were EB, CG, and YC.

The results in tables 41 through 46 have been reviewed for confirmation of our initial expectations concerning the suitability of the evaluation approaches. Table 46 presents a summary of the frequency with which various types of results were obtained.

Table 47 is interpreted as follows. First, the table shows that, for the 110 analyses performed, there were 46 statistically significant results for the EB approach, 45 for the CG approach, and 34 for the YC approach. While not definitive, this result is consistent with the theoretical expectation that the EB and CG approaches are preferable to the YC approach.

Second, for 32 cases where statistically significant results were obtained with the EB approach and at least one of the other approaches, the project effectiveness determined with the EB approach was lower than with the YC and CG in 18 cases and was higher in only 6 cases. The generally lower project effectiveness estimates obtained with the EB approach are consistent with the approach being less affected by regression to the mean than the YC and CG approaches.

Both of these observations from table 47 appear to confirm that the EB approach is the most suitable approach, followed by the CG approach, and then the YC approach. These findings support the use of the EB results in favor of the CG and YC results whenever the EB results are statistically significant. When the EB results are not statistically significant, the choice of which results to report is complex. One could:

- Use the EB results, even though the results are not statistically significant.
- Use the statistically significant CG or YC results, even though the results may be subject to regression to the mean.
- Report inconclusive results because no completely satisfactory result was obtained.

In the cases where the EB result was not statistically significant but the YC or CG result was statistically significant, we reviewed both the nonsignificant EB result and the significant YC or CG result. On engineering grounds, we generally found the significant YC or CG results to be more credible than the nonsignificant EB results. For example, at four-leg urban unsignalized intersections where left-turn lanes were added, the CG analysis shows a statistically significant decrease of 27 percent in total accidents, while the EB analysis shows a statistically non-significant decrease in total accidents of 0.1 percent. Both results are based on a limited sample of nine improved sites. The EB result suggests that installing left-turn lanes at urban unsignalized intersections has no safety benefit. By contrast, the 27 percent effectiveness estimate from the CG analysis for added left-turn lanes at four-leg urban unsignalized intersections is very consistent with the EB effectiveness estimate of 28 percent for four-leg *rural* intersections. We are not prepared to believe that this project type reduces total intersection accidents by 28 percent at rural unsignalized intersections, but has no effect at urban unsignalized intersections. However, it is also evident that the analysis results for this case are based on a very limited sample size and that a further evaluation with a larger sample of improved sites would be desirable.

Table 47. Comparison of Evaluation Approaches.

Project type	Total number of evaluations performed[a]	Number of evaluations with statistically significant results			Number of evaluations with statistically significant results for EB approach and at least one other approach	Relative magnitude of EB effectiveness estimates		
		YC	CG	EB		EB below YC and CG	EB between YC and CG	EB above YC and CG
Added LTLs	40	28	27	24	21	13	6	2
Added RTLs	30	1	5	10	3	3	0	0
Added LTLs and RTLs	26	5	11	9	6	2	2	2
Extended LTLs and RTLs	14	0	2	3	2	0	0	2
	110	34	45	46	32	18	8	6

[a] based on these evaluations included in Tables 40 through 45

For the reasons presented above, tables of final evaluation results have been prepared by applying the following rules to the results in tables 41 through 46:

- Use the effectiveness measure determined from the EB approach, if it is statistically significant.
- If the effectiveness measure determined from the EB approach is not statistically significant, but the effectiveness measure from the CG approach is statistically significant, use the CG result.
- If the effectiveness measures from both the EB and CG approaches are not statistically significant, but the effectiveness measure from the YC approach is statistically significant, use the YC result.

Projects Involving Added Left-Turn Lanes

Table 48 presents final evaluation results for projects involving added left-turn lanes at four-leg intersections. These results were derived from the results presented in table 41 using the guidelines for choice of evaluation approach presented above. All of the results in Table 48 are presented as percentage changes in accident frequency for installing one turn lane. Table 49 presents comparable effectiveness estimates for projects involving added left-turn lanes at three-leg intersections.

Each entry in the tables is presented in the format:

Percentage change ± standard error of percentage change

The percentage change is normally a negative value that represents the mean reduction in accident frequency that is expected to result from a specific type of improvement at a specific type of intersection. The standard error is a measure of the precision of the mean percentage change in accident frequency. The smaller the standard error, the smaller the magnitude of site-to-site and year-to-year variations in results would be expected. The standard error does not directly provide a confidence interval for the mean percentage change. In fact, as shown in the tables in appendix C of this report, the actual confidence intervals for the mean percentage change are asymmetrical (i.e., the width of the confidence interval below the mean is not the same as that above the mean). Thus, the interval containing one standard error on either side of the mean does not necessarily represent any particular proportion of the variation in the mean. Nevertheless, the standard error shown in tables 48 and 49 is useful as a measure of the relative precision of each result.

Table 48. Final Evaluation Results Involving Added Left-Turn Lanes for Four-Leg Intersections.

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	−28 ± 2.6	−35 ± 3.0	−37 ± 7.4	−55 ± 2.4	−61 ± 3.2	–
Newly Signalized[b]	−35 ± 7.6	−29 ± 6.3	–	−44 ± 7.3	−42 ± 7.6	–
URBAN INTERSECTIONS						
Unsignalized[b]	−27 ± 3.0	−29 ± 4.0	−25 ± 7.2	−20 ± 4.4	−55 ± 4.8	−51 ± 7.3
Signalized	−10 ± 0.8	−9 ± 1.3	−13 ± 3.2	−34 ± 0.8	−35 ± 1.3	−40 ± 1.8
Newly Signalized[b]	−24 ± 2.8	−28 ± 5.0	–	−28 ± 2.9	−43 ± 4.0	–

Note: Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.

[a] includes accidents of all severity levels

[b] based on a limited number of sites

Table 49. Final Evaluation Results Involving Added Left-Turn Lanes for Three-Leg Intersections.

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	−44 ± 5.5	−55 ± 8.3	−62 ± 14.5	−45 ± 6.5	−44 ± 10.9	−64 ± 10.5
Newly Signalized[b]	–	–	–	−68 ± 9.3	–	–
URBAN INTERSECTIONS						
Unsignalized[b]	−33 ± 12.1	–	–	−32 ± 13.1	–	–
Signalized[b]	–	–	–	−49 ± 13.9	−48 ± 23.4	–
Newly Signalized[b]	–	–	–	–	–	–

Note: Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.
[a] includes accidents of all severity levels
[b] based on a limited number of sites

For rural unsignalized intersections with two-way stop control, installation of a major-road left-turn lane was found to reduce total accidents at four-leg intersections by 28 percent. The corresponding reduction in fatal and injury intersection accidents was slightly larger, at 35 percent. In general, the effectiveness estimate for installing a left-turn lane was higher for the approach on which the turn lane was installed than for the intersection as a whole. Accident frequency was reduced by 55 percent for total accidents and by 61 percent for fatal and injury accidents on the specific intersection approach where the turn lane was installed.

For newly signalized four-leg intersections, the effectiveness of adding a left-turn lane appears to be slightly larger than at unsignalized intersections for total intersection accidents and slightly smaller than unsignalized intersections for individual intersection approaches.

Table 48 shows that the effectiveness of adding a major-road left-turn lane at an unsignalized intersection in an urban area is about the same as at a rural unsignalized intersection, although the urban result is based on a limited sample size. The effectiveness of adding a left-turn lane at an urban signalized intersection is a 10 percent reduction in total intersection accidents, which is substantially smaller than for urban unsignalized intersections.

The effectiveness measures for total intersection accidents in Table 48 address installation of a turn lane on a single major-road approach. If turn lanes are installed on both major-road approaches, the effectiveness measure for total intersection accidents would be expected to increase as follows:

$$E_2 = 100 - \left(\frac{100 - E_1}{100}\right)^2 x\, 100 \qquad (50)$$

where: E_2 = accident reduction effectiveness for adding turn lanes on two major-road approaches to an intersection

E_1 = accident reduction effectiveness for adding a turn lane on one major-road approach to an intersection

Equation (50) indicates that the second turn lane is effective in reducing only those intersection accidents not reduced by the first turn lane. Thus, the value of E_2 is always less than twice the value of E_1. Equation (50) is applicable only to the effectiveness measure for total intersection accidents, not those for accidents on individual intersection approaches.

For three-leg intersections, table 49 shows that total intersection accidents decreased by 44 percent with the addition of a major-road left-turn lane at rural unsignalized intersections and by 33 percent at urban unsignalized intersections.

The effectiveness of left-turn lanes in reducing accidents was generally higher for individual intersection approaches than for the intersection as a whole and generally higher for project-related accidents than for all accidents.

The results shown in table 48 are reasonably consistent with previous evaluations of left-turn lane installation. Table 3 shows a broad range of effectiveness measures for left-turn lane projects at unsignalized intersections—a reduction in total intersection accidents from 18 to 76 percent. Most of these projects were constructed at rural unsignalized intersections. The comparable result from table 48 is an accident reduction of 28 percent. While 28 percent is in the range from 18 to 76 percent reported in the literature, almost any credible evaluation result would also be in this range.

A more relevant comparison can be made with the results of the expert panel review of previous studies reported by Harwood et al.[25] This expert panel, in reviewing the literature, made estimates of the effectiveness of installing left turns at rural two-lane highway intersections. For four-leg unsignalized intersections, the expert panel estimated an effectiveness of 24 percent for major-road left-turn lane installation, while this study estimated 28 percent; thus, the results of the current study are quite comparable to previous studies. For three-leg unsignalized intersections, the expert panel estimated effectiveness of 22 percent for major-road left-turn lane installation, while the current study estimated 44 percent; thus, for three-leg unsignalized intersections this study estimates substantially more effectiveness than previous studies. It should be kept in mind that none of those previous studies used the formal evaluation approaches that have been used in this study.

Table 3 shows a range of effectiveness measures for installation of left-turn lanes at signalized intersections, most of them in urban and suburban areas, ranging from 6 to 70 percent. The effectiveness measure for urban signalized intersections found in this study is an accident reduction of 10 percent, which falls in the lower end of this range. For rural signalized intersections, the expert panel estimated the effectiveness of installing a left-turn lane as 18 percent.[25] No comparable effectiveness estimate was developed in this study, but the effectiveness of left-turn installation at urban signalized intersections was estimated as 10 percent.

Many of the results in the current study show lower effectiveness estimates for improvements at urban intersections than for comparable improvements at rural intersections.

Projects Involving Added Right-Turn Lanes

Table 50 presents the final evaluation results for projects involving added right-turn lanes at four-leg intersections. In general, the accident reduction effectiveness of installing right-turn lanes for total intersection accidents or total approach accidents is substantially smaller than for installing left-turn lanes. This is to be expected because right-turn

Table 50. Final Evaluation Results for Projects Involving Added Right-Turn Lanes for Four-Leg Intersections.

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	−14 ± 5.2	−23 ± 6.6	−	−27 ± 5.3	−24 ± 7.9	−
Newly Signalized[b]	−	−	−	−	−66 ± 7.6	−
URBAN INTERSECTIONS						
Unsignalized[b]	−40 ± 10.1	−	−	−	−	−
Signalized	−4 ± 2.0	−9 ± 3.0	−	−18 ± 2.0	−22 ± 3.1	−

Note: Results for unsignalized intersections apply only to right-turn lanes on major-road approaches.

[a] includes accidents of all severity levels

[b] based on a limited number of sites

collisions are typically less frequent than left-turn collisions. For the most part, statistically significant effectiveness measures for installation of right-turn lanes were obtained only for unsignalized intersections in rural areas and signalized intersections in urban areas.

At rural unsignalized four-leg intersections, right-turn lane projects reduced total intersection accidents by 14 percent and intersection approach accidents by 27 percent. The effectiveness measure of 14 percent for total intersection accidents is higher than the comparable value of 5 percent estimated by the expert panel convened by Harwood et al.(25)

At urban signalized intersections, right-turn lane projects reduced total intersection accidents by 4 percent and total intersection-approach accidents by 18 percent.

Where right-turn lanes are installed on two major-road approaches to an intersection, the combined effectiveness measure for both turn lanes should be determined using Equation (50).

Table 51 presents the final evaluation results for projects involving added right-turn lanes at three-leg intersections. Only limited results were obtained for this type of project.

Projects Involving Added Left- and Right-Turn Lanes

Table 52 presents final evaluation results for projects involving the addition of both left- and right-turn lanes at four-leg intersections. These projects combine installation of both left- and right-turn lanes on a single approach. For this reason, one would expect the results in table 52 to be between the results in tables 48 and 50; this appears to be the case for total intersection accidents at urban signalized intersections, but not at rural unsignalized intersections. The total effect of installing both left- and right-turn lanes on two major-road approaches can be obtained with Equation (50). There were no statistically significant results for projects involving the addition of both left- and right-turn lanes at three-leg intersections.

There is no obvious method to separate the effects of left- and right-turn lanes in table 52. A preferable method of determining the effects of adding both left- and right-turn lanes is to combine the relevant effectiveness measures from table 48 or 49 with those from table 50 or 51. For example, it can be shown from tables 48 and 50 and Equation (50) that at an urban four-leg signalized intersection, the addition of two major-road left-turn lanes would be expected to reduce total intersection accidents by 19 percent. The addition of two major-road right-turn lanes would be expected to reduce total intersection accidents by 8 percent. The combined effectiveness would be computed as 1- (1 - 0.19) (1 - 0.08) = 0.25, or a 25 percent reduction in total intersection accidents.

Table 51. Final Evaluation Results for Projects Involving Added Right-Turn Lanes for Three-Leg Intersections.

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	–	–	−46 ± 38.6	–	–	–
Newly Signalized	–	–	–		–	–
URBAN INTERSECTIONS						
Unsignalized	–	–	–	–	–	–
Signalized[b]	–	–	–	−45 ± 10.4	–	–

Note: Results for unsignalized intersections apply only to right-turn lanes on major-road approaches.

[a] includes accidents of all severity levels

[b] based on a limited number of sites

Table 52. Final Evaluation Results for Projects Involving Added Left- and Right-Turn Lanes for Four-Leg Intersections.

	Percent change in accident frequency for adding one turn lane					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	−13 ± 5.3	−22 ± 6.1	–	−14 ± 5.7	–	–
Newly Signalized[b]	–	–	–	−31 ± 8.2	−28 ± 11.6	–
URBAN INTERSECTIONS						
Unsignalized[b]	–	–	–	−33 ± 9.9	–	–
Signalized	−7 ± 1.2	−12 ± 1.7	−10 ± 2.2	−16 ± 1.1	−27 ± 1.5	−25 ± 1.8

Note: Results for unsignalized intersections apply only to turn lanes on major-road approaches.

[a] includes accidents of all severity levels

[b] based on a limited number of sites

Projects Involving Extension of the Length of Existing Turn Lanes

No separate table of final evaluation results is presented for projects involving the extension of the length of existing turn lanes. The available results, which are quite sparse, are presented in table 44.

Table 44 shows that for three projects in which the existing left-turn lanes at urban four-leg signalized intersections were extended, total intersection accidents increased by approximately 30 percent. This increase may result from substantial growth in left-turn volumes at these signalized intersections that was not accounted for in the evaluation. A weakness of this evaluation is that, while growth in the total major- and minor-road average daily traffic volumes was accounted for, no data on the growth in left-turn volumes are available. The decision by the highway agency to extend the length of the left-turn lane suggests that left-turn volumes were growing, but it is not known whether they were growing faster than the major-road volume as a whole.

At rural unsignalized four-leg intersections, for four intersection approaches where existing major-road left-turn lanes were extended in length, the effect of the projects was to reduce total accident frequency on the intersection approach by 43 percent. None of the other safety measures for these projects had statistically significant changes.

No statistically significant analysis results were found for the extension of the length of existing turn lanes at three-leg intersections.

Because the analyses of the extended-turn-lane projects are based on small sample sizes, no overall conclusions have been drawn from the evaluation of these projects.

Supplementary Analysis Results

Two supplementary analyses were conducted to evaluate intersection design and traffic control features that, because of sample size considerations, could be evaluated for some, but not all, intersection types. These supplementary analyses addressed the relative safety effectiveness of curbed vs. painted channelization for left-turn lanes and of protected vs. protected/permissive left-turn signal phasing. These analyses were conducted using the EB approach for three intersection types with sufficient data to make these comparisons.

Table 53 shows that at rural unsignalized intersections there appears to be a definite indication that left-turn lanes with curbed channelization are more effective than left-turn lanes with painted channelization. This appears to be particularly the case for rural four-leg unsignalized intersections in which channelized left-turn lanes reduced accidents by 57 percent while painted left-turn channelization reduced accidents by only 23 percent. By contrast, there appears to be no difference between the safety effectiveness of curbed and painted left-turn channelization for urban four-leg signalized intersections. However, the sample sizes for these comparisons are too small for the results to be definitive.

Table 53. Comparison of Safety Effectiveness of Added Left-Turn Lanes With Curbed and Painted Channelization.

			Number of improved sites			Percentage reduction in accidents from left-turn lane installation		
Area type	Type of traffic control	No. of legs	All LTL types	Curbed LTLs	Painted LTLs	All LTL types	Curbed LTLs	Painted LTLs
Rural	Unsignalized	3	36	5	31	-44	-49	-43
Rural	Unsignalized	4	24	6	18	-28	-57	-23
Urban	Signalized	4	38	8	30	-10	-10	-9

Table 54 shows a similar evaluation for protected and protected/permissive signal phasing at urban four-leg signalized intersections. The results suggest that there is essentially no effect of the type of signal phasing on the safety effectiveness of left-turn lanes. However, as in the previous analysis, there are too few data to obtain definitive results. Signalized intersections with no separate left-turn phasing were not included in the evaluation because data were available for only two sites without left-turn phasing.

Table 54. Comparison of Safety Effectiveness of Added Left-Turn Lanes With Protected and Protected/Permissive Signal Phasing.

			Number of improved sites			Percentage reduction in accidents from left-turn lane installation		
Area type	Type of traffic control	No. of legs	Combined	Protected	Protected/ permissive	Combined	Protected	Protected/ permissive
Urban	Signalized	4	36	5	31	-10	-10	-9

Recommended Accident Modification Factors

AMFs have been developed based on the results presented above for potential use to replace the AMFs for rural intersections presented in tables 2 and 4. In addition, AMFs for turn-lane installation at urban intersections have also been devleoped.

AMFs for installation of left-turn lanes at rural intersections are presented in table 55. The AMFs for STOP-controlled intersections are based on the results of the current study. The AMFs for signalized intersections are those developed by the expert panel convened by Harwood et al.,[25] since no results for rural signalized intersections were obtained in the current study.

Table 55. Recommended Accident Modification Factors for Installation of Left-Turn Lanes on the Major-Road Approaches to Rural Intersections.

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign[a] Traffic signal	0.56[b] 0.85[c]	— —
Four-leg intersection	STOP sign[a] Traffic signal	0.72[d] 0.82[c]	0.52[d] 0.67[c]

[a] STOP signs on minor-road approach(es)
[b] based on results in Table 49
[c] based on results in Reference 25
[d] based on results in Table 48

AMFs for installation of left-turn lanes at urban intersections are presented in Table 56. All of the AMFs in the table are based on the results of the current study, except for the AMF for three-leg signalized intersections. Since no results for three-leg signalized intersections in rural areas were obtained in the current study, the AMF of 0.93 in the table was derived by using the same proportional difference between the AMFs for three- and four-leg signalized intersections shown in table 55 (i.e., 0.90 x 0.85/0.83 = 0.93).

Table 56. Recommended Accident Modification Factors for Installation of Left-Turn Lanes on the Major-Road Approaches to Urban Intersections.

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign[a] Traffic signal	0.67[b] 0.93[c]	— —
Four-leg intersection	STOP sign[a] Traffic signal	0.73[d] 0.90[d]	0.53[d] 0.81[d]

[a] STOP signs on minor-road approach(es)
[b] based on Table 49
[c] estimated from Table 48 and Reference 25
[d] based on Table 48

Table 57 presents AMFs for installation of right-turn lanes based on the results of the current study. These AMFs, based on results obtained in the current study for rural unsignalized intersections and urban signalized intersections, should be applied to all rural and urban intersections, because no better estimates are available.

Table 57. Recommended Accident Modification Factors for Installation of Right-Turn Lanes on the Major-Road Approaches to Rural and Urban Intersections.

Intersection traffic control	Number of major-road approaches on which right-turn lanes are installed	
	One approach	Both approaches
STOP sign[a]	0.86[b]	0.74[b]
Traffic signal	0.96[c]	0.92[c]

[a] STOP signs on minor-road approach(es)
[b] based on rural unsignalized intersection results in Table 50
[c] based on urban signalized intersection results in Table 50

It is recommended that the AMFs presented in tables 55 through 57 be used for safety prediction in the FHWA Interactive Highway Safety Design Model (IHSDM) and in other ongoing initiatives such as the FHWA Comprehensive Highway Safety Improvement Model (CHSIM).

Economic Evaluation

Tables 58 through 65 present the results of an economic evaluation of the installation of left-turn lanes at intersections of various types. The primary measure of the cost effectiveness of improvement projects shown in the tables is the benefit-cost ratio (B/C), which is determined as the present value of future accident costs reduced, divided by the estimated cost of constructing the left-turn lanes. When the benefit-cost ratio is greater than 1.0, this indicates that the anticipated benefit of adding a left-turn lane will exceed its cost.

Each table presents an economic analysis for adding left-turn lanes at specific intersection types under specific traffic volume assumptions. The intersection types considered are:

- Rural three-leg unsignalized intersections.
- Rural four-leg unsignalized intersections.
- Urban four-leg unsignalized intersections.
- Urban four-leg signalized intersections.

The traffic volume assumptions are:

- Major-road ADT from 1,000 to 10,000 veh/day for unsignalized intersections.
- Major-road ADT from 10,000 to 40,000 veh/day for signalized intersections.
- Minor-road ADT equal to either 10 or 50 percent of major-road ADT for unsignalized intersections.

- Minor-road ADT equal to either 25 or 50 percent of major-road ADT for signalized intersections.

For each intersection type and traffic volume level, the expected number of accidents per year was estimated from the negative binomial regression models for total intersection accidents presented in appendix B. The AMFs for left-turn installation are those presented in tables 55 and 56. The number of accidents reduced per year by left-turn installation was derived by combining the expected number of accidents per year and the AMF.

The costs of accidents reduced were derived from FHWA estimates for 1994, updated to 2002 using the GDP implicit price deflator. These values are:

- Fatal and injury accidents—$103,000.
- Property-damage-only accidents—$2,300.

The present value of accident costs reduced was derived with the uniform series present worth factor based on the assumptions of a project service life of 30 years and a minimum attractive rate of return (MARR) of 4 percent.

The average cost of installing a single left-turn lane is $85,000 based on estimates from four of the states that participated in this study.

Tables 58 and 59 present the economic evaluation results for installing a single major-road left-turn lane at a rural three-leg unsignalized intersection. These results indicate that left-turn lane installation would become cost effective for a major-road ADT of 4,000 veh/day with 10 percent of the major-road volume on the minor road and at 2,000 veh/day with 50 percent of the major-road volume on the minor road.

Tables 60 and 61 present comparable data for rural four-leg unsignalized intersections. Left-turn lane installation would become cost-effective for a major-road ADT of 3,000 veh/day with 10 percent of the major-road volume on the minor road. With a minor-road volume equal to 50 percent of the major-road volume, left-turn lane installation would be cost effective at all of the major-road volume levels considered.

Tables 62 and 63 present comparable data for urban four-leg unsignalized intersections. Left-turn lane installation would become cost-effective for a major-road ADT of 2,000 veh/day with both 10 and 50 percent of the major-road volume on the minor road.

Tables 64 and 65 present comparable data for urban four-leg signalized intersections. Left-turn lane installation was found to be cost-effective for all combinations of major- and minor-road ADTs considered.

Table 58. Economic Evaluation for Rural Three-Leg Unsignalized Intersections with Minor-Road ADT Equal to 10 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & Injury	PDO					
1,000	100	0.03	0.56	0.01	1	85,000	85,000	103,000	2,300	46.0	30	4.0	10,246	0.1
2,000	200	0.09	0.56	0.04	1	85,000	85,000	103,000	2,300	46.0	30	4.0	31,780	0.4
3,000	300	0.17	0.56	0.07	1	85,000	85,000	103,000	2,300	46.0	30	4.0	61,618	0.7
4,000	400	0.27	0.56	0.12	1	85,000	85,000	103,000	2,300	46.0	30	4.0	98,567	1.2
5,000	500	0.38	0.56	0.17	1	85,000	85,000	103,000	2,300	46.0	30	4.0	141,901	1.7
6,000	600	0.52	0.56	0.23	1	85,000	85,000	103,000	2,300	46.0	30	4.0	191,113	2.2
7,000	700	0.66	0.56	0.29	1	85,000	85,000	103,000	2,300	46.0	30	4.0	245,818	2.9
8,000	800	0.83	0.56	0.36	1	85,000	85,000	103,000	2,300	46.0	30	4.0	305,713	3.6
9,000	900	1.00	0.56	0.44	1	85,000	85,000	103,000	2,300	46.0	30	4.0	370,550	4.4
10,000	1,000	1.19	0.56	0.52	1	85,000	85,000	103,000	2,300	46.0	30	4.0	440,117	5.2

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 59. Economic Evaluation for Rural Three-Leg Unsignalized Intersections with Minor-Road ADT Equal to 50 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident Costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
1,000	500	0.08	0.56	0.03	1	85,000	85,000	103,000	2,300	46.0	30	4.0	28,380	0.3
2,000	1,000	0.24	0.56	0.10	1	85,000	85,000	103,000	2,300	46.0	30	4.0	88,023	1.0
3,000	1,500	0.46	0.56	0.20	1	85,000	85,000	103,000	2,300	46.0	30	4.0	170,669	2.0
4,000	2,000	0.74	0.56	0.32	1	85,000	85,000	103,000	2,300	46.0	30	4.0	273,011	3.2
5,000	2,500	1.06	0.56	0.47	1	85,000	85,000	103,000	2,300	46.0	30	4.0	393,038	4.6
6,000	3,000	1.43	0.56	0.63	1	85,000	85,000	103,000	2,300	46.0	30	4.0	529,343	6.2
7,000	3,500	1.84	0.56	0.81	1	85,000	85,000	103,000	2,300	46.0	30	4.0	680,866	8.0
8,000	4,000	2.29	0.56	1.01	1	85,000	85,000	103,000	2,300	46.0	30	4.0	846,764	10.0
9,000	4,500	2.77	0.56	1.22	1	85,000	85,000	103,000	2,300	46.0	30	4.0	1,026,347	12.1
10,000	5,000	3.30	0.56	1.45	1	85,000	85,000	103,000	2,300	46.0	30	4.0	1,219,035	14.3

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 60. Economic Evaluation for Rural Four-Leg Unsignalized Intersections With Minor-Road ADT Equal to 10 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
1,000	100	0.12	0.52	0.06	2	85,000	170,000	103,000	2,300	46.3	30	4.0	47,994	0.3
2,000	200	0.26	0.52	0.13	2	85,000	170,000	103,000	2,300	46.3	30	4.0	106,802	0.6
3,000	300	0.42	0.52	0.20	2	85,000	170,000	103,000	2,300	46.3	30	4.0	170,525	1.0
4,000	400	0.59	0.52	0.28	2	85,000	170,000	103,000	2,300	46.3	30	4.0	237,666	1.4
5,000	500	0.76	0.52	0.36	2	85,000	170,000	103,000	2,300	46.3	30	4.0	307,469	1.8
6,000	600	0.93	0.52	0.45	2	85,000	170,000	103,000	2,300	46.3	30	4.0	379,469	2.2
7,000	700	1.12	0.52	0.54	2	85,000	170,000	103,000	2,300	46.3	30	4.0	453,350	2.7
8,000	800	1.30	0.52	0.63	2	85,000	170,000	103,000	2,300	46.3	30	4.0	528,879	3.1
9,000	900	1.49	0.52	0.72	2	85,000	170,000	103,000	2,300	46.3	30	4.0	605,879	3.6
10,000	1,000	1.68	0.52	0.81	2	85,000	170,000	103,000	2,300	46.3	30	4.0	684,211	4.0

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 61. Economic Evaluation for Rural Four-Leg Unsignalized Intersections With Minor-Road ADT Equal to 50 Percent of Major-Road ADT

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
1,000	500	0.47	0.52	0.22	2	85,000	170,000	103,000	2,300	46.3	30	4.0	190,331	1.1
2,000	1,000	1.04	0.52	0.50	2	85,000	170,000	103,000	2,300	46.3	30	4.0	423,543	2.5
3,000	1,500	1.67	0.52	0.80	2	85,000	170,000	103,000	2,300	46.3	30	4.0	676,249	4.0
4,000	2,000	2.32	0.52	1.11	2	85,000	170,000	103,000	2,300	46.3	30	4.0	942,510	5.5
5,000	2,500	3.00	0.52	1.44	2	85,000	170,000	103,000	2,300	46.3	30	4.0	1,219,326	7.2
6,000	3,000	3.71	0.52	1.78	2	85,000	170,000	103,000	2,300	46.3	30	4.0	1,504,857	8.9
7,000	3,500	4.43	0.52	2.13	2	85,000	170,000	103,000	2,300	46.3	30	4.0	1,797,843	10.6
8,000	4,000	5.16	0.52	2.48	2	85,000	170,000	103,000	2,300	46.3	30	4.0	2,097,367	12.3
9,000	4,500	5.92	0.52	2.84	2	85,000	170,000	103,000	2,300	46.3	30	4.0	2,402,727	14.1
10,000	5,000	6.68	0.52	3.21	2	85,000	170,000	103,000	2,300	46.3	30	4.0	2,713,367	16.0

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 62. Economic Evaluation for Urban Four-Leg Unsignalized Intersections With Minor-Road ADT Equal to 10 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
1,000	100	0.27	0.53	0.13	2	85,000	170,000	103,000	2,300	42.4	30	4.0	98,923	0.6
2,000	200	0.48	0.53	0.23	2	85,000	170,000	103,000	2,300	42.4	30	4.0	176,464	1.0
3,000	300	0.68	0.53	0.32	2	85,000	170,000	103,000	2,300	42.4	30	4.0	247,567	1.5
4,000	400	0.86	0.53	0.40	2	85,000	170,000	103,000	2,300	42.4	30	4.0	314,786	1.9
5,000	500	1.04	0.53	0.49	2	85,000	170,000	103,000	2,300	42.4	30	4.0	379,259	2.2
6,000	600	1.21	0.53	0.57	2	85,000	170,000	103,000	2,300	42.4	30	4.0	441,624	2.6
7,000	700	1.37	0.53	0.65	2	85,000	170,000	103,000	2,300	42.4	30	4.0	502,288	3.0
8,000	800	1.54	0.53	0.72	2	85,000	170,000	103,000	2,300	42.4	30	4.0	561,534	3.3
9,000	900	1.69	0.53	0.80	2	85,000	170,000	103,000	2,300	42.4	30	4.0	619,567	3.6
10,000	1,000	1.85	0.53	0.87	2	85,000	170,000	103,000	2,300	42.4	30	4.0	676,544	4.0

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 63. Economic Evaluation for Urban Four-Leg Unsignalized Intersections With Minor-Road ADT Equal to 50 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
1,000	500	0.37	0.53	0.17	2	85,000	170,000	103,000	2,300	42.4	30	4.0	135,175	0.8
2,000	1,000	0.66	0.53	0.31	2	85,000	170,000	103,000	2,300	42.4	30	4.0	241,133	1.4
3,000	1,500	0.93	0.53	0.43	2	85,000	170,000	103,000	2,300	42.4	30	4.0	338,293	2.0
4,000	2,000	1.18	0.53	0.55	2	85,000	170,000	103,000	2,300	42.4	30	4.0	430,146	2.5
5,000	2,500	1.42	0.53	0.67	2	85,000	170,000	103,000	2,300	42.4	30	4.0	518,246	3.0
6,000	3,000	1.65	0.53	0.78	2	85,000	170,000	103,000	2,300	42.4	30	4.0	603,466	3.5
7,000	3,500	1.88	0.53	0.88	2	85,000	170,000	103,000	2,300	42.4	30	4.0	686,362	4.0
8,000	4,000	2.10	0.53	0.99	2	85,000	170,000	103,000	2,300	42.4	30	4.0	767,320	4.5
9,000	4,500	2.32	0.53	1.09	2	85,000	170,000	103,000	2,300	42.4	30	4.0	846,620	5.0
10,000	5,000	2.53	0.53	1.19	2	85,000	170,000	103,000	2,300	42.4	30	4.0	924,477	5.4

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 64. Economic Evaluation for Urban Four-Leg Signalized Intersections With Minor-Road ADT Equal to 25 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
10,000	2,500	1.80	0.81	0.34	2	85,000	170,000	103,000	2,300	39.5	30	4.0	248,458	1.5
11,000	2,750	2.10	0.81	0.40	2	85,000	170,000	103,000	2,300	39.5	30	4.0	290,660	1.7
12,000	3,000	2.43	0.81	0.46	2	85,000	170,000	103,000	2,300	39.5	30	4.0	335,417	2.0
13,000	3,250	2.77	0.81	0.53	2	85,000	170,000	103,000	2,300	39.5	30	4.0	382,651	2.3
14,000	3,500	3.13	0.81	0.59	2	85,000	170,000	103,000	2,300	39.5	30	4.0	432,294	2.5
15,000	3,750	3.50	0.81	0.67	2	85,000	170,000	103,000	2,300	39.5	30	4.0	484,282	2.8
16,000	4,000	3.90	0.81	0.74	2	85,000	170,000	103,000	2,300	39.5	30	4.0	538,560	3.2
17,000	4,250	4.30	0.81	0.82	2	85,000	170,000	103,000	2,300	39.5	30	4.0	595,075	3.5
18,000	4,500	4.73	0.81	0.90	2	85,000	170,000	103,000	2,300	39.5	30	4.0	653,779	3.8
19,000	4,750	5.17	0.81	0.98	2	85,000	170,000	103,000	2,300	39.5	30	4.0	714,629	4.2
20,000	5,000	5.62	0.81	1.07	2	85,000	170,000	103,000	2,300	39.5	30	4.0	777,585	4.6
22,000	5,500	6.58	0.81	1.25	2	85,000	170,000	103,000	2,300	39.5	30	4.0	909,662	5.4
24,000	6,000	7.59	0.81	1.44	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,049,736	6.2
26,000	6,500	8.66	0.81	1.65	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,197,564	7.0
28,000	7,000	9.79	0.81	1.86	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,352,928	8.0
30,000	7,500	10.96	0.81	2.08	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,515,633	8.9
32,000	8,000	12.19	0.81	2.32	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,685,502	9.9
34,000	8,500	13.47	0.81	2.56	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,862,373	11.0
36,000	9,000	14.80	0.81	2.81	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,046,098	12.0
38,000	9,500	16.18	0.81	3.07	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,236,538	13.2
40,000	10,000	17.60	0.81	3.34	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,433,566	14.3

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

Table 65. Economic Evaluation for Urban Four-Leg Signalized Intersections With Minor-Road ADT Equal to 50 Percent of Major-Road ADT.

ADT		Expected number of accidents per year	AMF	No. of accidents reduced per year	No. of LTLs installed	Cost per turn lane installed ($)	Total cost ($)	Accident costs ($)		Percent fatal and injury accidents	Service life (years)	MARR	Percent value of accident costs reduced ($)	B/C
Major	Minor							Fatal & injury	PDO					
10,000	5,000	3.15	0.81	0.60	2	85,000	170,000	103,000	2,300	39.5	30	4.0	435,901	2.6
11,000	5,500	3.69	0.81	0.70	2	85,000	170,000	103,000	2,300	39.5	30	4.0	509,941	3.0
12,000	6,000	4.26	0.81	0.81	2	85,000	170,000	103,000	2,300	39.5	30	4.0	588,464	3.5
13,000	6,500	4.86	0.81	0.92	2	85,000	170,000	103,000	2,300	39.5	30	4.0	671,334	3.9
14,000	7,000	5.49	0.81	1.04	2	85,000	170,000	103,000	2,300	39.5	30	4.0	758,428	4.5
15,000	7,500	6.15	0.81	1.17	2	85,000	170,000	103,000	2,300	39.5	30	4.0	849,638	5.0
16,000	8,000	6.83	0.81	1.30	2	85,000	170,000	103,000	2,300	39.5	30	4.0	944,864	5.6
17,000	8,500	7.55	0.81	1.43	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,044,015	6.1
18,000	9,000	8.30	0.81	1.58	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,147,008	6.7
19,000	9,500	9.07	0.81	1.72	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,253,765	7.4
20,000	10,000	9.87	0.81	1.87	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,364,216	8.0
22,000	11,000	11.54	0.81	2.19	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,595,936	9.4
24,000	12,000	13.32	0.81	2.53	2	85,000	170,000	103,000	2,300	39.5	30	4.0	1,841,686	10.8
26,000	13,000	15.20	0.81	2.89	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,101,038	12.4
28,000	14,000	17.17	0.81	3.26	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,373,613	14.0
30,000	15,000	19.23	0.81	3.65	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,659,068	15.6
32,000	16,000	21.39	0.81	4.06	2	85,000	170,000	103,000	2,300	39.5	30	4.0	2,957,091	17.4
34,000	17,000	23.64	0.81	4.49	2	85,000	170,000	103,000	2,300	39.5	30	4.0	3,267,398	19.2
36,000	18,000	25.97	0.81	4.93	2	85,000	170,000	103,000	2,300	39.5	30	4.0	3,589,729	21.1
38,000	19,000	28.38	0.81	5.39	2	85,000	170,000	103,000	2,300	39.5	30	4.0	3,923,843	23.1
40,000	20,000	30.88	0.81	5.87	2	85,000	170,000	103,000	2,300	39.5	30	4.0	J4,269,515	25.1

MARR = minimum attractive rate of return
B/C = benefit-cost ratio

7. CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions and recommendations of the research on the effectiveness of left- and right-turn lane improvements for at-grade intersections.

Conclusions

The conclusions of the study are as follows:

1. Added left-turn lanes are effective in improving safety at signalized and unsignalized intersections in both rural and urban areas. Installation of a single left-turn lane on a major-road approach would be expected to reduce total intersection accidents at rural unsignalized intersections by 28 percent for four-leg intersections and by 44 percent for three-leg intersections. At urban unsignalized intersections, installation of a left-turn lane on one approach would be expected to reduce accidents by 27 percent for four-leg intersections and by 33 percent for three-leg intersections. At four-leg urban signalized intersections, installation of a left-turn lane on one approach would be expected to reduce accidents by 10 percent. Installation of left-turn lanes on both major-road approaches to a four-leg intersection would be expected to increase, but not quite double, the resulting effectiveness measures for total intersection accidents; the increased effectiveness measure for adding left-turn lanes on both major-road approaches can be determined using Equation (50). The complete set of effectiveness measures for left-turn lane installation is presented in Tables 48 and 49.

2. Added right-turn lanes are effective in improving safety at signalized and unsignalized intersections in both rural and urban areas. Installation of a single right-turn lane on a major-road approach would be expected to reduce total intersection accidents at rural unsignalized intersections by 14 percent and accidents at urban signalized intersections by 4 percent. Right-turn lane installation reduced accidents on individual approaches to four-leg intersections by 27 percent at rural unsignalized intersections and by 18 percent at urban signalized intersections. Only limited results were found for right-turn lane installation at three-leg intersections. Installation of right-turn lanes on both major-road approaches to a four-leg intersections would be expected to increase, but not quite double, the resulting effectiveness measures for total intersection accidents; the increased effectiveness measure for adding right-turn lanes on both major-road approaches can be determined using Equation (50). The complete set of effectiveness measures for right-turn lane installation is presented in tables 50 and 51.

3. For both left- and right-turn lane improvements, the results obtained from this study are within the range of all previous studies reported in the literature, but are slightly higher than the best estimates from previous studies recently made by an expert panel.

4. Evaluation results for adding both left- and right-turn lanes at the same intersection are presented in table 52.

5. A small sample of projects involving extension of the length of existing turn lanes at rural unsignalized and urban signalized intersections was evaluated. However, no reliable effectiveness measures could be developed from this small sample.

6. In general, turn-lane improvements at rural intersections resulted in larger percentage reductions in accident frequency than comparable improvements at urban intersections.

7. In the various evaluations performed, the effectiveness of turn-lane improvements in reducing fatal and injury accidents was greater than for total accidents in some cases, and less than for total accidents in others. Overall, there is no indication that any type of turn-lane improvement is either more or less effective for different accident severity levels.

8. Tables 48 through 52 include estimates of the standard error of the mean improvement effectiveness. The standard error is a measure of the precision of the mean improvement effectiveness (i.e., smaller standard errors represent more precise estimates). The most precise effectiveness estimates were generally obtained for the project and intersection types with the largest sample sizes, particularly added left-turn lanes at rural four-leg unsignalized intersections and at urban four-leg signalized intersections.

9. The results of economic analyses for addition of left-turn lanes at typical rural and urban intersections, as a function of traffic volume, are presented in tables 58 through 65. These economic analyses are based on the effectiveness estimates derived in this study and illustrate the traffic volume levels at which installation of left-turn lanes becomes cost effective.

10. The EB approach to observational before-after evaluations of safety improvements appears to perform effectively. Comparisons of the EB approach to the YC and CG approaches found that the EB approach was more likely to provide statistically significant effectiveness measures. Furthermore, the effectiveness measures obtained from the EB approach were generally smaller than those from the other approaches; this may have resulted from reduced effect of the regression-to-the-mean phenomenon; compensation for regression to the mean is highly desirable in providing accurate evaluation results.

Recommendations

The recommendations of the study are as follows:

1. The effectiveness measures for left-turn improvements in tables 48 and 49 and for right-turn improvements in tables 50 and 51 should be considered by highway agencies in evaluating potential improvements at intersections.

2. FHWA should consider incorporating these results in the AMFs used for safety prediction in the Interactive Highway Safety Design Model (IHSDM) and in other ongoing initiatives, such as the Comprehensive Highway Safety Improvement Model (CHSIM). Tables 55 through 57 present revised AMFs for use in these models.

3. The EB approach should be considered the most desirable approach for observational before-after evaluation of safety improvements. The EB approach is the only evaluation approach with the potential to compensate for regression to the mean. Where the EB approach cannot be applied, the CG and YC approaches should be considered as preferable to evaluation designs without comparison sites. The CG approach should generally be considered as preferable to the YC approach, because it incorporates a comparison group consisting of multiple sites. However, both the CG and YC approaches are likely to provide overly optimistic evaluation results.

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Appendix A

Summary of Intersection Safety Studies

APPENDIX A. SUMMARY OF INTERSECTION SAFETY STUDIES.

Overview

The findings of the literature review are presented in this extensive summary table, table A-1. The table presents the following information about each source identified in the literature:

- General topic (i.e., geometric design or traffic control element).
- Author, publication year, and reference number.
- Summary of major findings.
- Study type (e.g., before/after, comparative, predictive model).
- Data used in any analyses that were conducted (including the number of sites, if available).
- Type of sites.

The reference numbers in the table provide a link to the reference list presented at the end of this report. The summary of major findings describes the nature of the relationship between particular geometric design, traffic control, or traffic volume factors and safety indicated by each study. Where the safety relationship in a particular reference can be expressed as a simple percentage difference or algebraic difference, that quantitative value is presented in the major findings column. However, where the findings are more complex, such as the results of predictive modeling or classification and regression tree (CART) analysis, they could not always be presented quantitatively in the table.

Table A-1. Summary of Intersection Safety Studies of Intersection Design and Traffic Control Features.

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Intersection Geometric Design Features					
Left-turn lanes	Harwood et al. [2000][25]	• Based upon the judgement of an expert panel, installation of a left-turn lane along one major approach reduces intersection-related accidents by 18 to 24%, depending upon the type of traffic control and number of legs at the intersection. • Based upon the judgement of an expert panel, installation of left-turn lanes along both major approaches to a four-leg intersection reduces intersection-related accidents by 33 to 42 percent, depending upon the type of traffic control.	Accident prediction algorithm using negative binomial distribution and accident modification factors developed by expert panel.	Prediction algorithm combines elements of historical accident data, predictions from statistical models, results of before-after studies, and expert judgments made by experienced engineers.	Rural intersections along two-lane highways.
	Vogt [1999][24]	For a four-lane by two-lane STOP-controlled rural intersection, the predictive model indicates installation of left-turn lanes along the major approach reduced total accidents by 38 percent.	Accident prediction model using negative binomial distribution.	72 four-leg intersections in California and Michigan.	Four-lane by two-lane STOP-controlled rural intersections.
	Gluck et al. [1999][6]	Installation of left-turn lanes reduced the accident rates per million entering vehicles at unsignalized intersections by 50 percent and at signalized intersections by 18 percent. Combined the presence of left-turn lanes reduced the accident rate by 35 percent.	Synthesis of previous research conducted by Tamburri and Hammer[13] and Wilson et al.[14]	53 intersections in California.	
	Gluck et al. [1999][6]	Intersections without turn lanes had an accident rate of 1.65 accidents per million entering vehicles, while intersections with left-turn lanes had an accident rate of 0.59.	Synthesis of previous research conducted by Shaw and Michael.[65]	Eight inter-sections without lanes; three with left-turn lanes.	
	Gluck et al. [1999][6]	Installation of left-turn lanes reduced the accident rate per million entering vehicles by 38 percent.	Synthesis of previous research conducted by Ben-Yakov and Craus[11] and Craus and Mahalel.[12]	25 intersections.	

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Left-turn lanes (continued)	Gluck et al. [1999][6]	Installation of left-turn lanes reduced the accident rates per million left-turning vehicles at unsignalized intersections by 77 percent and at signalized intersections by 54 percent.	Synthesis of previous research conducted by Agent.[10]		
	Gluck et al. [1999][6]	Restriping the lane assignments to provide left-turn lanes reduced the number of accidents at eight intersection locations. The left-turn lanes reduced left-turn accidents by 62 percent and all accidents by 58 percent.	Synthesis of previous research conducted by Greiwe.[9]	Eight inter-sections in Indiana.	
	Gluck et al. [1999][6]	1.8-mile section of four-lane roadway was converted to three-lane cross-section. Total number of accidents before conversion was 109, and 67 accidents occurred during after period.	Synthesis of previous research conducted by New Jersey Department of Transportation.[7]	1.8 miles of Route 47 in New Jersey con-verted from four-lane road to three-lane road.	
	Gluck et al. [1999][6]	• Installation of left-turn lanes along eight-mile southern section of Route 130 reduced the accident rate per million entering vehicles by 35 percent. • Installation of left-turn lanes along 28-mile northern section of Route 130 reduced the accident rate per million entering vehicles by 51 percent.	Synthesis of previous research conducted by New Jersey Department of Transportation.[8]	Eight mile southern section of Route 130 in New Jersey and 28-mile northern section.	
	Bauer and Harwood [1996][20]	Left-turn channelization resulted in an increase in total multiple-vehicle accidents and fatal injury accidents.	Statistical modeling with negative binomial regression.	14,432 rural intersections in California.	Rural and urban signalized and unsignalized intersections.
	Poch and Mannering [1995][22]	Total accident frequencies were found to be higher on intersection approaches with a shared through-left lane and two or more total lanes than on approaches with other conditions. Approaches with a left-turn lane, a through lane, and a shared through-right lane had more rear-end accidents than those with other conditions.	Accident prediction model using negative binomial distribution.	63 intersections in Bellevue, Washington.	Urban areas. A large number of intersections were in residential areas which are characterized by low traffic volume. All intersections had some sort of operational improvement during 1988-92.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Left-turn lanes (continued)	Maze et al. [1994][23]	Predictive models indicate that a left-turn lane with permitted phasing at a signalized intersection has a positive effect on safety. A typical example developed by the authors indicates an anticipated reduction in left-turn accident rate of approximately 5.5 percent from installation of a left-turn lane with permitted phasing.	Statistical modeling based on multiple regression.	63 signalized intersections, including 248 intersection approaches. Five years of accident data were considered for each intersection.	At-grade signalized intersections in Iowa.
	Maze et al. [1994][23]	Predictive models indicate that a left-turn lane with protected/permitted phasing at a signalized intersection has a positive effect on safety. A typical example developed by the authors indicates an anticipated reduction in left-turn accident rate of approximately 35 percent from installation of a left-turn lane with protected/permitted phasing.	Statistical modeling based on multiple regression.	63 signalized intersections, including 248 intersection approaches. Five years of accident data were considered for each intersection.	At-grade signalized intersections in Iowa.
	McCoy and Malone [1989][4]	On urban four-lane roadways, left-turn lanes at signalized and unsignalized intersections significantly reduced rear-end, sideswipe, and left-turn accidents. At unsignalized intersections with left-turn lanes, there was also a significant increase in right-angle accidents.	Comparative.	63 intersections on urban, four-lane roadways.	Urban signalized and unsignalized intersections in Nebraska.
	Lau and May [1988][40]	Left-turn channelization on the crossroad was found to be a significant factor in predicting injury accidents at unsignalized intersections.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Left-turn lanes (continued)	Hauer [1988][15]	• Provision of left-turn channelization at unsignalized intersections reduced accidents by 70 percent in urban areas when combined with curbs or raised bars. Likewise, accidents were reduced by 65 and 60 percent, respectively, in suburban and rural areas. • When channelization was painted at unsignalized intersections, accidents decreased by 15, 30, and 50 percent in urban, suburban, and rural areas, respectively.	Synthesis of previous research conducted by McFarland et al. [1979].[16]	Not available.	Not available.
	Hauer [1988][15]	At signalized intersections, left-turn channelization with a left-turn phase reduced accidents by 36 percent and without the left-turn phase by 15 percent.	Synthesis of previous research conducted by McFarland et al. [1979].[16]	Not available.	Not available.
	Hauer [1988][15]	Adding left-turn lanes reduced accidents by varying amounts depending on the type of intersection, whether it was signalized or unsignalized, and whether the intersection was rural or urban.	Synthesis of previous research conducted by R. Jorgensen and Associates, Inc. [1978].[66]	Not available.	Not available.
	McCoy et al. [1985][21]	At unsignalized intersections on rural two-lane highways, there was no significant difference in rear-end and left-turn accident rates between intersections with left-turn lanes and those without left-turn lanes.	Comparative.	Intersections on rural two-lane highways in Nebraska.	Unsignalized intersections.
	Parker et al. [1983][3]	Passing-related accidents at rural intersections along two-lane highways do not represent a major safety problem, but when a left-turn lane is provided at new or reconstructed intersections, potential for passing-related accidents is greatly reduced.	Benefit/cost analysis not reviewed directly. Overview based on synthesis of previous research by Kuciemba and Cirillo [1992].[49]	Not available.	Not available.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Left-turn lanes (continued)	David and Norman [1976][26]	Signalized intersections with opposing left-turn lanes were found to have significantly more accidents than intersections without opposing left-turn lanes. Provision of opposing left-turn lanes at four-leg signalized intersections was found to increase accident frequencies by 2.4 to 6.1 accidents per year.	Comparative.	22 four-leg intersections with opposing left-turn lanes; it is not clear how many four-leg intersections without left-turn lanes were available. Three years of accident data were obtained for each intersection.	Urban intersections in the San Francisco Bay Area of California.
	Dale [1973][19]	At intersections along rural two-lane highways, installation of a traffic signal and left-turn lane reduced the total number of accidents by 19.7 percent, while the installation of a traffic signal without left-turn channelization reduced the total number of accidents by 6 percent.			
	Foody and Richardson [1973][5]	• For signalized intersections, the accident rate was reduced 38 percent with the addition of left-turn lanes. • For unsignalized intersections, the accident rate was reduced 76 percent with the addition of left-turn lanes.	Comparative.	Not available.	Not available.
	Lacy [1972][18]	Several improvements to the intersection, which included extending and rearranging the channelization and adding separate left-turn lanes, reduced the accident frequency by 35 percent and the accident severity by 80 percent. Additional improvements to the intersection included widening the approaches and modifying the traffic signals.	Before/After.	One urban intersection in Peoria, Illinois.	Urban intersection.
	Caltrans [1967][17]	Reduction in accident rates at unsignalized intersections was much higher with use of raised barrier left-turn lanes than with painted left-turn lanes.	Before/After.	53 safety improvement projects in California.	Urban and rural areas, including signalized and unsignalized intersections.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Offset left-turn lanes	Harwood et al. [1995][27]	A field review of traffic operations and an office review of three years of accident data were conducted for two signalized intersections with tapered offset left-turn lanes and one signalized intersection with parallel offset left-turn lanes. This review found no operational or accident problems at the intersections related to the offset left-turn lanes. However, no measures of effectiveness comparing offset and conventional left-turn lanes were developed.	Operational and safety review of intersection performance.	Field observation of undesirable driver behavior and three years of accident data for three intersections.	Signalized intersections on divided highways with tapered and parallel offset left-turn lanes.
	McCoy et al. [1992][28]	Developed guidelines concerning the amount of offset between opposing left-turn lanes to provide adequate sight distance, but performed no accident studies.	Engineering analysis.	Typical intersection geometrics.	Intersections with opposing left-turn vehicles.
	Joshua and Saka [1992][29]	Developed guidelines concerning the amount of offset between opposing left-turn lanes to provide adequate sight distance, but performed no accident studies.	Engineering analysis.	Typical intersection geometrics.	Intersections with opposing left-turn vehicles.
Right-turn lanes	Harwood et al. [2000][25]	• Based on the judgement of an expert panel, presence of a right-turn lane along one major approach to a rural STOP-controlled intersection reduces intersection-related accidents by 5 percent. • Based on the judgement of an expert panel, presence of right-turn lanes along both major approaches to a rural STOP-controlled intersection reduces intersection-related accidents by 10 percent.	Accident prediction algorithm using negative binomial distribution and accident modification factors developed by expert panel.	Prediction algorithm combines elements of historical accident data, predictions from statistical models, results of before-after studies, and expert judgments made by experienced engineers.	Rural intersections along two-lane highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Right-turn lanes (continued)	Harwood et al. [2000][25]	• Based on the judgement of an expert panel, presence of a right-turn lane along one major approach to a rural signalized intersection reduces intersection-related accidents by 2.5 percent. • Based on the judgment of an expert panel, presence of right-turn lanes along both major approaches to a rural signalized intersection reduces intersection-related accidents by 5 percent.	Accident prediction algorithm using negative binomial distribution and accident modification factors developed by expert panel.	Prediction algorithm combines elements of historical accident data, predictions from statistical models, results of before-after studies, and expert judg-ments made by experienced engineers.	Rural intersections along two-lane highways.
	Vogt and Bared [1998][30]	Presence of right-turn lanes at three-leg rural unsignalized intersections increases the total number of intersection-related accidents by 27 percent.	Poisson and negative binomial modeling.	389 rural three-leg intersections in Minnesota.	Unsignalized intersections on rural two-lane highways.
	Bauer and Harwood [1996][20]	Right-turn channelization resulted in an increase in total multiple-vehicle accidents and fatal injury accidents.	Statistical modeling with negative binomial regression.	14,432 rural intersections in California.	Rural and urban signalized and unsignalized intersections.
Channelization	Hauer [1988][15]	Channelization was found to reduce accidents by 32 percent and injury accidents by 50 percent. The average benefit-cost ratio of channelization was 2.3.	Synthesis of previous research conducted by Hagenaur et al. [1982][67]	Not available.	Not available.
	David and Norman [1976][26]	Raised pavement markings tended to decrease accidents, especially at cross intersections.	Comparative.	558 inter-sections with 4,372 accidents in three years in the San Francisco Bay Area of California.	Urban areas. 82 percent of intersections had some form of delineation.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Channelization (continued)	Exnicios [1967][33]	Several safety measures, including re-channelization, were implemented at three intersections. The improvements resulted in a 31 percent reduction in total accidents (over two years), a 58 percent reduction in total accidents (over one year), and a 100 percent reduction in total accidents (over 26 months) at the respective intersections.	Before/After.	Three intersections.	The intersections were located in a residential suburb in Chicago, in metropolitan New Orleans, and in Shreveport, Louisiana.
	Rowan and Williams [1966][34]	Accident rates, personal injuries, and rear-end type accidents were reduced due to the introduction of channelization.	Before/After.	US Route 290 in northwest Houston.	Arterial, four-lane, at signalized intersections.
Channelization • Island design	Forrestel [1994][37]	The pedestrian accident rate at an unsignalized intersection on a four-lane arterial was reduced by 11.5 percent when raised median islands were installed.	Synthesis of previous research efforts. Related article entitled “A Comparison of the Pedestrian Safety of Median Islands and Marked Crossings.” [1978][49]	One intersection in Western Australia.	Four-lane, unsignalized intersection.
	Washington et al. [1990][36]	Intersection approaches with raised medians have a 40 percent lower accident rate than those with flush medians.	Comparative.	40 intersections in California.	Not available.
	Templer [1980][32]	Raised medians reduced the number of conflicts between pedestrians and vehicles. However, the difference was not statistically significant.	Before/After.	Two intersections in Clearwater, Florida.	Signalized T-intersections, located in business and recreational areas.
Number of intersection legs (e.g., three, four, five)	Bauer and Harwood [1996][20]	Rural four-leg STOP-controlled intersections have about twice as many accidents as rural three-leg STOP-controlled intersections (1.1 vs. 0.6 accidents per intersection per year). A similar pattern was found for urban STOP-controlled intersections (2.2 accidents per intersection per year for four-leg intersections vs. 1.3 for three-leg intersections).	Comparative.	8,525 at-grade intersections in California.	Rural four-leg, rural three-leg, urban four-leg, and urban three-leg intersections, all with STOP control.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Number of intersection legs (e.g., three, four, five) (continued)	Harwood et al. [1995][27]	Predictive relationships were developed for number of multiple-vehicle intersection accidents per year as a function of major-road ADT, crossroad ADT, major-road median width, major-road lane and shoulder widths, major-road design speed, presence of left-turn lanes, and terrain. Results show that typical divided highway intersections with four legs have about twice as many accidents as three-leg intersections for narrow medians and more than five times as many accidents as three-leg intersections for wide medians.	Statistical modeling with Poisson regression.	1,200 intersections on California state highways.	Urban/suburban unsignalized intersections on divided highways in California.
	Hanna et al. [1976][38]	In rural areas, four-leg intersections have higher accident rates than T intersections (69 percent increase).	Comparative.	232 intersections in rural municipalities in Virginia.	Includes both STOP-controlled and signalized intersections.
	David and Norman [1976][26]	In urban areas at STOP-controlled intersections, accident frequencies were very similar for four-leg intersections and T/Y-type intersections with ADT under 20,000 veh/day. Once above 20,000 veh/day, the accidents doubled for four-leg intersections.	Comparative.	558 intersections with 4,372 accidents in three years in the San Francisco Bay Area of California.	Of 558 intersections, 269 were three-leg intersections, and 289 were four-leg intersections.
Intersection type (e.g., cross, T, Y, offset)	Lau and May [1988][39]	Intersection type was found to be a significant factor in predicting injury accidents at signalized intersections.	CART analysis of residuals from base model.	2,488 signalized intersections. seven years of injury accident data for each intersection.	Signalized intersections on California state highways.
	Lau and May [1988][40]	Intersection type was found to be a significant factor in predicting injury accidents at unsignalized intersections.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Intersection type (e.g., cross, T, Y, offset) (continued)	Hanna et al. [1976][38]	For three-leg intersections, Y intersections were found to have accident rates approximately 50 percent higher than T intersections.	Comparative.	232 intersections in rural municipalities in Virginia.	Includes both STOP-controlled and signalized intersections.
	Hanna et al. [1976][38]	For four-leg intersections, offset intersections had accident rates that were approximately 43 percent of the accident rate of conventional four-leg intersections.	Comparative.	232 intersections in rural municipalities in Virginia.	Includes both STOP-controlled and signalized intersections.
Angle of intersection (e.g., skew)	Harwood et al. [2000][25]	AMFs for intersection skew angle were derived from statistical modeling and apply to total intersection-related accidents. For a three-leg STOP-controlled intersection, the AMF was calculated as: AMF = exp (0.0040 SKEW) For a four-leg STOP-controlled intersection, the AMF was calculated as: AMF = exp (0.0054 SKEW) where: SKEW = intersection skew angle (degrees), expressed as the absolute value of the difference between 90 degrees and the actual intersection angle.	Accident prediction algorithm using negative binomial distribution and accident modification factors developed by expert panel.	Prediction algorithm combines elements of historical accident data, predictions from statistical models, results of before-after studies, and expert judgments made by experienced engineers.	Rural intersections along two-lane highways.
	Bauer and Harwood [1996][20]	Angle of intersection was found to have a statistically significant relationship to multiple-vehicle accident frequency at urban, four-leg, signalized intersections, but the direction of the effect was opposite to that expected. Skewed intersections were found to have accident frequencies approximately 20 percent less than 90° intersections. This finding may represent a surrogate effect of some uncontrolled variable.	Statistical modeling with negative binomial regression.	198 intersections on California state highways.	Urban four-leg signalized intersections in California.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Angle of intersection (e.g., skew) (continued)	McCoy et al. [1994][42]	At two-way STOP-controlled intersections on rural two-lane highways, the number of accidents per year increases with traffic volume and skew angle. Thus, more accidents will occur with higher volumes and/or greater skew angles. Three-leg intersections have fewer accidents than four-leg intersections with equivalent traffic conditions and skew angles.	Comparative.	29 skewed and 39 nonskewed rural intersections in Nebraska.	Two-way STOP-controlled intersections on rural two-lane highways. Included three-leg and four-leg intersections. Volumes on the major and minor roadways ranged from 400 to 5,200 veh/day and from 150 to 1,500 veh/day, respectively.
	Hauer [1988][15]	Stated as an important safety factor. No safety studies conducted.			
Roundabouts	See section of this table on type of traffic control.				
Curb return radius	Hauer [1988][15]	Stated as an important safety factor. No safety studies conducted.			
Sight distance • Intersection sight distance (clear sight triangles in intersection quadrants)	Harwood et al. [2000][25]	Based upon the judgement of an expert panel, the AMFs are as follows for intersection sight distance at intersections with STOP control on the minor leg(s): • 1.05 if sight distance is limited in one quadrant of the intersection. • 1.10 if sight distance is limited in two quadrants of the intersection. • 1.15 if sight distance is limited in three quadrants of the intersection. • 1.20 if sight distance is limited in four quadrants of the intersection. Sight distance in a quadrant is considered limited if the available sight distance is less than the sight distance specified by AASHTO policy for a design speed of 20 km/h less than the major road-design speed and the sight distance restrictions are due to roadway alignment and/or terrain.	Accident prediction algorithm using negative binomial distribution and accident modification factors developed by expert panel.	Prediction algorithm combines elements of historical accident data, predictions from statistical models, results of before-after studies, and expert judgments made by experienced engineers.	Rural intersections along two-lane highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Sight distance • Intersection sight distance (clear sight triangles in intersection quadrants) (continued)	David and Norman [1976][26]	Developed estimates of the reduction in annual accident frequency from improving sight distance as a function of the initial sight distance (termed "sight radius" in the study) from the minor-road approach and total entering ADT. The results indicated that, in most cases, the worse the initial sight distance, the greater the accident reduction obtained from a sight distance improvement. Magnitudes of the sight distance improvements were not specified.	Comparative.	558 inter-sections with 4,372 accidents in three years in the San Francisco Bay Area of California.	Urban areas where foliage and buildings obstructed the view of intersections.
	Hanna et al. [1976][38]	In this study, the average accident rate for all intersections was 1.13, while the average accident rate for intersections with "poor sight distance" is 1.33 accidents per million entering vehicles.	Comparative.	Examined 41 intersections in rural area of Virginia with total of 366 accidents.	Rural municipalities, including both STOP-controlled and signalized intersections.
	Mitchell [1972][43]	• Total accidents at intersections dropped 67 percent when intersection sight obstructions were removed. • The greatest percentage of reduction in accidents was experienced at the intersections where the sight distance was improved.	Before/After.	Five inter-sections in Concord, California.	Sight distance at five intersections that had been improved.
Sight distance • Stopping sight distance	Fambro et al. [1989][44]	Accident rates were high for intersections located on crest vertical curves with limited sight distance. Similar results were obtained in NCHRP Project 3-42 [1996].[28]	Comparative.		Rural two-lane roadways.
Sight distance • Sight distance to traffic control device (e.g., STOP sign, signal)	None found				

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Approach width	Bauer and Harwood [1996][20]	It was found that as lane width decreases, the total number of multiple-vehicle accidents and fatal injury accidents increases.	Statistical modeling with negative binomial regression.	2,999 inter-sections in California.	Urban four-leg signalized and unsignalized intersections.
	David and Norman [1976][26]	Higher accident occurrence for narrow streets was not evident.	Comparative.	558 inter-sections with 4,372 accidents in three years in the San Francisco Bay Area of California.	269 T-intersections, 289 four-leg intersections. 298 of the intersections were STOP-controlled.
	Lacy [1972][18]	Several improvements to the intersection, which included widening the approaches, reduced the accident frequency by 35 percent and the accident severity by 80 percent. Other improvements to the intersection included: extending and rearranging the channelization, adding separate left-turn lanes, and modifying the traffic signals.	Before/After.	One urban intersection in Peoria, Illinois.	Urban intersection.
Number of approach lanes	Bauer and Harwood [1996][20]	In the models for total multiple-vehicle accidents and fatal injury accidents at rural and urban unsignalized inter-sections, approaches with one lane were associated with higher accident frequencies, while approaches with two or more lanes were associated with lower total accident frequencies. The opposite appears to be the case for urban, four-leg, signalized intersections.	Statistical modeling with negative binomial regression.	2,262 rural intersections in California.	Rural four-leg STOP-controlled intersections.
	Lau and May [1988][39]	The number of lanes on the major roadway and the crossroad were found to be a significant factor in predicting injury accidents at signalized intersections.	CART analysis of residuals from base model.	2,488 signalized intersections. Seven years of injury accident data for each intersection.	Signalized intersections on California state highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Number of approach lanes (continued)	Lau and May [1988][40]	The number of lanes on the major roadway was found to be a significant factor in predicting injury accidents at unsignalized intersections.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.
	David and Norman [1976][26]	For roadways with ADT under 10,000 veh/day, accident frequencies can be reduced by providing through lanes.	Comparative.	558 inter-sections with 4,372 accidents in three years in the San Francisco Bay Area of California.	Of 558 intersections, 71 percent had 2x2 through lanes, 26 percent had 2x4, and 3 percent had 4x4 on the crossroad and major road, respectively.
Median width and type	Harwood et al. [1995][27]	• At rural four-leg unsignalized intersections, accident frequency decreases as median width increases. • At urban/suburban intersections (unsignalized and signalized), accident frequency increases with increasing median width.	Comparative study and statistical modeling with Poisson regression.	2,140 divided highway intersections in urban and rural areas of California.	Intersections include rural and urban/suburban unsignalized intersections (four-leg and three-leg), as well as urban/suburban four-leg signalized intersections.
	Van Maren [1977][47]	Found no statistically significant relationship between median width and intersection accident rate.			
	Priest [1964][46]	Except at very low volume levels, intersection accident frequencies decrease as the median width increases. The difference in intersection accident rate between medians less than 20 ft wide and medians 20 to 30 ft wide is greater than the difference in intersection accident rate between medians with widths of 20 to 39 ft and those of 40 ft or more.	Statistical modeling with regression analysis.	316 inter-sections in Ohio. Three years of accident data were available for each intersection.	Intersections on divided highways with partial or no access control in Ohio.
Vertical alignment on intersection approaches	Hanna et al. [1976][38]	Rural intersections with steep grades (greater than 5 percent) "generally operate safely." These intersections had an accident rate of 0.97 accidents per million entering vehicles, compared to an overall accident rate of 1.13.	Comparative.	232 inter-sections in Virginia.	Rural areas.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Horizontal alignment on intersection approaches	None found				
Design speed	Bauer and Harwood [1996][20]	As design speed decreases, there is an increase in total multiple-vehicle accidents and fatal injury accidents.	Statistical modeling with negative binomial regression.	1,434 rural intersections in California.	Rural and urban intersections.
Traffic Control and Operational Features					
Type of traffic control • Uncontrolled • YIELD control	Poch and Mannering [1995][22]	With no control on an intersection approach, total and angle accidents decrease.	Statistical modeling with negative binomial regression.	63 intersections in the city of Bellevue, Washington.	Urban areas. A large number of intersections are in residential areas which are characterized by low traffic volume. All intersections had some sort of operational improvement during 1988-92.
	Hauer [1988][15]	• 44 percent and 52 percent fewer accidents after conversion to YIELD-control. • Another study gives accident reduction of 23 and 63 percent after conversion of uncontrolled intersections to YIELD-control.	Synthesis of previous studies.	Not available.	Not available.
	Lau and May [1988][39]	Traffic control type was found to be a significant factor in predicting injury accidents at unsignalized intersections. However, the traffic control type variable was formulated in such a way that it is not easy to distinguish among the traffic control types used in this table.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.
	Hall et al. [1978][50]	Accidents can be reduced by 20 to 60 percent through proper use of YIELD signs at low-volume intersections. Little additional reduction is obtained if YIELD signs are replaced by STOP signs.	Not available.	Not available.	Not available.
	Agent and Deen [1975][51]	At YIELD signs, over half of the accidents were rear-end collisions, while angle collisions made up over half the accidents at STOP signs.	Comparative.	Data for intersections in Kentucky. Three years of accident data were available.	Intersections in rural areas.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Type of traffic control • STOP control	Hanna et al. [1976][38]	Accident rates at STOP-controlled intersections were lower at those intersections having high traffic flow.	Comparative.	232 inter-sections in Virginia.	Rural areas.
Type of traffic control • STOP control with flashing beacons	None found				
Type of traffic control • Signal control (phasing, timing, and operation)	Poch and Mannering [1995][22]	With signal control intersections, the total and angle accidents decrease.	Statistical modeling with negative binomial distribution.	63 intersections in city of Bellevue, Washington.	Urban areas. All intersections had some sort of operational improvement during 1988-92.
	Maze et al. [1994][23]	Predictive models indicate that a protected left-turn signal phase without a left-turn lane has a positive effect on safety. A typical example developed by the authors indicates an anticipated reduction in left-turn accident rate of approximately 50 percent from installation of a protected left-turn signal phase.	Statistical modeling based on multiple regression.	63 signalized intersections, including 248 intersection approaches. Five years of accident data were considered for each intersection.	At-grade signalized intersections in Iowa.
	Lau and May [1988][39]	A control-type variable based on signal phasing and actuation was found to be a significant factor in predicting injury accidents at signalized intersections. However, the control type variable was defined in such a way that explicit effects of phasing and actuation cannot be determined.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.
	Hanna et al. [1976][38]	Installation of traffic signal controls could result in slight increase in accident rates, significant increase in rear-end accidents, and comparable decreases in angle collisions.	Comparative.	232 inter-sections in Virginia.	Rural municipality area.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Type of traffic control • Signal control (phasing, timing, and operation) (continued)	David and Norman [1976][26]	In urban areas, multi-phase traffic signals appear to have lower percentages of fatal and injury accidents than two-phase signals.	Comparative.	558 inter-sections with 4,372 accidents in 3 years in the San Francisco Bay Area of California.	Of 558 intersections, 269 were T intersections and 289 were four-leg intersections. 298 of the intersections were STOP-controlled.
	King and Goldblatt [1975][52]	• Signalization leads to a reduction in right-angle accidents and an increase in rear-end accidents. • Signalized intersections have higher accident rates, but this is usually offset by less severity per accident.	Comparative analyses and review of related research.	Used a large nationwide accident data base.	Not available.
Type of traffic control • Roundabouts	Persaud et al. [2001][53]	Converting intersections with conventional traffic control (i.e.,STOP, signal) to roundabouts reduces all accidents by 40 percent, injury accidents by 80 percent, and fatal and incapacitating injury accidents by 90 percent.	Before/After.	23 intersections located in 7 states.	Mix of urban, suburban, and rural environments.
	Robinson et al. [2000][41]	Converting intersections with conventional traffic control (i.e.,STOP, signal) to roundabouts reduces all accidents by 37 percent and injury accidents by 51 percent.	Synthesis of research conducted in the U.S. and internationally.	Not available.	Not available.
Turn prohibitions	Lau and May [1988][39]	Left-turn prohibitions were found to be a significant factor in predicting injury accidents at signalized intersections.	CART analysis of residuals from base model.	2,488 signalized intersections. Seven years of injury accident data for each intersection.	Signalized intersections on California state highways.
	Lau and May [1988][40]	Left-turn prohibitions were found to be a significant factor in predicting injury accidents at unsignalized intersections.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Presence and type of crosswalks	Hauer [1988][15]	Marked crosswalks had more exposure, but fewer accidents, than unmarked crosswalks.	Synthesis of previous research conducted by Knoblauch et al. [1984][68]	Not available.	Not available.
	Hauer [1988][15]	Pedestrian accidents increased 86 percent after crosswalks were marked, and rear-end collisions increased 32 percent.	Synthesis of previous research entitled "What Not To Expect from Crosswalk Signals." [1976][69]	Not available.	Not available.
	Hauer [1988][15]	Pedestrian accidents may be reduced by approximately 50 percent by marking crosswalks.	Synthesis of previous research conducted by Untermann. [1984][70]	Not available.	Not available.
	Hauer [1988][15]	Painted crosswalks reduced violation of the pedestrian's right of way.	Synthesis of previous research cited in *Traffic Engineering Handbook*. [1965][71]	Not available.	Not available.
	Smith and Knoblauch [1987][53]	Accident analyses suggest use of crosswalks at all signalized intersections.	Comparative.	Not available.	Intersections with marked and unmarked crosswalks.
	Herms [1970][55]	More pedestrian accidents occurred in marked crosswalks than in unmarked crosswalks by a ratio of about 6 to 1. A crosswalk usage count showed the crosswalk use ratio was approximately 3 to 1, marked vs. unmarked. In terms of usage, approximately twice as many pedestrian accidents occurred in marked crosswalks as compared to unmarked crosswalks.	Comparative.	400 unsignal-ized inter-sections in San Diego, California.	Each intersection had one marked and one unmarked crosswalk crossing the major flow of traffic.
Posted speed limits on approaches	None found.				

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Advance warning signs	Gattis and Iqbal [1994][56]	The "Do Not Block the Intersection" sign was found to be ineffective in preventing drivers from blocking intersections.	Before/After.	Four intersections.	Two street intersections and two commercial driveway intersections.
	Klugman et al. [1992][58]	Accident rates for intersections equipped with advance warning signs with flashers (AWFs) decreased from 1.22 to 1.09 accidents per million entering vehicles for all accident types and decreased from 0.68 to 0.63 for right-angle and rear-end accidents.	Comparative and Before/After Study.	14 intersections.	Signalized intersections.
	Pant and Huang [1992][57]	• On tangent approaches to intersections, the Prepare to Stop When Flashing (PTSWF) sign showed no significant increase or decrease in conflict rate. • On curved approaches to intersections, the PTSWF sign increased the conflict rate by at least 15 percent. • The Flashing Symbolic Signal Ahead (FSSA) sign showed no effect on vehicle conflict rates.	Before/After.	Not available.	High-speed signalized intersections on rural or suburban highways in Ohio.
	Washington et al. [1991][36]	Implementation of AWFs can reduce approach accident rates at high-speed isolated signalized intersections by as much as 50 percent.	Comparative.	40 signalized intersections in California.	High-speed isolated signalized intersections.
	Washington et al. [1991][36]	• Right-angle accidents were significantly reduced with the presence of route markers and/or advance warning signs. • Accident rates increased on horizontal approaches with a skew that contained advance warning signs.	Synthesis of prior research conducted by Van Maren et al. [1980][47]	Not available.	Not available.
	Styles et al. [1982][59]	Red Signal Ahead signs reduced: • Right-angle accident rates by 42 percent on approaches with sharp vertical crests. • Total accident rates on horizontal curve approaches by 14 percent. • Total accident rates on flat approaches by 41 percent.	Before/After.	20 intersections.	High-speed signalized intersection approaches.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Advance warning signs (continued)	Styles et al. [1982][60]	All intersections showed a reduction in right-angle accidents with the implementation of a flashing red strobe light. One of the intersections showed reductions in right-angle, rear-end, and total accidents of 83 percent, 60 percent, and 61 percent, respectively.	Before/After.	Four intersections in Maryland.	High-speed signalized intersection approaches.
Lighting	Bauer and Harwood [1996][20]	At rural, four-leg, STOP-controlled intersections, lighted intersections had 21 percent fewer total and injury accidents than unlighted intersections. However, no similar effect was observed for total intersection accidents, and an effect in the opposite direction, indicating that lighted intersections had more accidents than unlighted intersections, was observed for urban four-leg STOP-controlled intersections. These results were based on accidents for all times of day (daytime plus nighttime).	Statistical modeling with negative binomial regression.	2,262 rural four-leg STOP-controlled intersections and 1,551 urban four-leg STOP-controlled intersections.	At-grade intersections on California state highways.
	Box [1989][61]	Lighting improvements along a suburban arterial street were found to reduce the percentage of total intersection accidents that occur at night as follows: Accident — Percent reduction • Pedestrian/bicycle — 50 to 33 • Fixed object — 57 to 25 • Sideswipe — 32 to 11 • Other — 33 to 25 Only nighttime head-on accidents increased as a proportion of total head-on accidents from 33 percent to 43 percent. There is no indication whether any of the observed changes in nighttime accident proportions are statistically significant.	Before/after comparison of the proportion of nighttime accidents.	Two years of accident data before and Two years after the improvement.	One 2.8-mi suburban arterial highway in Naperville (suburban Chicago, Illinois).

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Lighting (continued)	City of Los Angeles [1980][62]	Found no statistically significant reduction in nighttime accidents due to lighting improvements at intersections. Significant reductions in nighttime accidents were found for a few intersections. The assessment of this study is based on review by Keck [1990].[70]	Before/after evaluation based on regression analysis.	528 urban intersections; 2 years of data for nighttime accidents and persons injured at the study intersections were used.	Urban intersections on city streets in Los Angeles, California.
Traffic Characteristics					
Average daily traffic • Total entering ADT, all approaches	Many studies used total entering ADT as traffic exposure in their studies (e.g., to calculate intersection accident rates).				
	Hauer [1988][15]	Explicitly examined safety effects of signalized intersections on traffic flow impacts. He concluded that logically sound models require that the accidents be related to the traffic flows to which the colliding vehicles belong and not the sum of the entering volumes.	Comparative and review of past studies.	Sample data from past studies and simulated data.	Mostly urban settings.
	Lau and May [1988][39]	The total entering ADT on all approaches combined was found to have a statistically significant relationship to injury accidents at signalized intersections.	Linear regression model.	2,488 signalized intersections. Seven years of injury accident data for each intersection.	Signalized intersections on California state highways.
	Lau and May [1988][40]	The total entering ADT on all approaches combined was found to have a statistically significant relationship to injury accidents at unsignalized intersections.	Linear regression model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Average daily traffic • Entering ADTs for major and minor approaches	Bauer and Harwood [1996][20]	Major-road and crossroad ADT variables were present in all models as significant predictors of accident frequency. The relative effects for major-road ADT ranged from 1.77 to 2.68, depending on intersection settings (rural/urban, four-leg/three-leg, signalized/STOP-controlled). The relative effects of minor-road ADT ranged from 1.24 to 1.80.	Statistical modeling with negative binomial regression.	14,432 intersections in California.	Rural and urban, four-leg and three-leg inter-sections, STOP-controlled and signalized. Inter-section major-road ADT above 400 veh/day, minor-road ADT above 100 veh/day.
	Lau and May [1988][39]	Percentage of total entering traffic on crossroad was found to be a significant factor in predicting injury accidents at signalized intersections.	CART analysis of residuals from base model.	2,400 signalized intersections. Seven years of injury accident data for each intersection.	Signalized intersections on California state highways.
	Lau and May [1988][40]	Percentage of total entering traffic on crossroad was found to be a significant factor in predicting injury accidents at unsignalized intersections.	CART analysis of residuals from base model.	17,000 unsignalized intersections. Seven years of injury accident data for each intersection.	Unsignalized intersections on California state highways.
Turning movements	Hauer et al. [1988][63]	Developed relationships between accident frequency for specific accident types (e.g., left turn) and associated turning volumes.	Predictive modeling with negative binomial regression.	Three years of accident data for 145 inter-sections in Toronto, Ontario, Canada; turning movement data by approach and time of day.	Urban, four-leg, fixed-time, signalized intersections with two-way traffic on all approaches and no turn restrictions.
Peak hour approach volumes	None found				
Vehicle mix / percent trucks	None found				
Distribution of total entering volume by hour of the day	None found				

Table A-1 (Continued).

Design and control elements	Related literature	Major findings	Study type	Data used	Type of site
Distribution of approach volume by hour of the day	None found				
Average approach speed	None found				
Volume of bicycle traffic	None found				
Volume of pedestrian traffic	None found				

Appendix B

Negative Binomial Regression Models

APPENDIX B. NEGATIVE BINOMIAL REGRESSION MODELS

In each of the three approaches to before-after evaluation discussed in Section 5, an adjustment for differences in traffic volumes was made. In the YC approach, a simple proportional traffic volume adjustment was used. In the CG and EB approaches, an adjustment based on a regression relationship between accident frequencies and traffic volumes was used. This appendix discusses the development of these regression relationships through negative binomial modeling of accident frequencies as a function of traffic volumes and other variables. The application of these models has been illustrated in Figures 5 and 6 in the main text of this report.

Statistical Approach

Accident counts at a given intersection are inherently discrete, positive numbers, and often small, as in the case of fatal and injury accidents. Furthermore, the distribution of accidents is often skewed in that most sites experience few accidents while a small number of sites experience relatively many more accidents. The Poisson distribution is generally thought of when dealing with rare discrete events such as accidents. The Poisson distribution has only one parameter, namely its mean. The variance of a Poisson distribution is, by definition, equal to its mean. This relationship between the mean and the variance (dispersion) is often violated for accident counts due to inherent overdispersion in the data (i.e., the variance of accident counts typically exceeds the mean). A flexible distribution that can be used to effectively model overdispersed count data is the negative binomial (NB) distribution. This distribution has two parameters, the mean and a dispersion parameter. When the dispersion parameter nears zero, the NB distribution approaches the Poisson distribution.

The relationship between the expected number of accidents, Y_i, occurring at intersection *i* with a set of *q* intersection parameters, $X_{i1}, X_{i2}, ..., X_{iq}$, is

$$Function(Y_i) = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_q X_{iq} \qquad \text{(B-1)}$$

where $\beta_0, \beta_1 ..., \beta_q$ are the regression coefficients and with the assumption that the number of accidents, Y_i, follows a negative binomial distribution with parameters α and d (with $0 \le \alpha \le 1$ and $d \ge 0$). That is, the probability that an intersection defined by a known set of predictor variables, $X_{i1}, X_{i2}, ..., X_{iq}$, experiences $Y_i = y_i$ accidents can be expressed as:

$$\Pr(Y_i = y_i; \alpha, d) = \frac{(y_i + d - 1)!}{y_i!(d-1)!} \frac{\alpha^{y_i}}{(1+\alpha)^{y_i+d}}; \; y_i = 0,1,2\ldots \qquad \text{(B-2)}$$

where $y_i!$ denotes the factorial of y_i.

The mean and variance of the negative binomial distribution of accident counts can then be expressed in terms of the parameters α and d as follows:

$$mean = E(Y) = \mu_i = d\alpha, \; and \tag{B-3}$$

$$variance = Var(Y) = d\alpha + d\alpha^2 = \mu_i + \mu_i^2 / d \tag{B-4}$$

The term μ_i can be referred to as the Poisson variance function and μ_i^2/d as the extra component arising from combining the Poisson distribution with a gamma distribution for the mean to obtain the negative binomial distribution. The overdispersion parameter d is not known *a priori*, but can be estimated so that the mean deviance becomes unity or the Pearson chi-square statistic equals its expectation (i.e., equals its degrees of freedom).[(74)]

The model regression coefficients, β_0, β_1 ..., β_q, are estimated by the method of maximum likelihood. The asymptotic normality of maximum likelihood estimates is used to obtain tests of significance of the parameters and goodness of fit measures for the models.

The parameters α and k of the negative binomial distribution can be indirectly estimated using a generalized linear model to obtain the model regression coefficients β_0, β_1 ..., β_q. The commercially available software SAS provides a procedure, PROC GENMOD (a generalized linear model procedure), that can be used to estimate the regression coefficients.[(75)]

To assess the goodness of fit of a model, a number of statistics are available:

Model Statistic	**Explanation**
Deviance/(n - p)	The deviance of the model containing all the parameters (including the intercept) divided by its degrees of freedom, n - p. This statistic (mean deviance) provides a test for overdispersion and a measure of fit of the model. Asymptotically, this value tends toward 1.[(74)]
Pearson chi-square/(n - p)	The Pearson chi-square statistic divided by its degrees of freedom, n - p. This statistic provides another measure of fit of the model.[(74)]
R^2	A goodness-of-fit parameter based on the ordinary multiple correlation coefficient.
R^2_{FT}	A goodness-of-fit parameter based on the Freeman-Tukey variance stabilizing transformation of variables discussed in Fridstrøm et al.[(76)]

R^2_k — A goodness-of-fit parameter proposed by Miaou,[77] a function of the overdispersion parameter of the regression model and that of a means only model. [This measure has not been estimated in this study, but is being considered for inclusion in the final report.]

Selection of Independent and Dependent Variables in the Regression Model

Using the reference group data, yearly accident counts were modeled as a function of three independent or explanatory variables, as appropriate:

- Major-road traffic volume in vehicles per day.
- Minor-road traffic volume in vehicles per day.
- State.

Based on experience in previous intersection modeling by Bauer and Harwood (20) and preliminary modeling in this study, the regression models included separate terms for major- and minor-road traffic volumes rather than a combined term for the total traffic volume entering the intersection. In all of the NB models developed in this study, the natural logarithm of the major-road and minor-road traffic volumes was used. Thus, in the NB model described in Equation (B-1), X_1 and X_2 generally represent log(MajADT) and log(MinADT), respectively.

A state factor was included because the multistate database assembled for the study exhibited large state-to-state variations which needed to be accounted for in the CG and EB approaches to insure that these state effects were not mistaken for treatment effects. In most cases, the negative binomial modeling was limited to intersections in the comparison and reference groups that had no existing turn lanes. For modeling of urban signalized intersections, a fourth independent variable, the number of existing left-turn lanes was added because there were not enough of such intersections without turn lanes in the comparison and reference groups for modeling.

In summary, the multiplicative model relating the expected accident counts and the selected independent variables can be rewritten as:

$$Function(Y_i) = \exp(\beta_0)\,(MajADT)^{\beta_1}\,(MinADT)^{\beta_2}\,\exp(\beta_3\,State)\,\exp(\beta_4\,ExLTL) \qquad \text{(B-5)}$$

where β_3 and β_4, the coefficients for the categorical variables—state and existing left-turn lanes—vary with the levels of the variables.

As discussed in section 5, a number of dependent variables (safety measures) were considered for modeling, including:

- Total intersection accidents.
- Fatal and injury intersection accidents.
- Project-related intersection accidents.
- Fatal and injury project-related intersection accidents.
- Total accidents for individual intersection approaches.
- Fatal and injury accidents for individual intersection accidents.
- Project-related accidents for individual intersection approaches.
- Fatal and injury project-related accidents for individual intersection approaches.

Selection of Intersection Types

Regression relationships were developed for as many combinations of the following intersection characteristics as possible using the comparison and reference site data:

- Area type (urban/rural).
- Type of traffic control (signalized/unsignalized).
- Number of intersection legs (three or four).
- Number of lanes on major road (two-lane/multilane).

Negative Binomial Repression Results

The coefficients β_0, β_1, β_2, β_3, and β_4 of the negative binomial regression in Equation (B-5) and the dispersion parameter, k, were estimated by maximum likelihood using PROC GENMOD of SAS. In all cases, a 10 percent significance level was chosen. Of the 300 available sites in the reference group, models were developed for a total of 252 sites, grouped as follows:

- Rural, unsignalized, three- and four-leg, two- and multilane sites (only sites without existing left- or right-turn lanes were included)—N=120.
- Urban, signalized, three- and four-leg, two- and multilane sites (including sites with up to four existing left-turn lanes; no consideration was given to the number of existing right-turn lanes)—N=86.
- Urban, unsignalized, three- and four-leg, two- and multilane sites (only sites without existing left- or right-turn lanes were included)—N=46.

The eight types of safety measures discussed above were then considered as dependent variables in the NB modeling, resulting in 96 models to be estimated (8 safety measures x 12 combinations of types of sites).

In each case, a variation of the model shown in Equation (B-5) was investigated, including either all possible independent variables, or excluding selected ones, to assess which model best fits the data. The following four models (Model Types 1 through 4) were investigated:

- Model Type 1: Major-road traffic volume, minor-road traffic volume, and state—all intersection types.
- Model Type 2: Major-road traffic volume and minor-road traffic volume—all intersection types.
- Model Type 3: Major-road traffic volume, minor-road traffic volume, state, and number of existing left-turn lanes—urban, signalized intersections only.
- Model Type 4: Major-road traffic volume, minor-road traffic volume, and number of existing left-turn lanes—urban, signalized intersections only.

In summary, an attempt was made to estimate the regression coefficients and dispersion parameter of a total of 256 models (4 variations on 96 models), and of these 256, select the best model, if one was available, for each of the 96 cases.

An investigation of the number of accidents in each of the eight safety measure categories found that the number of some types of accidents in a group of intersections defined by area type, traffic control, number of lanes, and number of legs was too small (less than 10 over the entire study period) to warrant modeling. This was true in the following situations:

- Fatal and injury project-related intersection accidents at all types of sites (12 cases).
- Fatal and injury project-related accidents for individual intersection approaches at all types of sites (12 cases).
- Project-related intersection accidents at rural, unsignalized, three-leg, two-and multilane intersections (two cases).
- Project-related intersection accidents at urban, signalized, three-leg, multilane intersections (one case).
- Project-related intersection accidents at urban, unsignalized, three-leg, two-and multilane intersections (two cases).
- Project-related accidents for individual intersection approaches at rural, unsignalized, three-leg, two-and multilane intersections (two cases).
- Project-related accidents for individual intersection approaches at urban, signalized, three-leg, multilane intersections (one case).
- Project-related accidents for individual intersection approaches at urban, signalized, three-leg, two-and multilane intersections (two cases).

Thus no modeling was attempted in any of these 34 cases. This left a total of 62 (96-34) models to estimate.

The significance of the model as a whole and of the regression coefficients in particular, the magnitude and signs of the measures of fit discussed above, whether the maximum likelihood algorithm to estimate the regression coefficients converged, and whether the coefficients made engineering sense, were all part of the decision process in choosing a model in a particular case. Using these criteria, models for the final 64 cases were selected. The models were rated as follows:

- A statistically significant model could be estimated, satisfying engineering criteria such as the coefficients of the two traffic volumes were positive and 1 or below.
- The model developed had all the proper attributed, e.g., the coefficients of the two traffic volumes were positive and 1 or below, but was not statistically significant. In that case, the model was considered to provide the best available estimate of accident counts and was therefore selected. Generally, the two measures of model fit, R^2 and R_{FT}^2, are also low in these cases.
- No model could be estimated.

The negative binomial regression results are shown in tables B-1 through B-6 for six of the eight types of safety measures. No tables are shown for fatal and injury project-related accidents because there were no statistically significant models for these safety measures. Each table includes the following statistics:

- Intersection type.
- Model type (Model Types 0 through 4, where Model Types 1 through 4 were defined above and Model Type 0 denotes that no model was available through regression analysis).
- The number of site-years or approach-years, depending on the type of safety measure.
- The regression coefficients, β_0, β_1, β_2, representing the intercept and the exponents of major-road and minor-road traffic volumes, respectively.
- The state coefficients, β_3.
- The coefficients for the number of existing left-turn lanes, β_4 (applicable for Model Types 3 and 4 only).
- The negative binomial dispersion parameter (d).
- The two measures of model fit, R^2 and R_{FT}^2.

Table B-1. Negative Binomial Regression Models for Total Intersection Accidents.

Area type	Traffic control type	No. of inter-section legs	No. of lanes on major road (two-lane or multi-lane)	Model type	No. of site-years	Intercept	Traffic volume coefficients		State coefficients								Existing left-turn lane coefficient (0 lanes)	Dispersion parameter (d)	R^2%	R_{FT}^2
							LogMajADT	LogMinADT	IA	IL	LA	MN	NC	NE	OR	VA				
R	U	3	M	2,2	63	−6.523	0.078	0.864	0	0	0	0	0	0	0	0	0	0.079	18.26	12.74
R	U	3	T	1,1	579	−12.153	1.000	0.633	−2.232	−1.145	0	0	−0.406	0	−1.242	0	0	0.506	32.32	28.37
R	U	4	M	2,1	80	−12.493	0.797	0.868	0	0	0	0	0	0	0	0	0	0.197	57.55	50.32
R	U	4	M	2,1	662	−8.136	0.298	0.856	0	0	0	0	0	0	0	0	0	0.354	34.53	32.78
U	S	3	M	0,3	34															
U	S	3	T	0,3	47															
U	S	4	M	3,1	747	−6.749	0.692	0.178	0.921	0.772	1.552	0.905	−0.788	0.444	−0.098	0	−0.123	0.371	32.65	31.10
U	S	4	T	1,1	177	−12.231	0.835	0.811	0	−1.030	−0.908	0	−1.718	0	0	0	0	0.220	35.27	37.42
U	U	3	M	0,3	25															
U	U	3	T	1,1	195	−8.887	0.745	0.293	0.815	−0.029	1.385	0	0	0	0	0	0	0.460	11.11	30.87
U	U	4	M	1,2	121	−1.426	0.061	0.184	1.434	0.438	0	0.066	0	0.609	0	0	0	0.184	43.92	36.04
U	U	4	T	1,1	200	−7.740	0.641	0.194	1.108	1.481	0	1.269	0.587	0	0	0	0	0.408	32.22	22.90

Table B-2. Negative Binomial Regression Models for Fatal and Injury Intersection Accidents.

Area type	Traffic control type	No. of inter-section legs	No. of lanes on major road (two-lane or multi-lane)	Model type	No. of site-years	Inter-cept	Traffic volume coefficients		State coefficients								Existing left-turn lane coefficient (0 lanes)	Dispersion parameter (d)	R^2%	R_{FT}^2
							LogMajADT	LogMinADT	IA	IL	LA	MN	NC	NE	OR	VA				
R	U	3	M	0.3	63															
R	U	3	T	0,3	579															
R	U	4	M	2,1	80	−13.081	0.933	0.676	0	0	0	0	0	0	0	0	0	0.432	25.95	31.38
R	U	4	T	2,1	662	−8.365	0.233	0.877	0	0	0	0	0	0	0	0	0	0.377	24.89	22.33
U	S	3	M	0,3	34															
U	S	3	T	0,3	47															
U	S	4	M	3,1	747	−6.055	0.521	0.178	1.060	0.752	1.498	0.904	−0.299	0.414	−0.154	0	−0.219	0.295	27.48	24.39
U	S	4	T	1,1	177	−8.899	0.533	0.633	0	−1.228	−0.835	0	−1.380	0	0	0	0	0.162	10.62	13.29
U	U	3	M	0,3	25															
U	U	3	T	1,2	195	−8.073	0.715	0.051	1.087	0.013	1.426	0	0	0	0	0	0	0.060	32.49	33.34
U	U	4	M	0,3	121															
U	U	4	T	1.1	200	−10.709	0.824	0.294	0.997	1.113	0	0.654	0.541	0	0	0	0	0.375	23.91	17.89

Table B-3. Negative Binomial Regression Models for Project-Related Intersection Accidents.

Area type	Traffic control type	No. of inter-section legs	No. of lanes on major road (two-lane or multi-lane)	Model type	No. of site-years	Intercept	Traffic volume coefficients		State coefficients								Existing left-turn lane coefficient (0 lanes)	Dispersion parameter (d)	R^2%	R_{FT}^2
							LogMajADT	LogMinADT	IA	IL	LA	MN	NC	NE	OR	VA				
R	U	3	M	0,0	63															
R	U	3	T	0.0	579															
R	U	4	M	2,2	80	−10.732	0.652	0.539	0	0	0	0	0	0	0	0	0	2.010	3.68	3.88
R	U	4	T	2,1	662	−11.201	0.648	0.462	0	0	0	0	0	0	0	0	0	0.263	3.07	1.66
U	S	3	M	0,0	34															
U	S	3	T	0,3	47															
U	S	4	M	0,3	747															
U	S	4	T	0,3	177															
U	U	3	M	0,0	25															
U	U	3	T	0,0	195															
U	U	4	M	2,2	121	−11.185	0.736	0.434	0	0	0	0	0	0	0	0	0	1.280	5.80	3.63
U	U	4	T	0,3	200															

Table B-4. Negative Binomial Regression Models for Total Accidents on Individual Intersection Approaches.

Area type	Traffic control type	No. of inter-section legs	No. of lanes on major road (two-lane or multi-lane)	Model type	No. of approach years	Intercept	Traffic volume coefficients		State coefficients								Existing left-turn lane coefficient (0 lanes)	Dispersion parameter (d)	R^2%	R_{FT}^2
							LogMajADT	LogMinADT	IA	IL	LA	MN	NC	NE	OR	VA				
R	U	3	M	0,3	126															
R	U	3	T	1,1	1,158	−11.966	0.974	0.519	−23.164	−1.250	0	0	−1	0	−1.493	0	0	1.049	13.59	10.59
R	U	4	M	2,1	160	−13.413	0.818	0.863	0	0	0	0	0	0	0	0	0	0.142	43.52	40.55
R	U	4	T	2,1	1,324	−9.347	0.297	0.918	0	0	0	0	0	0	0	0	0	0.274	25.89	23.61
U	S	3	M	4,2	102	−11.606	0.880	0.409	0	0	0	0	0	0	0	0	0.343	0.348	21.12	20.20
U	S	3	T	2,1	141	−14.419	0.642	0.905	0	0	0	0	0	0	0	0	0	0.462	9.42	6.39
U	S	4	M	1,1	2,976	−7.620	0.740	0.107	0.715	0.576	1.456	0.655	−0.706	0.105	−0.209	0	0	0.479	29.38	32.89
U	S	4	T	2,1	708	−9.908	0.974	0.156	0	0	0	0	0	0	0	0	0	0.373	21.62	21.87
U	U	3	M	0,3	50															
U	U	3	T	1,1	390	−8.638	0.722	0.137	0.930	0.221	1.400	0	0	0	0	0	0	0.647	12.76	16.00
U	U	4	M	1,2	242	−5.515	0.421	0.124	1.909	0.655	0	0.433	0	0.948	0	0	0	0.222	31.90	28.03
U	U	4	T	1,1	400	−7.885	0.589	0.187	1.099	1.357	0	1.048	0.382	0	0	0	0	0.509	18.76	13.19

Table B-5. Negative Binomial Regression Models for Total Fatal and Injury Accidents on Individual Intersection Approaches.

Area type	Traffic control type	No. of inter-section legs	No. of lanes on major road (two-lane or multi-lane)	Model type	No. of approach years	Intercept	Traffic volume coefficients		State coefficients								Existing left-turn lane coefficient (0 lanes)	Dispersion parameter (d)	R^2%	R_{FT}^2
							LogMajADT	LogMinADT	IA	IL	LA	MN	NC	NE	OR	VA				
R	U	3	M	0,3	126															
R	U	3	T	0,3	1,158															
R	U	4	M	1,2	160	−9.994	0.695	0.348	0	−0.367	0	0	0	0.958	0	0	0	0.235	24.9	29.21
R	U	4	T	2,1	1,324	−9.935	0.281	0.932	0	0	0	0	0	0	0	0	0	0.381	16.04	13.90
U	S	3	M	4,2	102	−11.609	0.796	0.401	0	0	0	0	0	0	0	0	0	0.318	5.96	4.97
U	S	3	T	2,2	141	−13.457	0.980	0.313	0	0	0	0	0	0	0	0	0	0.383	2.33	0.68
U	S	4	M	1,1	2,976	−9.073	0.798	0.080	0.996	0.685	1.554	0.811	−0.092	0.329	−0.151	0	0	0.459	21.94	22.10
U	S	4	T	0,3	708															
U	U	3	M	0,3	50															
U	U	3	T	0,3	390															
U	U	4	M	1,2	242	−2.985	0.074	0.141	1.842	−0.312	0	−0.507	0	0.874	0	0	0	0.215	29.24	26.58
U	U	4	T	2,1	400	−11.081	0.826	0.373	0	0	0	0	0	0	0	0	0	0.538	11.49	8.25

Table B-6. Negative Binomial Regression Models for Project-Related Accidents on Individual Intersection Approaches.

Area type	Traffic control type	No. of inter-section legs	No. of lanes on major road (two-lane or multi-lane)	Model type	No. of approach years	Intercept	Traffic volume coefficients		State coefficients								Existing left-turn lane coefficient (0 lanes)	Dispersion parameter (d)	R^2%	R_{FT}^2
							LogMajADT	LogMinADT	IA	IL	LA	MN	NC	NE	OR	VA				
R	U	3	M	0,0	126															
R	U	3	T	0,0	1,158															
R	U	4	M	2,2	160	−12.004	0.745	0.492	0	0	0	0	0	0	0	0	0	2.816	2.73	1.03
R	U	4	T	2,1	1,324	−12.162	0.679	0.466	0	0	0	0	0	0	0	0	0	0.000	1.67	0.85
U	S	3	M	0,0	102															
U	S	3	T	0,3	141															
U	S	4	M	1,1	2,976	−13.191	0.827	0.279	2.081	1.859	3.220	2.467	1.194	1.292	2.309	0	0	2.661	9.54	6.99
U	S	4	T	0,3	708															
U	U	3	M	0,0	50															
U	U	3	T	0,0	390															
U	U	4	M	2,2	242	−11.106	0.659	0.434	0	0	0	0	0	0	0	0	0	1.429	3.21	1.45
U	U	4	T	0,3	400															

Overall Assessment of the Final Models

The combination of types of sites and safety measures required a total of 96 models to be estimated. Of these 96 models, 26 models (27 percent) could be estimated with fully satisfactory results and 13 models (14 percent) could be developed, but were not statistically significant. These latter models were used, despite the lack of statistical significance, because they represented the best available model. No models could be estimated in 23 cases (24 percent). In 34 cases (35 percent), models could not be developed because of sparse accident data over the entire study period. The R^2 and R_{FT}^2 values range from 1.7 to 57.6 percent and from 0.9 to 50.3 percent, respectively, for the 26 statistically significant models. The R^2 and R_{FT}^2 values range from 2.33 to 43.9 percent and from 0.68 to 36.0 percent, respectively, for the 13 models that were not statistically significant but were still used.

The types of model used in adjusting accidents frequencies for traffic volumes, state effect and, where applicable, the effect of existing left-turn lanes in the CG and EB approaches can be summarized as follows:

- Type 1—17 models, including major-road traffic volume, minor-road traffic volume, and state (18 percent).
- Type 2—18 models, including major-road traffic volume and minor-road traffic volume (19 percent).
- Type 3—two models, including major-road traffic volume, minor-road traffic volume, state, and number of existing left-turn lane (urban, signalized intersections only) (2 percent).
- Type 4—two models, including major-road traffic volume, minor-road traffic volume, and number of existing left-turn lane (urban, signalized intersections only) (2 percent).
- Type 0—57 models; in these cases, no usable model was available (59 percent).

Models like those in tables B-1 through B-6 are intended for predicting annual accident frequencies. Caution should be exercised in interpreting the individual coefficients in the model as representing the effect on an individual factor on safety. However, it is interesting to note that the coefficient of EXLEFT for urban four-leg signalized intersections on multilane highways shown in table B-1, when evaluated with the average of the eight state effects shown in the table, represents an accident reduction effectiveness of 12 percent for installation of a left-turn lane on one intersection approach. This is in good agreement with the 10 percent effectiveness for this project type determined with the EB approach, as shown in table 47.

Use of the Negative Binomial Regression Models in the CG and EB Evaluation Approaches

The overall adjustment procedures to account for traffic volumes changes in the CG and EB evaluation approaches are discussed separately in section 5. To use any of the regression equations shown in tables B-1 through B-6, proceed as follows: (a) select the proper table (i.e., type of safety measure) and type of site within that table; (b) use the coefficients shown for the intercept, major-road and minor-road traffic volumes; (c) select the coefficient for the appropriate state, if state is included in the model; and (d) select the coefficient for the zero existing left-turn lanes, if that parameter is included in the model (four cases only—Model Types 3 and 4). In these four cases, the number of existing left-turn lanes was set equal to zero because the models were applied to sites with no existing turn lanes.

When no usable model was available, a simple proportional adjustment for traffic volume was made in the CG approach. When no usable model was available, sites of that type were not used in the EB approach.

Appendix C

Detailed Evaluation Results

APPENDIX C. DETAILED EVALUATION RESULTS

This appendix presents the detailed results of the evaluation of the effectiveness of left- and right-turn lane improvement projects performed in this study. The results for the yoked comparison (YC), comparison group (CG), and Empirical Bayes (EB) approaches are presented separately. This appendix presents the results of all evaluations that were performed. Only those results that were found to be statistically significant are presented and interpreted in the main text of this report (see section 6).

Yoked Comparison Evaluations

The results of the YC evaluations performed in this study are presented in tables C-1 through C-10. These tables include the results for four specific dependent variables, two different target areas, and two different types of analysis approaches.

The YC approach to before-after evaluation has been described conceptually in section 5 of this report. The procedures presented in that section were used to obtain the analysis results in tables C-1 through C-10. These analyses involved one-to-one matching of treatment and similar unimproved comparison sites. Two analyses presented below involved only treatment site data; in this approach, the project-related accidents for the treatment site were evaluated using the non-project-related accidents for that same site as the “comparison site” data. These were referred to as *auto-matching* analyses.

Description of Results Tables

Each of the tables of YC results presents the results of a set of similar YC evaluation for a specific dependent variable, target area, and analysis type. Each row in a table presents the results of the evaluation performed for a specific type of improvement project. The following discussion guides the interpretation of individual columns in these tables.

Area type. The first column for each row of the table identifies the area type for the intersections evaluated. The codes used in this column are:

R = rural
U = urban

Traffic control: The second column identifies the type of traffic control at the intersections evaluated. The codes used in this column are:

N = Newly signalized intersection
S = Signalized intersection
U = Unsignalized intersection

Table C-1. Yoked Comparison Evaluation Results for Total Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Treatment effect: Ratio[a]	Calculated Z	Significant at 5% level?	Test for homogeneity: Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	-70.31	-35.15	7.60	-44.56	-9.52	4.63	-2.37	SIG	0.39	Yes
R	N	LR	4	1	8.58	4.29	65.60	-44.92	529.83	0.07	0.07	n/a		n/a
R	N	R	4	1	-10.38	-5.19	20.07	-31.38	57.82	0.26	-0.24	n/a		n/a
R	S	XL	3	2	-27.76	-27.76	54.20	-83.40	214.40	0.51	-0.43	NS	0.41	Yes
R	S	XL	4	3	-30.64	-30.64	27.62	-68.21	51.37	1.11	-0.92	NS	0.87	Yes
R	S	XLR	4	1	-44.32	-11.08	7.85	-20.39	17.07	1.41	-1.04	n/a		n/a
R	U	L	3	31	-63.68	-63.68	7.21	-75.39	-46.41	8.83	-5.10	SIG	0.20	Yes
R	U	L	4	21	-58.08	-32.10	4.70	-39.70	-20.78	6.83	-4.28	SIG	0.04	No
R	U	LR	3	11	-56.64	-44.50	15.08	-64.27	2.57	2.95	-1.89	NS	0.76	Yes
R	U	LR	4	12	1.96	0.98	13.39	-19.53	35.31	0.07	0.07	NS	0.74	Yes
R	U	R	3	11	88.66	88.66	77.59	-15.75	322.45	1.14	1.54	NS	0.86	Yes
R	U	R	4	27	-23.91	-15.37	10.99	-32.80	11.69	1.40	-1.22	NS	0.86	Yes
R	U	XL	4	1	82.06	82.06	222.08	-83.33	1,888.76	0.37	0.49	n/a		n/a
U	N	L	3	4	-30.29	-20.19	14.09	-41.01	17.52	1.43	-1.19	NS	0.02	No
U	N	L	4	24	-43.77	-22.35	3.18	-27.95	-15.39	7.03	-5.20	SIG	0.03	No
U	S	L	3	3	-32.62	-32.62	30.80	-72.49	65.08	1.06	-0.86	NS	0.18	Yes
U	S	L	4	33	-42.00	-12.95	1.16	-15.09	-10.53	11.17	-8.40	SIG	0.00	No
U	S	LR	4	9	-21.25	-5.46	2.20	-9.35	-0.65	2.48	-2.20	SIG	0.01	No
U	S	R	3	1	-36.52	-18.26	15.54	-37.84	32.85	1.18	-0.93	n/a		n/a
U	S	R	4	14	-13.65	-6.82	4.23	-14.37	2.32	1.61	-1.50	NS	0.00	No
U	S	XL	3	1	-25.11	-25.11	43.24	-75.85	132.21	0.58	-0.50	n/a		n/a
U	S	XL	4	2	14.95	9.97	15.24	-14.77	46.50	0.65	0.70	NS	0.80	Yes
U	U	L	3	10	-36.55	-36.55	17.52	-63.07	9.00	2.09	-1.65	NS	0.28	Yes
U	U	L	4	8	-70.46	-35.23	2.92	-39.97	-28.24	12.07	-6.17	SIG	0.63	Yes
U	U	LR	4	1	-0.85	-0.42	37.06	-38.55	164.58	0.01	-0.01	n/a		n/a
U	U	R	4	1	22.76	22.76	228.29	-96.79	4,599.26	0.10	0.11	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

C-3

Table C-2. Yoked Comparison Evaluation Results for Fatal and Injury Intersection Accidents.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	-82.61	-41.31	6.58	-48.03	-11.64	6.27	-2.31	SIG	0.69	Yes
R	N	LR	4	1	-3.95	-1.97	61.88	-46.16	550.18	0.03	-0.03	n/a		n/a
R	N	R	4	1	-2.86	-1.43	32.03	-36.67	126.92	0.04	-0.04	n/a		n/a
R	S	XL	3	2	-35.44	-35.44	63.34	-90.56	341.70	0.56	-0.45	NS	0.72	Yes
R	S	XL	4	3	63.45	63.45	85.33	-41.25	354.74	0.74	0.94	NS	0.98	Yes
R	S	XLR	4	1	18.67	4.67	24.66	-19.18	126.30	0.19	0.21	n/a		n/a
R	U	L	3	34	-58.55	-58.55	11.78	-76.26	-27.63	4.97	-3.10	SIG	0.78	Yes
R	U	L	4	22	-70.41	-39.72	4.85	-46.97	-26.90	8.18	-4.19	SIG	0.88	Yes
R	U	LR	3	11	-51.67	-40.60	22.18	-66.48	40.71	1.83	-1.25	NS	0.99	Yes
R	U	LR	4	14	-7.72	-3.86	16.19	-26.80	41.77	0.24	-0.23	NS	0.98	Yes
R	U	R	3	11	18.83	18.83	62.88	-57.88	235.23	0.30	0.33	NS	1.00	Yes
R	U	R	4	28	-22.28	-14.51	15.09	-36.91	25.69	0.96	-0.85	NS	0.94	Yes
R	U	XL	4	2	156.22	156.22	335.09	-80.26	3,225.51	0.47	0.72	NS	0.27	Yes
U	N	L	3	4	-10.57	-7.04	28.32	-43.17	84.60	0.25	-0.24	NS	0.11	Yes
U	N	L	4	23	-42.68	-21.81	5.40	-30.70	-9.05	4.04	-3.02	SIG	0.67	Yes
U	S	L	3	3	-41.97	-41.97	40.03	-84.99	124.28	1.05	-0.79	NS	0.25	Yes
U	S	L	4	35	-39.35	-12.41	2.04	-16.01	-7.96	6.08	-4.69	SIG	0.00	No
U	S	LR	4	8	-27.75	-7.16	3.75	-13.23	1.84	1.91	-1.62	NS	0.36	Yes
U	S	R	3	1	-74.25	-37.13	12.09	-47.96	31.17	3.07	-1.44	n/a		n/a
U	S	R	4	12	-20.22	-9.71	7.22	-21.54	7.41	1.34	-1.20	NS	0.38	Yes
U	S	XL	3	1	-0.14	-0.14	99.86	-85.93	608.91	0.00	0.00	n/a		n/a
U	S	XL	4	3	-7.71	-4.62	19.19	-31.92	49.21	0.24	-0.23	NS	0.14	Yes
U	U	L	3	10	-41.59	-41.59	24.13	-74.01	31.27	1.72	-1.30	NS	0.67	Yes
U	U	L	4	8	-79.48	-39.74	3.04	-44.26	-31.65	13.06	-5.34	SIG	0.93	Yes
U	U	LR	4	1	-73.75	-36.88	18.17	-49.13	147.92	2.03	-0.97	n/a		n/a
U	U	R	4	1	84.14	84.14	379.61	-96.76	10,370.69	0.22	0.30	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-3. Yoked Comparison Evaluation Results for Project-Related Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Percent change in accident frequency: Mean per added lane	Percent change in accident frequency: Standard error	Percent change in accident frequency: Lower 95% confidence limit	Percent change in accident frequency: Upper 95% confidence limit	Treatment effect: Ratio[a]	Treatment effect: Calculated Z	Treatment effect: Significant at 5% level?	Test for homogeneity: Calculated H probability	Test for homogeneity: Homogeneous at 5% level?
R	N	L	4	2	-33.84	-16.92	44.21	-47.59	404.14	0.38	-0.31	NS	1.00	Yes
R	N	LR	4	1	-47.97	-23.99	68.83	-49.85	4,598.55	0.35	-0.25	n/a		n/a
R	N	R	4	1	-0.01	0.00	141.41	-49.80	12,730.59	0.00	0.00	n/a		n/a
R	S	XL	3	2	-7.57	-7.57	184.85	-98.17	4,558.33	0.04	-0.04	NS	0.98	Yes
R	S	XL	4	4	23.06	23.06	119.45	-81.64	724.77	0.19	0.21	NS	0.99	Yes
R	S	XLR	4	1	-2.90	-0.73	47.01	-24.45	1,055.24	0.02	-0.02	n/a		n/a
R	U	L	3	34	-1.04	-1.04	47.90	-61.68	155.56	0.02	-0.02	NS	1.00	Yes
R	U	L	4	23	-38.43	-21.56	16.71	-42.72	33.06	1.29	-1.00	NS	1.00	Yes
R	U	LR	3	12	-15.23	-12.18	53.44	-65.53	237.78	0.23	-0.21	NS	1.00	Yes
R	U	LR	4	15	68.38	34.19	44.25	-19.95	185.88	0.77	0.99	NS	0.95	Yes
R	U	R	3	11	4.90	4.90	89.46	-80.28	458.06	0.05	0.06	NS	1.00	Yes
R	U	R	4	28	-7.41	-4.83	28.83	-41.50	88.81	0.17	-0.16	NS	1.00	Yes
R	U	XL	4	2	50.26	50.26	242.29	-93.63	3,443.23	0.21	0.25	NS	0.57	Yes
U	N	L	3	4	-32.95	-21.97	59.60	-63.39	543.20	0.37	-0.30	NS	0.99	Yes
U	N	L	4	26	22.55	11.73	23.61	-21.17	79.74	0.50	0.55	NS	0.76	Yes
U	S	L	3	3	0.06	0.06	155.01	-95.20	1,984.29	0.00	0.00	NS	1.00	Yes
U	S	L	4	35	-39.09	-12.55	3.17	-17.87	-5.25	3.96	-3.06	SIG	0.53	Yes
U	S	LR	3	2	222.83	148.55	351.45	-57.90	5,216.77	0.42	0.72	NS	0.96	Yes
U	S	LR	4	7	-59.77	-15.50	2.24	-19.09	-10.02	6.90	-4.23	SIG	0.84	Yes
U	S	R	3	1	-46.90	-23.45	35.12	-48.01	304.93	0.67	-0.48	n/a		n/a
U	S	R	4	13	9.10	5.38	19.84	-23.82	58.74	0.27	0.28	NS	0.00	No
U	S	XL	3	1	299.43	299.43	1,018.34	-97.30	59,004.76	0.29	0.54	n/a		n/a
U	S	XL	4	2	5.15	3.44	118.54	-64.12	1861.12	0.03	0.03	NS	0.78	Yes
U	U	L	3	10	12.61	12.61	100.01	-80.25	542.02	0.13	0.13	NS	1.00	Yes
U	U	L	4	8	-78.97	-39.49	4.87	-45.76	-23.93	8.11	-3.37	SIG	0.57	Yes
U	U	LR	4	1	162.46	81.23	215.63	-44.76	3236.40	0.38	0.59	n/a		n/a
U	U	R	4	1	-7.93	-7.93	260.41	-99.64	23,435.42	0.03	-0.03	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-4. Yoked Comparison Evaluation for Project-Related Fatal and Injury Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Treatment effect: Ratio[a]	Calculated Z	Significant at 5% level?	Test for homogeneity: Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	-28.78	-14.39	57.63	-48.51	799.48	0.25	-0.21	NS	0.83	Yes
R	N	LR	4	1	-47.97	-23.99	68.83	-49.85	4,598.55	0.35	-0.25	n/a		n/a
R	N	R	4	1	-0.01	0.00	141.41	-49.80	12,730.59	0.00	0.00	n/a		n/a
R	S	XL	3	2	-7.57	-7.57	184.85	-98.17	4,558.33	0.04	-0.04	NS	0.98	Yes
R	S	XL	4	4	177.73	177.73	311.15	-69.10	2,396.19	0.57	0.91	NS	0.86	Yes
R	S	XLR	4	1	45.65	11.41	80.05	-24.51	2,682.84	0.14	0.17	n/a		n/a
R	U	L	3	34	1.31	1.31	49.14	-60.85	162.14	0.03	0.03	NS	1.00	Yes
R	U	L	4	23	-36.33	-20.38	18.87	-43.42	44.50	1.08	-0.85	NS	1.00	Yes
R	U	LR	3	12	-17.33	-13.87	53.37	-66.40	241.59	0.26	-0.24	NS	1.00	Yes
R	U	LR	4	15	-4.91	-2.46	30.40	-36.42	116.47	0.08	-0.08	NS	1.00	Yes
R	U	R	3	11	4.90	4.90	89.46	-80.28	458.06	0.05	0.06	NS	1.00	Yes
R	U	R	4	28	-4.40	-2.87	31.87	-42.30	104.69	0.09	-0.09	NS	1.00	Yes
R	U	XL	4	2	143.69	143.69	451.22	-93.53	9,082.86	0.32	0.48	NS	0.73	Yes
U	N	L	3	4	-3.68	-2.46	90.81	-62.65	959.95	0.03	-0.03	NS	1.00	Yes
U	N	L	4	26	-8.78	-4.57	22.33	-33.14	67.33	0.20	-0.20	NS	1.00	Yes
U	S	L	3	3	1.06	1.06	165.02	-95.88	2,380.82	0.01	0.01	NS	1.00	Yes
U	S	L	4	35	-32.67	-10.49	6.31	-19.91	6.21	1.66	-1.35	NS	1.00	Yes
U	S	LR	3	2	-25.28	-16.86	96.24	-65.54	2,131.34	0.18	-0.15	NS	0.89	Yes
U	S	LR	4	8	-49.63	-12.81	4.96	-19.65	1.64	2.58	-1.80	NS	0.65	Yes
U	S	R	3	1	-73.45	-36.72	33.85	-49.91	1,914.45	1.09	-0.52	n/a		n/a
U	S	R	4	14	40.32	20.16	30.02	-19.67	112.29	0.67	0.79	NS	0.59	Yes
U	S	XL	3	1	99.71	99.71	528.39	-98.88	35,587.40	0.19	0.26	n/a		n/a
U	S	XL	4	3	34.97	20.98	109.53	-54.29	1,087.46	0.19	0.22	NS	0.79	Yes
U	U	L	3	10	3.97	3.97	92.99	-81.99	500.14	0.04	0.04	NS	1.00	Yes
U	U	L	4	8	-81.50	-40.75	5.62	-47.19	-19.58	7.25	-2.78	SIG	0.95	Yes
U	U	LR	4	1	-47.51	-23.75	69.44	-49.85	4,639.94	0.34	-0.24	n/a		n/a
U	U	R	4	1	-7.93	-7.93	260.41	-99.64	23,435.42	0.03	-0.03	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-5. Yoked Comparison Evaluation Results for Total Accidents on Individual Intersection Approaches.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Treatment effect: Ratio[a]	Calculated Z	Significant at 5% level?	Test for homogeneity: Calculated H probability	Homogeneous at 5% level?
R	N	L	4	4	-67.45	-67.45	9.33	-44.71	0.07	3.61	-1.96	SIG	0.65	Yes
R	N	LR	4	2	-11.77	-5.88	47.18	-44.58	308.79	0.12	-0.12	NS	0.78	Yes
R	N	R	4	2	-7.11	-7.11	23.17	-32.53	73.49	0.15	-0.15	NS	0.49	Yes
R	S	XL	3	2	61.29	61.29	189.96	-83.96	1,522.35	0.32	0.41	NS	0.62	Yes
R	S	XL	4	4	-50.86	-50.86	26.61	-83.00	42.03	1.91	-1.31	NS	0.69	Yes
R	S	XLR	4	2	-39.42	-19.71	7.49	-14.31	26.55	0.88	-0.68	NS	0.41	Yes
R	U	L	3	34	-47.46	-47.46	16.56	-71.67	-2.55	2.87	-2.04	SIG	0.61	Yes
R	U	L	4	40	-47.32	-47.32	6.35	-35.29	-9.58	3.97	-2.84	SIG	0.70	Yes
R	U	LR	3	23	-51.34	-25.67	18.04	-63.87	17.14	2.26	-1.54	NS	0.99	Yes
R	U	LR	4	27	5.26	2.63	14.21	-19.00	39.36	0.19	0.19	NS	0.99	Yes
R	U	R	3	11	79.25	79.25	107.95	-44.94	483.59	0.73	0.97	NS	1.00	Yes
R	U	R	4	43	-18.72	-18.72	11.48	-28.98	17.69	0.96	-0.86	NS	1.00	Yes
R	U	XL	4	1	0.00	0.00	193.65	-97.75	4,350.15	0.00	0.00	n/a		n/a
U	N	L	3	6	-25.86	-25.86	19.80	-41.41	46.43	0.78	-0.67	NS	0.24	Yes
U	N	L	4	47	-55.50	-55.50	3.36	-34.08	-20.70	8.43	-5.47	SIG	0.32	Yes
U	S	L	3	3	70.74	70.74	121.99	-57.92	592.68	0.58	0.75	NS	0.98	Yes
U	S	L	4	106	-42.02	-42.02	1.19	-13.98	-9.32	9.97	-7.50	SIG	0.00	No
U	S	LR	3	3	-8.02	-4.01	31.23	-41.79	107.29	0.15	-0.15	NS	0.46	Yes
U	S	LR	4	32	-30.94	-15.47	1.56	-8.74	-2.55	3.84	-3.17	SIG	0.65	Yes
U	S	R	3	2	-62.59	-62.59	15.45	-46.30	44.46	2.02	-1.19	NS	0.04	No
U	S	R	4	28	-25.74	-25.74	3.86	-16.67	-1.36	2.59	-2.23	SIG	0.04	No
U	S	XL	3	1	33.33	33.33	238.82	-96.02	4,362.97	0.14	0.16	n/a		n/a
U	S	XL	4	4	-4.97	-4.97	15.07	-25.62	36.40	0.19	-0.18	NS	0.08	Yes
U	U	L	3	10	-55.44	-55.44	17.53	-79.39	-3.65	3.16	-2.05	SIG	0.61	Yes
U	U	L	4	16	-69.37	-69.37	3.26	-39.91	-26.76	10.64	-5.56	SIG	0.59	Yes
U	U	LR	4	2	53.64	26.82	80.23	-40.08	545.03	0.33	0.41	NS	0.18	Yes
U	U	R	4	1	-69.49	-69.49	71.55	-99.69	2,924.77	0.97	-0.51	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-6. Yoked Comparison Evaluation Results for Fatal and Injury Accidents on Individual Intersection Approaches.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	4	-78.75	-78.75	8.67	-47.85	2.62	4.54	-1.90	NS	0.65	Yes
R	N	LR	4	2	-24.25	-12.12	44.62	-46.24	331.17	0.27	-0.24	NS	0.50	Yes
R	N	R	4	2	32.74	32.74	48.91	-34.35	231.36	0.33	0.38	NS	0.80	Yes
R	S	XL	3	2	64.93	64.93	203.08	-85.24	1,742.63	0.32	0.41	NS	0.86	Yes
R	S	XL	4	4	21.37	21.37	78.62	-65.90	332.02	0.27	0.30	NS	1.00	Yes
R	S	XLR	4	2	21.91	10.96	24.06	-14.67	190.29	0.15	0.17	NS	0.51	Yes
R	U	L	3	34	-40.80	-40.80	22.53	-71.92	24.82	1.81	-1.38	NS	0.99	Yes
R	U	L	4	41	-54.97	-54.97	6.89	-39.60	-11.12	4.25	-2.77	SIG	1.00	Yes
R	U	LR	3	24	-28.23	-14.11	28.77	-58.50	73.32	0.78	-0.66	NS	1.00	Yes
R	U	LR	4	29	-6.43	-3.22	15.69	-25.76	40.29	0.20	-0.20	NS	1.00	Yes
R	U	R	3	11	26.71	26.71	86.25	-66.62	381.08	0.31	0.35	NS	0.99	Yes
R	U	R	4	43	-10.90	-10.90	15.76	-29.77	35.65	0.41	-0.38	NS	1.00	Yes
R	U	XL	4	2	121.96	121.96	319.21	-86.75	3,619.01	0.38	0.55	NS	0.30	Yes
U	N	L	3	6	-38.23	-38.23	24.38	-49.79	74.56	0.94	-0.73	NS	0.80	Yes
U	N	L	4	49	-58.14	-58.14	4.99	-37.53	-17.26	5.94	-3.73	SIG	1.00	Yes
U	S	L	3	3	210.12	210.12	284.05	-48.49	1,767.16	0.74	1.24	NS	0.94	Yes
U	S	L	4	114	-39.99	-39.99	1.93	-14.58	-6.97	5.81	-4.46	SIG	0.81	Yes
U	S	LR	3	4	55.16	27.58	74.90	-41.65	360.97	0.49	0.61	NS	0.88	Yes
U	S	LR	4	34	-34.35	-17.17	2.62	-10.95	-0.39	2.56	-2.06	SIG	0.92	Yes
U	S	R	3	2	-86.69	-86.69	9.25	-49.56	51.49	4.69	-1.45	NS	0.78	Yes
U	S	R	4	30	-29.85	-29.85	6.36	-21.30	4.57	1.78	-1.48	NS	0.98	Yes
U	S	XL	3	1	-28.57	-28.57	148.85	-98.80	4,143.93	0.19	-0.16	n/a		n/a
U	S	XL	4	4	-53.37	-53.37	14.86	-48.21	22.37	2.05	-1.37	NS	0.30	Yes
U	U	L	3	10	-52.96	-52.96	26.42	-84.35	41.44	2.00	-1.34	NS	0.84	Yes
U	U	L	4	16	-77.79	-77.79	3.70	-44.22	-28.66	10.51	-4.52	SIG	0.90	Yes
U	U	LR	4	2	-62.87	-31.43	29.45	-49.17	365.89	1.07	-0.62	NS	0.58	Yes
U	U	R	4	1	-38.98	-38.98	149.46	-99.50	7,321.45	0.26	-0.20	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-7. Yoked Comparison Evaluation Results for Project-Related Accidents on Individual Intersection Approaches.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	4	-29.35	-29.35	40.58	-46.28	285.61	0.36	-0.30	NS	0.85	Yes
R	N	LR	4	2	-28.14	-14.07	69.42	-49.19	1,535.50	0.20	-0.17	NS	0.87	Yes
R	N	R	4	2	0.01	0.01	100.01	-49.01	2,470.19	0.00	0.00	NS	1.00	Yes
R	S	XL	3	2	-12.07	-12.07	175.87	-98.26	4,331.89	0.07	-0.06	NS	0.96	Yes
R	S	XL	4	4	15.21	15.21	111.82	-82.81	672.11	0.14	0.15	NS	0.98	Yes
R	S	XLR	4	2	14.57	7.29	32.12	-15.96	499.57	0.08	0.08	NS	0.67	Yes
R	U	L	3	34	2.03	2.03	49.49	-60.57	164.00	0.04	0.04	NS	1.00	Yes
R	U	L	4	41	-25.66	-25.66	15.50	-34.87	32.03	0.88	-0.76	NS	1.00	Yes
R	U	LR	3	24	-10.95	-5.48	40.46	-56.60	136.84	0.22	-0.20	NS	1.00	Yes
R	U	LR	4	30	19.17	9.58	26.34	-24.94	91.70	0.36	0.40	NS	1.00	Yes
R	U	R	3	11	5.84	5.84	90.26	-80.11	463.06	0.06	0.07	NS	1.00	Yes
R	U	R	4	43	-9.68	-9.68	21.27	-34.60	57.55	0.27	-0.25	NS	1.00	Yes
R	U	XL	4	2	30.05	30.05	209.71	-94.48	2,966.70	0.14	0.16	NS	0.57	Yes
U	N	L	3	6	-21.71	-21.71	51.73	-54.57	346.63	0.25	-0.22	NS	1.00	Yes
U	N	L	4	50	-8.21	-8.21	15.32	-26.36	37.90	0.27	-0.26	NS	1.00	Yes
U	S	L	3	3	-0.44	-0.44	162.58	-95.94	2,344.12	0.00	-0.00	NS	0.99	Yes
U	S	L	4	115	-33.88	-33.88	2.87	-14.34	-2.90	3.30	-2.66	SIG	1.00	Yes
U	S	LR	3	5	95.11	47.55	140.81	-49.82	1,109.84	0.42	0.58	NS	0.99	Yes
U	S	LR	4	32	-59.67	-29.83	1.77	-14.68	-7.51	6.69	-4.10	SIG	0.79	Yes
U	S	R	3	2	-41.79	-41.79	47.53	-48.81	664.46	0.44	-0.33	NS	0.88	Yes
U	S	R	4	34	66.04	66.04	15.90	1.30	66.00	1.64	2.09	SIG	0.01	No
U	S	XL	3	1	0.00	0.00	282.84	-99.61	25,462.64	0.00	0.00	n/a		n/a
U	S	XL	4	5	108.84	108.84	113.24	-38.42	730.24	0.53	0.75	NS	0.71	Yes
U	U	L	3	10	14.06	14.06	101.30	-79.99	550.30	0.14	0.15	NS	1.00	Yes
U	U	L	4	16	-78.11	-78.11	5.15	-45.65	-22.50	7.59	-3.23	SIG	0.97	Yes
U	U	LR	4	2	141.99	70.99	169.28	-42.21	1,828.13	0.42	0.63	NS	0.65	Yes
U	U	R	4	1	-38.98	-38.98	172.58	-99.76	15,497.21	0.23	-0.17	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-8. Yoked Comparison Evaluation Results for Project-Related Fatal and Injury Accidents on Individual Intersection Approaches.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Percent change in accident frequency: Mean per added lane	Percent change in accident frequency: Standard error	Percent change in accident frequency: Lower 95% confidence limit	Percent change in accident frequency: Upper 95% confidence limit	Treatment effect: Ratio[a]	Treatment effect: Calculated Z	Treatment effect: Significant at 5% level?	Test for homogeneity: Calculated H probability	Test for homogeneity: Homogeneous at 5% level?
R	N	L	4	4	-15.07	-15.07	52.96	-46.32	439.40	0.14	-0.13	NS	1.00	Yes
R	N	LR	4	2	-28.14	-14.07	69.42	-49.19	1,535.50	0.20	-0.17	NS	0.87	Yes
R	N	R	4	2	0.01	0.01	100.01	-49.01	2,470.19	0.00	0.00	NS	1.00	Yes
R	S	XL	3	2	-12.07	-12.07	175.87	-98.26	4,331.89	0.07	-0.06	NS	0.96	Yes
R	S	XL	4	4	163.58	163.58	295.30	-70.67	2,268.98	0.55	0.87	NS	0.86	Yes
R	S	XLR	4	2	29.41	14.70	37.44	-15.95	631.00	0.13	0.15	NS	0.90	Yes
R	U	L	3	34	2.03	2.03	49.49	-60.57	164.00	0.04	0.04	NS	1.00	Yes
R	U	L	4	41	-23.73	-23.73	16.79	-35.19	38.08	0.75	-0.66	NS	1.00	Yes
R	U	LR	3	24	-11.66	-5.83	40.56	-57.05	137.67	0.23	-0.22	NS	1.00	Yes
R	U	LR	4	30	-2.49	-1.25	23.43	-30.99	75.04	0.05	-0.05	NS	1.00	Yes
R	U	R	3	11	5.84	5.84	90.26	-80.11	463.06	0.06	0.07	NS	1.00	Yes
R	U	R	4	43	-5.70	-5.70	23.30	-34.49	67.48	0.14	-0.14	NS	1.00	Yes
R	U	XL	4	2	110.86	110.86	390.43	-94.40	7,845.84	0.28	0.40	NS	0.73	Yes
U	N	L	3	6	2.78	2.78	71.21	-53.59	532.89	0.02	0.02	NS	1.00	Yes
U	N	L	4	50	-16.09	-16.09	15.63	-30.09	36.55	0.53	-0.48	NS	1.00	Yes
U	S	L	3	3	-0.44	-0.44	162.58	-95.94	2,344.12	0.00	0.00	NS	0.99	Yes
U	S	L	4	116	-2.23	-2.23	5.62	-9.66	13.00	0.11	-0.11	NS	1.00	Yes
U	S	LR	3	5	-3.01	-1.51	75.60	-57.24	636.13	0.02	-0.02	NS	1.00	Yes
U	S	LR	4	33	-50.96	-25.48	3.37	-14.93	-0.69	3.01	-2.06	SIG	1.00	Yes
U	S	R	3	2	-10.24	-10.24	89.76	-49.11	2,211.92	0.06	-0.05	NS	0.97	Yes
U	S	R	4	35	62.30	62.30	21.67	-6.69	84.83	1.12	1.41	NS	0.96	Yes
U	S	XL	3	1	0.00	0.00	282.84	-99.61	25,462.64	0.00	0.00	n/a		n/a
U	S	XL	4	5	29.49	29.49	80.25	-47.48	584.96	0.20	0.23	NS	0.99	Yes
U	U	L	3	10	5.30	5.30	94.18	-81.76	507.82	0.06	0.06	NS	1.00	Yes
U	U	L	4	16	-68.60	-68.60	8.60	-44.63	-4.08	3.99	-2.12	SIG	1.00	Yes
U	U	LR	4	2	-27.38	-13.69	70.16	-49.18	1,552.27	0.20	-0.17	NS	0.86	Yes
U	U	R	4	1	-38.98	-38.98	172.58	-99.76	15,497.21	0.23	-0.17	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-9. Yoked Comparison Evaluation for Project-Related Intersection Accidents—Auto Matched.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	109.08	54.54	104.11	-35.16	686.24	0.52	0.74	NS	0.99	Yes
R	N	LR	4	1	283.33	141.67	393.27	-46.56	10,643.71	0.36	0.65	n/a		n/a
R	N	R	4	1	-38.64	-19.32	61.82	-49.41	1,542.16	0.31	-0.24	n/a		n/a
R	S	XL	3	2	350.52	350.52	705.43	-79.07	9,595.30	0.50	0.96	NS	0.94	Yes
R	S	XL	4	4	7.61	7.61	82.50	-76.06	383.60	0.09	0.10	NS	0.91	Yes
R	S	XLR	4	1	-9.38	-2.34	36.95	-24.07	528.79	0.06	-0.06	n/a		n/a
R	U	L	3	34	123.68	123.68	83.83	7.30	366.29	1.48	2.15	SIG	1.00	Yes
R	U	L	4	22	3.70	2.09	20.20	-26.68	58.70	0.10	0.11	NS	0.90	Yes
R	U	LR	3	12	120.86	96.69	118.15	-32.36	575.28	0.82	1.18	NS	0.98	Yes
R	U	LR	4	15	66.35	33.17	30.01	-9.00	118.72	1.11	1.41	NS	1.00	Yes
R	U	R	3	11	7.02	7.02	75.92	-73.36	329.86	0.09	0.10	NS	1.00	Yes
R	U	R	4	28	27.10	17.64	30.75	-25.16	106.30	0.57	0.65	NS	1.00	Yes
R	U	XL	4	2	89.07	89.07	190.91	-73.87	1,268.04	0.47	0.63	NS	0.22	Yes
U	N	L	3	4	33.86	22.57	89.80	-54.25	574.73	0.25	0.29	NS	0.81	Yes
U	N	L	4	24	92.22	48.12	23.77	10.85	107.42	2.02	2.76	SIG	0.41	Yes
U	S	L	3	3	72.16	72.16	220.51	-86.02	2,019.53	0.33	0.42	NS	0.64	Yes
U	S	L	4	37	-0.32	-0.10	3.88	-6.86	8.50	0.03	-0.03	NS	0.05	Yes
U	S	LR	3	2	21.81	14.54	107.34	-60.58	1,016.60	0.14	0.15	NS	0.64	Yes
U	S	LR	4	9	-44.51	-11.45	2.30	-15.31	-6.15	4.98	-3.66	SIG	0.28	Yes
U	S	R	3	1	237.50	118.75	181.91	-29.60	1,345.85	0.65	1.13	n/a		n/a
U	S	R	4	12	2.36	1.23	8.42	-12.97	20.58	0.15	0.15	NS	0.02	No
U	S	XL	3	1	100.00	100.00	406.20	-96.27	10,611.75	0.25	0.34	n/a		n/a
U	S	XL	4	3	-31.92	-19.15	21.37	-45.35	53.87	0.90	-0.73	NS	0.78	Yes
U	U	L	3	10	202.64	202.64	213.44	-24.04	1,105.75	0.95	1.57	NS	0.90	Yes
U	U	L	4	8	-38.17	-19.09	12.07	-35.62	16.45	1.58	-1.23	NS	0.56	Yes
U	U	LR	4	1	66.67	33.33	115.87	-44.54	1,221.71	0.29	0.37	n/a		n/a
U	U	R	4	1	500.00	500.00	1,509.97	-95.68	83,140.41	0.33	0.71	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-10. Yoked Comparison Evaluation Results for Project-Related Fatal and Injury Intersection Accidents—Auto Matched.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	326.58	163.29	262.40	-30.87	2,327.76	0.62	1.18	NS	0.39	Yes
R	N	LR	4	1	225.00	112.50	338.02	-47.24	9,532.79	0.33	0.57	n/a		n/a
R	N	R	4	1	-11.76	-5.88	89.61	-49.18	2,313.44	0.07	-0.06	n/a		n/a
R	S	XL	3	2	311.85	311.85	700.77	-85.33	11,464.18	0.45	0.83	NS	0.84	Yes
R	S	XL	4	4	42.50	42.50	132.34	-76.91	779.64	0.32	0.38	NS	0.94	Yes
R	S	XLR	4	1	-35.00	-8.75	27.08	-24.38	400.92	0.32	-0.26	n/a		n/a
R	U	L	3	34	117.81	117.81	87.87	-1.22	380.28	1.34	1.93	NS	1.00	Yes
R	U	L	4	23	72.85	40.87	38.93	-11.95	156.90	1.05	1.36	NS	0.98	Yes
R	U	LR	3	12	86.17	68.94	103.92	-42.06	504.69	0.66	0.89	NS	1.00	Yes
R	U	LR	4	15	58.74	29.37	39.34	-19.96	159.68	0.75	0.93	NS	1.00	Yes
R	U	R	3	11	-0.17	-0.17	75.13	-77.17	336.41	0.00	0.00	NS	1.00	Yes
R	U	R	4	28	34.30	22.34	38.64	-28.33	142.81	0.58	0.67	NS	1.00	Yes
R	U	XL	4	2	137.27	137.27	332.77	-84.81	3,607.34	0.41	0.62	NS	0.89	Yes
U	N	L	3	4	-15.45	-10.30	62.03	-60.14	420.50	0.17	-0.15	NS	0.86	Yes
U	N	L	4	25	107.23	55.85	34.87	5.22	151.21	1.60	2.26	SIG	0.95	Yes
U	S	L	3	3	2.14	2.14	143.17	-93.45	1,493.64	0.01	0.02	NS	0.64	Yes
U	S	L	4	36	15.98	5.09	7.60	-7.17	23.44	0.67	0.72	NS	0.67	Yes
U	S	LR	3	2	19.14	12.76	106.15	-60.88	1,023.81	0.12	0.13	NS	0.55	Yes
U	S	LR	4	9	-44.71	-11.50	4.42	-17.98	0.42	2.60	-1.91	NS	0.40	Yes
U	S	R	3	1	450.00	225.00	589.23	-45.87	18,280.96	0.38	0.80	n/a		n/a
U	S	R	4	14	8.34	4.17	12.30	-15.28	34.52	0.34	0.35	NS	0.81	Yes
U	S	XL	3	1	100.00	100.00	412.31	-96.48	11,272.58	0.24	0.34	n/a		n/a
U	S	XL	4	3	60.80	36.48	77.90	-40.18	409.57	0.47	0.59	NS	0.45	Yes
U	U	L	3	10	149.46	149.46	185.68	-42.00	972.97	0.80	1.23	NS	0.99	Yes
U	U	L	4	8	-15.40	-7.70	21.44	-34.34	64.22	0.36	-0.33	NS	0.92	Yes
U	U	LR	4	1	300.00	150.00	458.26	-47.76	17,790.77	0.33	0.61	n/a		n/a
U	U	R	4	1	100.00	100.00	529.15	-98.88	35,638.72	0.19	0.26	n/a		n/a

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

All of the unsignalized intersections evaluated in the study had two-way stop control; i.e., there were stop signs on the minor-road approach(es) and no control on the major road approaches. A newly signalized intersection is one that was unsignalized before the improvement and signalized after the improvement; i.e., the intersection was signalized in conjunction with the turn lane improvement.

Project type: The third column identifies the type of improvement project that was evaluated. the codes used in this column are:

L	=	Added left-turn lane(s)
LR	=	Added left- and right-turn lanes
R	=	Added right-turn lane(s)
XL	=	Extended the length of existing left-turn lane(s)
XLR	=	Extended the length of existing left- and right-turn lanes

Number of intersection legs: The fourth column identifies the number of intersection legs for the intersections evaluated. Only three- and four-leg intersections were considered in the evaluation.

Number of improved sites: The fifth column presents the number of improved or treatment sites included in the evaluation in question. In tables C-1 through C-4, C-9, and C-10, this represents the number of intersections evaluated. In tables C-5 through C-8, this represents the number of intersection approaches evaluated. The number of improved sites includes only those that were actually evaluated. Some sites were excluded because they were found to be outliers (see discussion in section 6 of this report). In the CG and EB analyses, some sites were excluded because no satisfactory regression model was available. For any given type of intersection and project type, the total number of sites available before such exclusions can be determined from tables in section 4 of this report.

Percent change in accident frequency: The sixth through tenth columns present the mean percent change in accident frequency determined in the YC analysis, the mean percent change in accident frequency per turn lane installed, the standard error, and upper and lower confidence limits of the mean change in accident frequency per turn lane installed. A negative value of percent change in accident frequency represents a reduction in accidents, while a positive value represents an increase in accidents. The values in these five columns correspond to E_{mean} for projects as a whole and E_{mean}, $E_{mean(se)}$, $E_{mean(upper)}$, and $E_{mean(lower)}$ per turn lane added, as determined in Equations (12), (19), (20), and (21).

The value in the seventh column is the value in the sixth column divided by the mean number of turn lanes added in the projects evaluated. For example, the analysis in table C-1 addresses total intersection accidents. However, in some projects, turn lanes were added on one approach; in some projects, turn lanes were added on two approaches; and in some projects at signalized intersections, left-turn lanes were added on all four approaches. The value in this seventh column of the table expresses the effectiveness of the project on a per-added-lane basis to facilitate comparisons across project types. It represents the best overall measure of treatment effectiveness for the projects evaluated.

In results tables for analyses conducted for individual intersection approaches, the project effectiveness estimate, E_{mean}, and the effectiveness estimate on a per-added-lane basis are usually the same because, in most cases, only one turn lane was added to each approach. However, for projects involving the addition of both left- and right-turn lanes, the two effectiveness measures may differ.

The standard error and confidence limits presented in the eighth through tenth columns of the table are measures of the precision of the mean accident frequency per turn lane added presented in the seventh column. The confidence interval for the analysis results, shown by the limits in the ninth and tenth columns of the tables, is not symmetrical above and below the mean because, as shown in section 5 of this report, the evaluation was performed on a logarithmic scale. The standard error shown in the eighth column of the tables is the best single estimate of the precision of the estimated mean project effectiveness per turn lane installed.

Treatment effect: The eleventh through thirteenth columns of the tables provide an assessment of the statistical significance of the treatment effect determined above. The ratio in the eleventh column is the mean percent change in accident frequency per turn lane installed divided by its standard error. While this ratio was not used directly in the YC and CG approaches, a similar ratio was used to determine statistical significance for the EB approach.

The twelfth and thirteen columns present the calculated Z-score for the treatment effect and the significance of that Z-score at the 5 percent significance level (i.e., the 95-percent confidence level). The codes for significance of the results are:

SIG	=	Treatment effect is statistically significant
NS	=	Treatment effect is not statistically significant
n/a	=	Significance of treatment effect cannot be determined (typically because only one site is available for evaluation)

Only those effectiveness measures found to be statistically significant should be relied upon.

Test for homogeneity: The fourteenth and fifteenth columns present the test for homogeneity discussed for the YC approach in section 5 of this report. The fourteenth column gives the value of P_H determined as shown in table 23. The fifteenth column shows whether the treatment group is homogenous at the 5 percent significance level (i.e, 95-percent confidence level). The homogeneity result was noted, but no results were excluded based on this criterion.

Specific Evaluation Results

Table C-1 presents the results of the evaluation of treatment effectiveness for accidents of all severity levels and for a target area including the entire intersection (i.e., including all at-intersection and intersection-related accidents). Analyses of this type are referred to in this report as addressing *total intersection accidents*. Table C-2 presents comparable data to table C-1 for a dependent variable that includes only fatal and nonfatal injury accidents (i.e., property-damage-only accidents were excluded). Analyses of this type are referred to in this report as addressing *fatal and injury intersection accidents*.

Table C-3 is analogous to table C-1 in that it addresses all accident severity levels and includes the entire intersection as the target area, but it includes only project-related accidents. Project-related accidents have been defined in section 4 of this report as those accidents that involve a turning maneuver that was related to the added or extended turn lane(s) being evaluated. Analyses of this type are referred to in this report as addressing *total project-related intersection accidents*. Table C-4 is similar to table C-3, but includes only fatal and nonfatal injury accidents. Analyses of this type are referred to in this report as addressing *fatal and injury project-related intersection accidents*.

Tables C-5 through C-8 are analogous to tables C-1 through C-4 except that they present results for evaluations in which each observation represents a treated intersection approach rather than a treated intersection as a whole. Only those approaches at the treated intersections on which a turn lane was added or extended were included in the analyses. The comparison site for each treated approach was comparable to the unimproved comparison site matched to that particular treatment site. Table C-5 presents the results for *total accidents for individual intersection approaches*. Table C-6 presents the results for *fatal and injury accidents for individual intersection approaches*. The results for *project-related accidents for individual intersection approaches* are presented in table C-7 and the results for *project-related fatal and injury accidents for individual intersection approaches* are presented in table C-8.

The results of the auto-matching approach referred to above are presented in table C-9 and C-10.

Comparison Group Evaluations

The results of the CG evaluation performed in this study are presented in tables C-11 through C-16. These tables include results for three of the four specific dependent variables that were included in the YC evaluation and for the same two different target areas included in the YC evaluation. No CG analyses were performed for project-related fatal and injury accidents because the available sample size of such accidents was too small to develop satisfactory regression relationships for use in the traffic volume adjustments.

Table C-11. Comparison Group Evaluation Results for Total Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Treatment effect: Ratio[a]	Calculated Z	Significant at 5% level?	Test for homogeneity: Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	-12.66	-6.33	9.22	-21.13	16.07	0.69	-0.64	NS	0.55	Yes
R	N	LR	4	1	-64.48	-32.24	9.19	-43.56	-1.05	3.51	-2.00	n/a		n/a
R	N	R	4	1	18.80	9.40	14.97	-13.76	47.35	0.63	0.68	n/a		n/a
R	U	L	3	35	-53.53	-53.53	5.63	-63.34	-41.08	9.52	-6.33	SIG	0.35	Yes
R	U	L	4	25	-60.61	-33.67	2.54	-38.14	-28.07	13.23	-8.01	SIG	0.00	No
R	U	LR	3	12	-37.67	-30.13	12.57	-49.57	1.72	2.40	-1.88	NS	0.20	Yes
R	U	LR	4	15	-25.20	-12.60	5.28	-21.64	-0.68	2.39	-2.06	SIG	0.31	Yes
R	U	R	3	12	4.98	4.98	30.96	-41.11	87.14	0.16	0.16	NS	1.00	Yes
R	U	R	4	29	-35.07	-22.60	5.16	-31.58	-11.17	4.38	-3.51	SIG	0.86	Yes
R	U	XL	4	2	-20.58	-20.58	27.89	-60.09	58.07	0.74	-0.66	NS	0.19	Yes
U	N	L	3	4	29.35	19.57	13.88	-3.77	51.55	1.41	1.60	NS	0.01	No
U	N	L	4	28	-46.43	-24.08	2.01	-27.75	-19.85	11.98	-8.63	SIG	0.00	No
U	S	L	3	3	21.24	21.24	50.03	-46.00	172.22	0.42	0.47	NS	0.04	No
U	S	L	4	37	-18.28	-5.78	1.05	-7.76	-3.64	5.50	-4.96	SIG	0.00	No
U	S	LR	3	2	5.44	3.63	15.27	-20.75	40.93	0.24	0.24	NS	0.45	Yes
U	S	LR	4	10	-26.59	-6.82	1.30	-9.20	-4.08	5.24	-4.47	SIG	0.11	Yes
U	S	R	3	1	-26.37	-13.19	15.84	-34.16	35.54	0.83	-0.71	n/a		n/a
U	S	R	4	17	-8.82	-4.05	2.46	-8.61	1.07	1.64	-1.57	NS	0.00	No
U	S	XL	3	1	84.98	84.98	82.12	-22.51	341.59	1.03	1.39	n/a		n/a
U	S	XL	4	3	42.34	25.40	11.20	6.04	50.44	2.27	2.69	SIG	0.60	Yes
U	U	L	3	10	-34.95	-34.95	13.11	-56.18	-3.43	2.67	-2.13	SIG	0.12	Yes
U	U	L	4	9	-53.42	-26.71	2.95	-31.83	-20.15	9.06	-6.04	SIG	0.20	Yes
U	U	LR	4	1	-59.39	-29.69	12.06	-43.66	15.03	2.46	-1.52	n/a		n/a
U	U	R	3	1	129.38	129.38	403.35	-92.69	7,100.71	0.32	0.47	n/a		n/a
U	U	R	4	3	-35.85	-21.51	23.30	-48.25	66.11	0.92	-0.73	NS	0.46	Yes

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-12. Comparison Group Evaluation Results for Fatal and Injury Intersection Accidents.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	-57.47	-28.74	6.30	-38.10	-12.01	4.56	-2.89	SIG	0.48	Yes
R	N	LR	4	1	-68.83	-34.42	9.97	-45.55	4.61	3.45	-1.82	n/a		n/a
R	N	R	4	1	-40.11	-20.05	10.97	-35.39	11.39	1.83	-1.40	n/a		n/a
R	U	L	3	35	-54.80	-54.80	8.30	-68.46	-35.23	6.60	-4.33	SIG	0.81	Yes
R	U	L	4	25	-73.90	-41.06	2.40	-45.08	-35.49	17.07	-8.10	SIG	0.41	Yes
R	U	LR	3	12	-32.38	-25.90	17.21	-51.00	20.92	1.51	-1.23	NS	0.80	Yes
R	U	LR	4	15	-44.67	-22.34	6.07	-32.01	-7.46	3.68	-2.70	SIG	0.77	Yes
R	U	R	3	12	5.33	5.33	40.07	-50.03	122.02	0.13	0.14	NS	0.99	Yes
R	U	R	4	29	-37.21	-23.98	6.59	-35.05	-8.76	3.64	-2.86	SIG	0.97	Yes
R	U	XL	4	2	24.09	24.09	64.90	-55.49	245.89	0.37	0.41	NS	0.05	Yes
U	N	L	3	4	32.94	21.96	24.56	-15.18	85.91	0.89	1.03	NS	0.07	Yes
U	N	L	4	28	-48.65	-25.23	3.12	-30.69	-18.35	8.08	-5.69	SIG	0.00	No
U	S	L	3	3	2.67	2.67	71.14	-73.60	299.23	0.04	0.04	NS	0.31	Yes
U	S	L	4	39	-17.95	-5.79	1.73	-8.97	-2.17	3.35	-3.03	SIG	0.00	No
U	S	LR	3	2	-0.94	-0.62	21.64	-31.92	58.84	0.03	-0.03	NS	0.83	Yes
U	S	LR	4	10	-45.93	-11.78	1.80	-14.89	-7.76	6.54	-4.73	SIG	0.54	Yes
U	S	R	3	1	-61.42	-30.71	17.17	-46.63	60.41	1.79	-1.07	n/a		n/a
U	S	R	4	17	-8.61	-3.85	3.89	-10.81	4.54	0.99	-0.95	NS	0.01	No
U	S	XL	3	1	80.37	80.37	120.37	-51.23	567.14	0.67	0.88	n/a		n/a
U	S	XL	4	3	8.75	5.25	15.70	-19.29	44.56	0.33	0.35	NS	0.36	Yes
U	U	L	3	10	-31.93	-31.93	20.81	-62.62	23.95	1.53	-1.26	NS	0.65	Yes
U	U	L	4	9	-58.81	-29.40	4.04	-35.98	-19.74	7.28	-4.52	SIG	0.39	Yes
U	U	LR	4	1	-73.31	-36.66	15.56	-48.64	81.13	2.36	-1.13	n/a		n/a
U	U	R	3	1	135.84	135.84	425.90	-93.15	8,024.99	0.32	0.48	n/a		n/a
U	U	R	4	3	-1.49	-0.89	47.52	-47.77	225.77	0.02	-0.02	NS	0.82	Yes

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-13. Comparison Group Evaluation Results for Project-Related Intersection Accidents.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	2	119.39	59.70	108.53	-34.22	712.68	0.55	0.79	NS	0.95	Yes
R	N	LR	4	1	105.35	52.67	206.39	-48.00	5,228.66	0.26	0.36	n/a		n/a
R	N	R	4	1	11.81	5.91	112.35	-48.91	2,821.20	0.05	0.06	n/a		n/a
R	U	L	3	35	-62.33	-62.33	14.53	-82.32	-19.76	4.29	-2.53	SIG	1.00	Yes
R	U	L	4	25	-38.23	-21.24	9.33	-35.41	2.90	2.28	-1.77	NS	0.99	Yes
R	U	LR	3	12	-50.64	-40.51	27.28	-69.80	72.91	1.49	-1.02	NS	1.00	Yes
R	U	LR	4	14	6.66	3.33	20.51	-24.90	63.32	0.16	0.17	NS	0.94	Yes
R	U	R	3	12	-46.82	-46.82	38.63	-87.19	120.84	1.21	-0.87	NS	1.00	Yes
R	U	R	4	29	0.88	0.57	20.49	-29.39	56.15	0.03	0.03	NS	1.00	Yes
R	U	XL	4	2	-30.26	-30.26	66.53	-89.25	352.44	0.45	-0.38	NS	0.39	Yes
R	N	L	3	4	119.85	79.90	149.53	-46.82	1,015.85	0.53	0.77	NS	0.99	Yes
U	N	L	4	27	38.91	20.21	15.26	-4.27	57.26	1.32	1.55	NS	0.49	Yes
U	S	L	3	3	44.59	44.59	185.80	-88.35	1,694.62	0.24	0.29	NS	0.82	Yes
U	S	L	4	39	-7.22	-2.33	3.16	-7.92	4.56	0.74	-0.71	NS	0.20	Yes
U	S	LR	3	2	249.52	166.35	356.90	-55.09	4,623.02	0.47	0.82	NS	0.51	Yes
U	S	LR	4	9	-40.18	-10.33	2.19	-14.07	-5.39	4.73	-3.62	SIG	0.09	Yes
U	S	R	3	1	-8.81	-4.40	55.35	-45.78	442.35	0.08	-0.08	n/a		n/a
U	S	R	4	17	5.88	2.78	8.38	-11.22	22.21	0.33	0.34	NS	0.00	No
U	S	XL	3	1	683.87	683.87	1,960.49	-94.17	105,378.46	0.35	0.82	n/a		n/a
U	S	XL	4	3	25.14	15.08	38.48	-32.51	145.03	0.39	0.44	NS	0.88	Yes
U	U	L	3	10	59.28	59.28	113.90	-60.78	546.90	0.52	0.65	NS	1.00	Yes
U	U	L	4	9	-60.42	-30.21	7.58	-40.66	-8.07	3.99	-2.42	SIG	0.78	Yes
U	U	LR	4	1	-5.67	-2.83	61.43	-46.33	555.81	0.05	-0.04	n/a		n/a
U	U	R	3	1	48.58	48.58	401.88	-99.26	29,705.68	0.12	0.15	n/a		n/a
U	U	R	4	3	36.47	21.88	91.63	-50.87	674.17	0.24	0.28	NS	0.81	Yes

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-14. Comparison Group Evaluation Results for Total Accidents on Individual Intersection Approaches.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	4	-44.09	-44.09	7.26	-33.19	-3.51	3.04	-2.24	SIG	0.60	Yes
R	N	LR	4	2	-68.84	-34.42	8.75	-44.82	-3.15	3.93	-2.08	SIG	0.90	Yes
R	N	R	4	2	-29.49	-29.49	10.30	-30.11	12.49	1.43	-1.20	NS	0.17	Yes
R	U	L	3	70	-51.91	-51.91	7.31	-64.29	-35.23	7.10	-4.82	SIG	0.99	Yes
R	U	L	4	50	-61.03	-61.03	2.74	-38.66	-27.81	12.38	-7.45	SIG	0.17	Yes
R	U	LR	3	24	-29.08	-14.54	16.75	-48.20	21.21	1.39	-1.16	NS	0.64	Yes
R	U	LR	4	30	-27.90	-13.95	5.70	-23.55	-0.85	2.45	-2.07	SIG	0.99	Yes
R	U	R	3	24	5.74	5.74	37.73	-47.46	112.78	0.15	0.16	NS	1.00	Yes
R	U	R	4	58	-31.55	-31.55	5.53	-29.95	-8.04	3.67	-3.02	SIG	1.00	Yes
R	U	XL	4	4	6.54	6.54	42.74	-51.47	133.90	0.15	0.16	NS	0.65	Yes
U	N	L	3	8	30.27	30.27	17.86	-8.64	63.30	1.13	1.29	NS	0.22	Yes
U	N	L	4	56	-45.73	-45.73	2.35	-27.96	-18.71	10.09	-7.32	SIG	0.02	No
U	S	L	3	9	34.12	34.12	58.51	-42.97	215.40	0.58	0.67	NS	0.57	Yes
U	S	L	4	147	-27.96	-27.96	1.03	-10.89	-6.85	8.70	-7.35	SIG	0.00	No
U	S	LR	3	6	-10.13	-5.06	14.65	-29.57	30.09	0.46	-0.44	NS	0.62	Yes
U	S	LR	4	39	-34.45	-17.23	1.24	-11.10	-6.23	7.14	-5.74	SIG	0.90	Yes
U	S	R	3	3	-23.41	-23.41	19.93	-36.19	56.22	0.59	-0.51	NS	0.25	Yes
U	S	R	4	66	-6.98	-6.98	2.59	-8.09	2.10	1.27	-1.22	NS	0.01	No
U	S	XL	3	1	-57.24	-57.24	66.62	-97.98	806.21	0.86	-0.55	n/a		n/a
U	S	XL	4	12	45.26	45.26	12.11	6.38	54.43	2.24	2.69	SIG	0.08	Yes
U	U	L	3	20	-49.26	-49.26	11.15	-67.02	-21.93	4.42	-3.09	SIG	0.83	Yes
U	U	L	4	18	-54.42	-54.42	3.11	-32.56	-20.21	8.74	-5.75	SIG	0.39	Yes
U	U	LR	4	2	-56.21	-28.11	15.45	-44.51	37.27	1.82	-1.17	NS	0.21	Yes
U	U	R	3	2	-2.67	-2.67	141.65	-94.39	1,587.02	0.02	-0.02	NS	1.00	Yes
U	U	R	4	6	-20.14	-20.14	27.03	-44.14	84.77	0.45	-0.40	NS	0.90	Yes

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-15. Comparison Group Evaluation Results for Fatal and Injury Accidents on Individual Intersection Approaches.

					Percent change in accident frequency					Treatment effect			Test for homogeneity	
Area type	Traffic control	Project type	No. of legs	No. of improved sites	Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Ratio[a]	Calculated Z	Significant at 5% level?	Calculated H probability	Homogeneous at 5% level?
R	N	L	4	4	-76.35	-76.35	4.15	-44.06	-26.46	9.19	-4.11	SIG	0.84	Yes
R	N	LR	4	2	-69.73	-34.86	9.97	-45.84	5.02	3.50	-1.81	NS	0.43	Yes
R	N	R	4	2	-65.60	-65.60	7.55	-42.73	-9.32	4.34	-2.43	SIG	0.09	Yes
R	U	L	3	70	-43.57	-43.57	10.90	-61.35	-17.61	4.00	-2.96	SIG	1.00	Yes
R	U	L	4	50	-70.83	-70.83	2.73	-43.91	-33.01	14.41	-7.31	SIG	0.99	Yes
R	U	LR	3	24	-15.48	-7.74	23.51	-45.79	53.66	0.53	-0.48	NS	0.91	Yes
R	U	LR	4	30	-35.96	-17.98	7.57	-29.86	0.90	2.37	-1.88	NS	0.99	Yes
R	U	R	3	24	-20.87	-20.87	30.78	-63.09	69.62	0.68	-0.60	NS	1.00	Yes
R	U	R	4	58	-36.95	-36.95	6.33	-34.50	-9.31	3.76	-2.96	SIG	1.00	Yes
R	U	XL	4	4	100.52	100.52	121.69	-38.96	558.79	0.83	1.15	NS	0.75	Yes
U	N	L	3	8	-11.37	-11.37	21.91	-38.10	55.55	0.35	-0.33	NS	0.50	Yes
U	N	L	4	55	-46.93	-46.93	3.67	-30.68	-16.12	6.63	-4.75	SIG	0.92	Yes
U	S	L	3	9	18.52	18.52	73.44	-64.81	299.22	0.25	0.27	NS	0.95	Yes
U	S	L	4	154	-22.58	-22.58	1.71	-10.45	-3.71	4.26	-3.74	SIG	0.94	Yes
U	S	LR	3	6	-5.03	-2.51	23.09	-35.68	62.72	0.15	-0.14	NS	0.94	Yes
U	S	LR	4	39	-49.70	-24.85	1.83	-15.88	-8.62	6.98	-4.85	SIG	0.97	Yes
U	S	R	3	3	-31.42	-31.42	30.06	-43.85	141.11	0.52	-0.43	NS	0.68	Yes
U	S	R	4	70	1.18	1.18	4.61	-7.68	10.52	0.12	0.12	NS	0.28	Yes
U	S	XL	3	2	5.75	5.75	124.45	-89.47	961.68	0.05	0.05	NS	0.99	Yes
U	S	XL	4	12	0.93	0.93	15.15	-22.91	38.89	0.04	0.04	NS	0.99	Yes
U	U	L	3	20	-37.99	-37.99	19.50	-66.53	14.86	1.95	-1.52	NS	0.96	Yes
U	U	L	4	18	-55.38	-55.38	4.78	-35.34	-16.06	5.80	-3.77	SIG	0.72	Yes
U	U	LR	4	2	-41.19	-20.60	31.78	-46.46	194.57	0.65	-0.49	NS	0.41	Yes
U	U	R	3	2	-19.16	-19.16	123.35	-95.94	1,508.78	0.16	-0.14	NS	1.00	Yes
U	U	R	4	6	46.78	46.78	60.66	-37.17	279.74	0.46	0.56	NS	0.99	Yes

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-16. Comparison Group Evaluation Results for Project-Related Accidents on Individual Intersection Approaches.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Mean per added lane	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	Treatment effect: Ratio[a]	Calculated Z	Significant at 5% level?	Test for homogeneity: Calculated H probability	Homogeneous at 5% level?
R	N	L	4	4	6.61	6.61	45.97	-40.17	238.93	0.07	0.07	NS	0.96	Yes
R	N	LR	4	2	83.23	41.61	130.98	-44.44	1,459.75	0.32	0.42	NS	1.00	Yes
R	N	R	4	2	-3.71	-3.71	68.71	-47.06	739.57	0.03	-0.03	NS	1.00	Yes
R	U	L	3	70	-64.29	-64.29	10.51	-79.95	-36.41	6.11	-3.50	SIG	1.00	Yes
R	U	L	4	50	-23.25	-23.25	10.03	-28.67	12.07	1.29	-1.12	NS	1.00	Yes
R	U	LR	3	24	-50.45	-25.23	20.80	-65.83	30.86	1.94	-1.34	NS	1.00	Yes
R	U	LR	4	30	11.61	5.80	16.19	-18.40	48.55	0.36	0.38	NS	1.00	Yes
R	U	R	3	24	-47.37	-47.37	30.26	-82.94	62.40	1.57	-1.12	NS	1.00	Yes
R	U	R	4	58	20.39	20.39	19.36	-16.87	62.08	0.68	0.74	NS	1.00	Yes
R	U	XL	4	4	-25.90	-25.90	62.07	-85.65	282.72	0.42	-0.36	NS	0.84	Yes
U	N	L	3	8	84.44	84.44	94.58	-39.44	488.65	0.60	0.80	NS	1.00	Yes
U	N	L	4	56	44.56	44.56	14.47	-0.51	57.58	1.60	1.91	NS	1.00	Yes
U	S	L	3	9	-0.47	-0.47	80.28	-79.52	383.64	0.01	-0.01	NS	1.00	Yes
U	S	L	4	155	7.92	7.92	3.46	-3.60	10.04	0.74	0.77	NS	1.00	Yes
U	S	LR	3	6	132.10	66.05	147.45	-42.76	934.97	0.60	0.88	NS	0.99	Yes
U	S	LR	4	38	-39.11	-19.56	2.28	-13.92	-4.88	4.41	-3.41	SIG	0.99	Yes
U	S	R	3	3	-21.65	-21.65	44.34	-45.74	310.13	0.24	-0.22	NS	1.00	Yes
U	S	R	4	72	-73.15	73.15	12.06	14.32	62.26	2.89	3.76	SIG	0.44	Yes
U	S	XL	3	3	156.21	156.21	385.19	-86.55	4,778.84	0.41	0.63	NS	1.00	Yes
U	S	XL	4	12	36.34	36.34	38.97	-27.85	148.12	0.56	0.65	NS	0.99	Yes
U	U	L	3	20	54.97	54.97	82.88	-45.67	342.06	0.66	0.82	NS	1.00	Yes
U	U	L	4	18	-60.46	-60.46	6.92	-40.04	-10.76	4.37	-2.65	SIG	0.99	Yes
U	U	LR	4	2	31.64	15.82	72.94	-42.50	527.63	0.22	0.25	NS	0.77	Yes
U	U	R	3	2	46.13	46.13	335.89	-98.39	13,121.00	0.14	0.17	NS	1.00	Yes
U	U	R	4	6	91.07	91.07	98.90	-38.87	561.85	0.55	0.75	NS	1.00	Yes

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

The CG approach to before-after evaluation has been described conceptually in section 5 of this report. The procedures presented in that section have been used to derive the analysis results in tables C-11 through C-16. These analyses involved the matching of individual treatment sites to an entire group of similar unimproved comparison sites.

Description of Results Tables

The results tables for the CG approach are identical in format to the tables for the YC approach.

Specific Evaluation Results

The results of the CG evaluation are presented in the following tables:

- Table C-11—total intersection accidents.
- Table C-12—fatal and injury intersection accidents.
- Table C-13—project-related intersection accidents.
- Table C-14—total accidents for individual intersection approaches.
- Table C-15—fatal and injury accidents for individual intersection approaches.
- Table C-16—project-related accidents for individual intersection approaches.

Empirical Bayes Evaluations

The results of the EB evaluation are presented in tables C-17 through C-22. The tables include results for the same three dependent variables and the same two target areas that were included in the CG evaluation. No EB analyses were performed for project-related fatal and injury accidents because the available sample size of such accidents was too small to develop satisfactory regression relationships to represent expected accident frequencies in the EB analysis.

The EB approach to before-after evaluation has been described conceptually in section 5 of this report. The procedures presented in that section have been used to derive the analysis results in tables C-17 through C-22. These analyses involved weighing of observed and expected accident frequencies to obtain the best estimate of accident frequency for the before study period, which is then compared to the observed accident frequency for the after period.

Table C-17. Empirical Bayes Evaluation Results for Total Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency			Ratio[a]	Significant?
					Mean	Mean per added lane	Standard error		
R	N	L	4	2	6.59	3.30	9.79	0.3	NS
R	N	LR	4	1	−55.96	−27.98	9.56	2.9	n/a
R	N	R	4	1	46.76	23.38	16.22	1.4	n/a
R	U	L	3	36	−43.67	−43.67	5.47	8.0	SIG
R	U	L	4	25	−49.61	−27.56	2.63	10.5	SIG
R	U	LR	3	12	−29.42	−23.54	10.96	2.1	SIG
R	U	LR	4	15	2.06	1.03	5.35	0.2	NS
R	U	R	3	11	20.54	20.54	26.28	0.8	NS
R	U	R	4	28	−21.97	−13.98	5.17	2.7	SIG
R	U	XL	4	2	−22.00	−22.00	22.51	1.0	NS
U	N	L	3	3	46.57	27.94	13.78	2.0	SIG
U	N	L	4	25	−19.96	−10.40	2.77	3.8	SIG
U	S	L	4	39	−29.53	−9.52	0.83	11.4	SIG
U	S	LR	4	10	−27.80	−7.13	1.21	5.9	SIG
U	S	R	4	18	−9.01	−4.05	1.96	2.1	SIG
U	S	XL	4	3	49.45	29.67	10.62	2.8	SIG
U	U	L	3	8	−33.15	−33.15	12.11	2.7	SIG
U	U	L	4	9	−0.33	−0.17	4.97	0.0	NS
U	U	LR	4	1	−57.63	−28.82	11.01	2.6	n/a
U	U	R	3	1	7.05	7.05	111.08	0.1	n/a
U	U	R	4	3	−67.11	−40.26	10.08	4.0	SIG

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-18. Empirical Bayes Evaluation Results for Fatal and Injury Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Mean per added lane	Standard error	Ratio[a]	Significant?
R	N	L	4	2	−18.46	−9.23	10.11	0.9	NS
R	N	LR	4	1	−48.10	−24.05	13.71	1.8	n/a
R	N	R	4	1	4.07	2.03	16.28	0.1	n/a
R	U	L	4	24	−63.41	−35.39	3.01	11.8	SIG
R	U	LR	4	15	−22.50	−11.25	6.25	1.8	NS
R	U	R	4	28	−15.86	−10.33	7.93	1.3	NS
R	U	XL	4	2	1.19	1.19	39.29	0.0	NS
U	N	L	3	3	100.06	60.04	38.69	1.6	NS
U	N	L	4	14	−54.19	−28.10	4.95	5.7	SIG
U	S	L	4	39	−28.40	−9.15	1.31	7.0	SIG
U	S	LR	4	10	−45.23	−11.60	1.68	6.9	SIG
U	S	R	4	17	−20.55	−9.19	2.99	3.1	SIG
U	S	XL	4	3	31.88	19.13	15.83	1.2	NS
U	U	L	3	8	−23.54	−23.54	19.75	1.2	NS
U	U	L	4	2	−7.87	−3.93	33.49	0.1	NS
U	U	R	3	1	149.31	149.31	250.55	0.6	n/a
U	U	R	4	2	−53.41	−35.61	31.50	1.1	NS

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-19. Empirical Bayes Evaluation Results for Project-Related Intersection Accidents.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Percent change in accident frequency: Mean per added lane	Percent change in accident frequency: Standard error	Ratio[a]	Significant?
R	N	L	4	2	51.84	25.92	40.88	0.6	NS
R	N	LR	4	1	−100.00	−50.00			n/a
R	N	R	4	1	−100.00	−50.00			n/a
R	U	L	4	23	−66.23	−37.16	7.42	5.0	SIG
R	U	LR	4	14	53.05	26.52	22.68	1.2	NS
R	U	R	4	29	33.90	21.85	26.57	0.8	NS
R	U	XL	4	2	62.88	62.88	108.20	0.6	NS
U	N	L	4	13	6.03	3.13	9.49	0.3	NS
U	U	L	4	7	−51.15	−25.58	7.24	3.5	SIG
U	U	LR	4	1	−45.44	−22.72	29.05	0.8	n/a
U	U	R	4	1	−100.00	−50.00			n/a

[a] Ratio of mean percent change in accident frequency to standard deviation of percent change in accident frequency per turn lane installed.

Table C-20. Empirical Bayes Analysis Results for Total Accidents on Individual Intersection Approaches.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Percent change in accident frequency: Mean per added lane	Percent change in accident frequency: Standard error	Ratio[a]	Significant?
R	N	L	4	4	-22.62	-22.62	7.26	1.6	NS
R	N	LR	4	2	-61.41	-30.71	8.18	3.8	SIG
R	N	R	4	2	6.00	6.00	11.64	0.3	NS
R	U	L	3	62	-45.20	-45.20	6.50	7.0	SIG
R	U	L	4	50	-54.63	-54.63	2.41	12.6	SIG
R	U	LR	3	16	-30.38	-15.19	17.12	1.8	NS
R	U	LR	4	30	-16.76	-8.38	4.39	1.9	NS
R	U	R	3	18	104.41	104.41	61.09	1.7	NS
R	U	R	4	57	-26.66	-26.66	5.26	3.3	SIG
R	U	XL	4	4	-43.02	-43.02	17.03	2.5	SIG
U	N	L	3	6	44.68	44.68	18.88	1.4	NS
U	N	L	4	49	-28.02	-28.02	2.92	5.0	SIG
U	S	L	3	9	-49.26	-49.26	13.87	3.6	SIG
U	S	L	4	148	-34.15	-34.15	0.79	13.9	SIG
U	S	LR	3	6	-19.32	-9.66	9.15	1.4	NS
U	S	LR	4	38	-32.49	-16.24	1.14	7.3	SIG
U	S	R	3	3	-44.48	-44.48	10.42	2.1	SIG
U	S	R	4	67	-17.62	-17.62	1.96	4.2	SIG
U	S	XL	3	2	7.17	7.17	40.41	0.2	NS
U	S	XL	4	11	57.80	57.80	11.72	3.0	SIG
U	U	L	3	16	-32.28	-32.28	13.14	2.5	SIG
U	U	L	4	17	-20.13	-20.13	4.40	2.3	SIG
U	U	LR	4	2	-66.27	-33.13	9.93	3.3	SIG
U	U	R	3	2	-100.00	-100.00			NS
U	U	R	4	6	-75.80	-75.80	8.48	5.4	SIG

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-21. Empirical Bayes Evaluation Results for Fatal and Injury Accidents on Individual Intersection Approaches.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Percent change in accident frequency: Mean per added lane	Percent change in accident frequency: Standard error	Ratio[a]	Significant?
R	N	L	4	4	−42.11	−42.11	7.57	2.8	SIG
R	N	LR	4	2	−55.36	−27.68	11.57	2.4	SIG
R	N	R	4	2	−22.53	−22.53	12.25	0.9	NS
R	U	L	4	49	−60.99	−60.99	3.15	10.8	SIG
R	U	LR	4	30	−10.73	−5.37	7.33	0.7	NS
R	U	R	4	55	−24.28	−24.28	7.94	2.0	SIG
R	U	XL	4	4	80.35	80.35	70.18	1.1	NS
U	N	L	4	48	−43.18	−43.18	3.99	5.6	SIG
U	S	L	3	9	−47.59	−47.59	23.93	2.0	SIG
U	S	L	4	122	−35.32	−35.32	1.25	8.9	SIG
U	S	LR	3	5	−8.05	−4.03	19.49	0.3	NS
U	S	LR	4	35	−53.41	−26.70	1.51	9.1	SIG
U	S	R	3	3	−38.69	−38.69	22.06	0.9	NS
U	S	R	4	64	−22.20	−22.20	3.07	3.4	SIG
U	S	XL	3	2	−43.84	−43.84	56.78	0.8	NS
U	S	XL	4	11	31.47	31.47	14.96	1.2	NS
U	U	L	4	17	−5.21	−5.21	7.80	0.3	NS
U	U	LR	4	2	−42.22	−21.11	29.10	0.7	NS
U	U	R	4	6	−41.08	−41.08	25.25	1.0	NS

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Table C-22. Empirical Bayes Analysis Results for Project-Related Accidents on Individual Intersection Approaches.

Area type	Traffic control	Project type	No. of legs	No. of improved sites	Percent change in accident frequency: Mean	Percent change in accident frequency: Mean per added lane	Percent change in accident frequency: Standard error	Ratio[a]	Significant?
R	N	L	4	4	29.19	29.19	32.30	0.5	NS
R	N	LR	4	2	−100.00	−50.00			NS
R	N	R	4	2	−100.00	−100.00			NS
R	U	L	4	50	−22.11	−22.11	11.06	1.1	NS
R	U	LR	4	30	97.51	48.76	24.04	2.0	SIG
R	U	R	4	58	34.23	34.23	26.33	0.8	NS
R	U	XL	4	4	50.96	50.96	97.67	0.5	NS
U	N	L	4	26	6.24	6.24	9.10	0.4	NS
U	S	L	4	127	−40.40	−40.40	1.82	6.9	SIG
U	S	LR	4	34	−49.50	−24.75	1.80	7.1	SIG
U	S	R	4	67	1.98	1.98	5.22	0.2	NS
U	S	XL	4	12	108.85	108.85	50.09	1.3	NS
U	U	L	4	14	−50.53	−50.53	7.24	3.5	SIG
U	U	LR	4	2	−42.14	−21.07	30.13	0.7	NS
U	U	R	4	2	−100.00	−100.00			NS

[a] Ratio of mean percent change in accident frequency to standard error of percent change in accident frequency per turn lane installed.

Description of Results Tables

The first seven columns of the results tables for the EB analysis are identical to the first five columns of the results tables for the YC and CG analysis. In particular, the sixth column presents the mean treatment effectiveness, $\hat{\theta}^*$ from Equation (44), expressed as a percentage change in accident frequency. The seventh column presents the mean percentage change in accident frequency per turn lane added, determined in the same manner that it was for the YC and CG analyses.

The eighth column of the results tables for the EB analysis presents the standard error of the mean treatment effectiveness per turn lane added. This standard error is the square root of $VAR\{\hat{\theta}^*\}$ from Equation (47), expressed as a percentage change in accident frequency.

The ninth column is a ratio determined as the mean treatment effectiveness (in the seventh column) divided by the standard error of treatment effectiveness (in the eighth column).

The tenth column shows the significance of the mean treatment effectiveness. The treatment effectiveness is considered to be significant if the ratio in the ninth column is greater than or equal to 2.0. This significance criterion is not a formal test of statistical significance at a specified confidence interval but, rather, is a criterion recommended by Hauer[2] for judging the results of EB analyses. This criterion is, however, equivalent to the statistical significance criteria used for the YC and CG approaches.

Specific Evaluation Results

The results of the EB evaluation are presented in the following tables:

- Table C-17—total intersection accidents.
- Table C-18—fatal and injury intersection accidents.
- Table C-19—project-related intersection accidents.
- Table C-20—total accidents for individual intersection approaches.
- Table C-21—fatal and injury accidents for individual intersection approaches.
- Table C-22—project-related accidents for individual intersection approaches.

Appendix D

Field Data Collection for Geometric Design and Traffic Control Features

APPENDIX D. FIELD DATA COLLECTION FOR GEOMETRIC DESIGN AND TRAFFIC CONTROL FEATURES

This appendix documents the definitions and codes used to record geometric and traffic control data during the field data collection. Data for each intersection visited in the field were recorded on a standard form (figure D-1). Most data items were recorded for each of the three or four approaches to the intersection. A few items (angle of intersection, lighting, character of development, and level of pedestrian activity) apply to the intersection as a whole, rather than to any specific approach. Location information was also collected on the form.

More types of data were gathered in the field than were used in the final analyses. The intent was to collect as broad a set of geometric and traffic control data as feasible during the initial field visits so that, if a question arose during the analysis about the geometrics or traffic control of a specific intersection, data from the field would be available to answer the question. This would eliminate the need to make additional field visits during the latter stages of the project. Photographs were also taken in the field on each intersection approach.

Some data items were gathered solely for site selection purposes. For example, data were recorded on whether each intersection leg had one-way or two-way operation. In fact, all legs of the study intersections had two-way operation. However, if one-way operation had been present, this data item would have alerted the research team to that fact.

Each data item in figure D-1 is discussed below:

1. **Number of through lanes:**
   Number of lanes used by through traffic on each approach. This included all lanes used exclusively by through traffic and lanes shared by through traffic and right- or left-turning traffic.

2. **Number of left-turn lanes:**
   Number of lanes used exclusively by left-turning traffic. A shared lane used by both through traffic and left-turning traffic was counted as a through lane, not as a left-turn lane.

3. **Number of right-turn lanes:**
   Number of exclusive right-turn lanes on the approach. A shared lane used by both through and right-turning traffic was counted as a through lane, not as a right-turn lane. If there was a separate right-turn roadway created by a channelizing island, the number of right-turn lanes was recorded as 1 or more, even if vehicles entered the channelizing roadway from a lane shared with through traffic (i.e., even if there was no exclusive right-turn lane upstream of the right-turn roadway created by the channelizing island).

Figure D-1. Key Intersection Geometric and Traffic Control Variables.

Site Number ____________________ County ______________ Data Collector Name ________________

Intersection ________________________________ B______ A______ C ______ Date _______ Time______

	Acceptable Codes	Major Road NB or EB	Crossroad NB or EB	Major Road SB or WB	Crossroad SB or WB	Comments (use back if needed)
Name of Street:						
1. Number of through lanes	Numeric					
2. Number of left-turn lanes	Numeric					
3. Number of right-turn lanes	Numeric					
4. Type of left-turn treatment	N,C,P					
5. Type of right-turn treatment	N,I,L,R					
6. Horizontal alignment	T,G,M,S					
7. Approach grades	L,M,S / U,D					
8. Crest/sag vertical curves	N,C,S					
9. Total through-lane width (ft)	Numeric					
10. Right shoulder type	P,G,T,C					
11. Right shoulder width (ft)	Numeric					
12. Total LTL width (ft)	Numeric					
13. Total LTL length (ft)	Numeric					
14. Total RTL width (ft)	Numeric					
15. Total RTL length (ft)	Numeric					
16. Divided/undivided	D,U					
17. Median width (ft)	Numeric					
18. Median type	N,R,D,F					
19. One-way/two-way	1 or 2					
20. Left-turn prohibition	N,A,M,E,B					
21. Number of driveways within 250 ft	Numeric					
22. Type of driveways	N,C,I,R					
23. Curb parking within 250 ft	N,P,A					
24. Traffic control	N,ST,SG					
25. Left-turn phasing (arrows)	N,A,B					
26. Pedestrian signals	Y,N					
27. Painted crosswalk on approach	Y,N					
28. Advance warning signs	Y,F,N					
29. Posted speed limit (mph)	Numeric					
30. Angle of intersection	Numeric					
31. Lighting	N,H,S,I/Y,N					
32. Character of development	C,B,I,M,R,X					
33. Level of pedestrian activity	L,M,H					

4. **Type of left-turn treatment:**

N = No left-turn lanes.
C = Left-turn channelization defined by raised (curbed) or depressed median.
P = Painted left-turn channelization (no median or flush median).

NOTE: If number of left-turn lanes was zero, the type of left-turn treatment was N.

5. **Type of right-turn treatment:**

N = None.
I = Right-turn roadway created by a channelizing island *without* an exclusive right-turn lane upstream of it (i.e., traffic entered the right-turn roadway from a shared lane used by both through and right-turning traffic).
L = Right-turn roadway created by a channelizing island *with* an exclusive right-turn lane upstream of it (i.e., traffic entered the right-turn roadway from an exclusive right-turn lane).
R = Conventional exclusive right-turn lane with no channelizing island.

6. **Horizontal alignment (of approach):**

T = Tangent.
G = Gentle curve (radius over 600 m or 2,000 ft).
M = Moderate curve (radius from 150 to 600 m or 500 to 2,000 ft).
S = Sharp curve (radius less than 600 m or 500 ft).

NOTE: The G, M, and S codes were used if the intersection was located on a horizontal curve or if there was a horizontal curve on the approach within 250 feet of the intersection. The curve radius was estimated visually in the three categories shown.

7. **Approach grades (within 75 m or 250 ft of the intersection):**

L = Level (less than 2 percent grade).
M = Moderate grade (2 to 4 percent grade).
S = Steep grade (over 4 percent grade).

NOTE: The percent grade was estimated visually.

8. **Crest/sag vertical curve (on approach):**

N = None.
C = Crest vertical curve on approach.
S = Sag vertical curve on approach.

NOTE: Recorded presence of crest and sag vertical curves that extended through the intersection or were within 75 m (250 ft) of the intersection.

9. **Total through-lane width (ft):**

Combined total width of all the through lanes, including both shared left-turn and right-turn lanes. Widths of exclusive right- and left-turn lanes were not included in the total through-lane width. The number of lanes whose widths were measured matched the number of through lanes recorded.

NOTE: The through-lane width was measured at the stop line or crosswalk with a measuring wheel. The total through-lane width was recorded such that the total through-lane width divided by the number of through lanes equaled the average lane width for the through lanes.

10. Right shoulder type:
P = Paved.
G = Gravel.
T = Turf.
C = Curb.

11. Right shoulder width (ft):
Measured from the outside edge of the through lane or right-turn lane to the outside edge of the shoulder. This measurement was made with a measuring wheel.

12. Total LTL width (ft):
Combined total width of all exclusive left-turn lanes. The number of lanes whose widths were measured matched the total number of exclusive left-turn lanes recorded.

NOTE: The total left-turn lane width was measured at the stop line or crosswalk. This measurement was made with a measuring wheel. The total left-turn lane width was recorded such that the total left-turn lane width divided the total number of exclusive left-turn lanes equaled the average left-turn lane width.

13. Total LTL length (ft):
Total length of all exclusive left-turn lanes.

NOTE: The total left-turn lane length was measured from the stop line or crosswalk to the upstream end of the left-turn lane(s). This measurement was made with a measuring wheel. If the left-turn lane included a taper at its upstream end, the length of the left-turn lane was measured to the last point at which the left-turn lane had its full width.

14. Total RTL width (ft):
Combined total width of all right-turn lanes. The number of lanes whose widths were measured matched the total number of right-turn lanes recorded.

NOTE: The total right-turn lane width was measured at the stop line or crosswalk. This measurement was made with a measuring wheel. The total right-turn lane width was recorded such that the total right-turn lane width divided by the total number of right-turn lanes equaled the average right-turn lane width.

15. Total RTL length (ft):
Total length of all right-turn lanes.

NOTE: The total right-turn lane length was measured from the stop line or crosswalk to the upstream end of the right-turn lane(s). This measurement was made with a measuring wheel. If the right-turn lane included a taper at its upstream end, the length of the right-turn lane was measured to the last point at which the right-turn lane had its full width.

16. Divided/undivided:
D = Divided (a raised or depressed median, or a flush median at least 1.2 m (4 ft) in width, was present between the lanes in opposing direction of travel).
U = Undivided (no median present; a roadway with a flush median less than 1.2 m (4 ft) in width.

17. Median width (ft):
Measured from inside edge of the through lane to inside edge of through lane in the opposite direction of travel (i.e., left-turn lanes cut into the median were included in the median width). This measurement was made with a measuring wheel. If the approach was undivided, the median width as recorded as 0 m (0 ft).

18. Median type:
N = No median.
R = Raised median (curbed with turf or pavement in the median).
D = Depressed median (turf median with no curbs). This type of median typically had a ditch or swale below roadway grade.
F = Flush median (paved median that was flush with the roadway grade).

19. One-way/two-way operation:
1 = One-way traffic operation on the intersection leg containing the approach.
2 = Two-way traffic operation on the intersection leg containing the approach.

20. Left-turn prohibition:
N = No left-turn prohibition on this approach.
A = Left turns prohibited from this approach at all times.
M = Left turns prohibited from this approach during the morning peak period only, but not at other times.
E = Left turns prohibited from this approach during the evening peak period only, but not at other times.
B = Left turns prohibited from this approach during both peak periods, but not at other times.

21. Number of driveways within 75 m or 250 ft:
Total number of driveways within 75 m (250 ft) of the intersection on both sides of the street on the intersection leg containing the approach in question.

22. Type of driveways:

N = No driveways (recorded as such if the number of driveways was equal to zero).

C = One or more commercial driveways included in the driveway count for this leg of the intersection.

I = One or more industrial/institutional driveways included in the driveway count for this leg, but no commercial driveways.

R = One or more residential driveways included in the driveway count for this leg, but no commercial or industrial/institutional driveways.

NOTE: This category was intended to establish a hierarchy in which the driveway type for the most heavily used driveway(s) was recorded. Commercial driveways are usually more heavily used throughout the day than industrial/institutional driveways, which in turn are usually more heavily used than residential driveways. Industrial/institutional driveways include those that serve factories, non-retail businesses, government buildings, hospitals, schools, churches, and apartment complexes (with more than 10 apartments).

23. Curb parking within 75 m or 250 ft:

N = No curb parking on the right side of the intersection approach within 250 ft of the intersection.

P = Parallel parking on the right side of the intersection approach within 250 ft of the intersection.

A = Angle parking on right side of the intersection approach within 250 ft of the intersection.

NOTE: Width of angle parking area was not included in width of through lanes.

24. Traffic control:

N = None.

ST = STOP controlled.

SG = Signalized.

25. Left-turn phasing (arrows):

N = No protected left-turn phase (i.e., there was no green arrow so all left turns were made on the green ball).

A = Protected left-turn phase with left turns allowed only during the protected phase (i.e., all left turns were made with a green arrow, while no left turns were allowed on green ball).

B = Protected left-turn phase with left turns permitted both during the protected phase and on the green ball (i.e., protected/permissive operation).

26. Pedestrian signals:

Y = Pedestrian signals (WALK/DON'T WALK) present for crossing the approach in question.

N = No pedestrian signals for crossing the approach.

27. Painted crosswalk on approach:

Y = Painted or marked pedestrian crosswalk present on the approach in question.
N = No painted crosswalk on the approach in question.

28. Advance warning signs:

Y = Advance warning signs (e.g., SIGNAL AHEAD) present on the approach in question.
F = Advance warning signs present AND the warning signs were accompanied by flashing beacons.
N = No advance warning signs on the approach.

NOTE: If there was an advance warning sign with any legend other than SIGNAL AHEAD (or the SIGNAL AHEAD symbol sign), the sign legend was noted as a comment. Advisory speed limits are not typically used in conjunction with SIGNAL AHEAD signs; however, if an advisory speed limit was used on the approach (except for a temporary work zone speed limit), the magnitude of the advisory speed limit was noted as a comment.

29. Posted speed limit (mph):

The posted regulatory speed limit (mph) on each approach.

NOTE: Regulatory speed limit signs are normally repeated at intervals to make sure that drivers are aware of the speed limit. If there were no speed limit signs within the immediate vicinity of the intersection, data collectors drove up to 1.6 km (1 mile) upstream to check for speed limit signs that applied to the approach in question. If there were no regulatory speed limits signs on the street, the following default speed limits were used:

25 mph = Business or residential district on a non-state highway.

55 mph = State highways or outside of business and residential areas on non-State highways.

30. Angle of intersection:

The angle between the intersecting approaches. The angle entered was the smallest angle between the intersecting approaches (i.e., entered as 90 degrees or an acute angle between 0 and 90 degrees).

NOTE: If the angle was other than 90 degrees, a sketch was made of the three or four approaches to illustrate which approaches intersected at acute, right, and obtuse angles.

31. Lighting:

N = None.
H = High-mast lighting (not expected at conventional highway intersections; more typical of freeway interchanges).

S = Street lighting (individual luminaires) continuously along one or both intersecting streets.
I = Street lighting (individual luminaires) at the intersection, but not along the intersecting streets.

NOTE: Ambient light sources other than street lighting present at the intersection were noted by a supplementary code of Y (Yes) or N (No).

32. Character of development:
A = Agricultural area.
C = Central business district/downtown.
B = Outlying commercial business district.
I = Industrial district.
M = Mixed commercial and residential development.
R = Residential development.
X = Other (describe in comment).

33. Level of pedestrian activity:
L = Low (almost no pedestrian activity).
M = Medium (pedestrian activity with some frequency).
H = High (pedestrian activity with some frequency).