Safety Evaluation of Turning Movement Restrictions at Stop-Controlled Intersections

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program *Report 500 Guides* as part of the implementation of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan.(1) The ELCSI-PFS studies provide a crash modification factor and benefit–cost economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member States.

This study evaluated the safety effects of converting full movement, stop-controlled intersections to right-in-right-out (RIRO) operation with physical barriers. The results indicated reductions for all crash types (i.e., total, all intersection-related and fatal and injury intersection-related) for stop-controlled intersections with RIRO compared to full movement intersections. While the economic analysis suggests the strategy can be cost-effective in reducing crashes at stop-controlled intersections, potential costs and benefits need to be analyzed on a case-by-case basis. This document is intended for safety engineers, highway designers, planners, and practitioners at State and local agencies involved with AASHTO Strategic Highway Safety Plan implementation.

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16. Abstract The Development of Crash Modification Factors program conducted a safety evaluation of turning movement restrictions at stop-controlled intersections for the Evaluation of Low Cost Safety Improvements Pooled Fund Study. This study evaluated the safety effects of converting full movement, stop-controlled intersections to right-in-right-out (RIRO) operation using physical barriers, as measured by the change in crash frequency. The project team obtained geometric, traffic, and crash data for urban, three-legged, full movement and RIRO stop-controlled intersections, as well as the downstream four-legged, stop-controlled or signalized intersection with full movement in California. The team used a cross-sectional analysis to estimate the effects of turning movement restrictions while controlling for other differences between sites with RIRO and full movement. Aggregate results indicated reductions for all crash types analyzed (i.e., total, all intersection-related, and fatal and injury intersection-related) for stop-controlled intersections with RIRO compared to full movement. Reductions were statistically significant at the 95-percent confidence level for all crash types. Crash modification factors for total, all intersection-related, and fatal and injury intersection-related crashes were 0.55, 0.32, and 0.20, respectively. Based on the disaggregate results, RIRO intersections do not appear to have differing effects for different levels of traffic, design speed, or number of lanes. Potential for crash migration in determining net benefits needs to be considered. Results indicated potential increases at downstream intersections, but many increases are not statistically significant even at the 90-percent confidence level. While the economic analysis suggests the strategy can be cost-effective in reducing crashes at a hypothetical stop-controlled intersection, potential costs and benefits with site-specific values need to be analyzed on a case-by-case basis.		
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
B/C	benefit–cost
CMF	crash modification factor
DCMF	Development of Crash Modification Factors (program)
FHWA	Federal Highway Administration
FID	feature identifier, feature ID
GIS	Geographic Information System
HSIS	Highway Safety Information System
KML	Keyhole Markup Language
MVMT	million vehicle miles traveled
NCHRP	National Cooperative Highway Research Program
RIRO	right-in-right-out
USDOT	United States Department of Transportation

EXECUTIVE SUMMARY

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

This study investigated the safety effects of converting full movement, stop-controlled intersections to right-in-right-out (RIRO) intersections using physical barriers. The intent of this strategy was to reduce the frequency and severity of crashes by eliminating left turns into and out of the target intersections—the highest severity conflicts at an intersection. Studies have explored various access management techniques and the installation of median barriers at the corridor level. However, no quantitative information is available to quantify the safety effects of restricting left turns at specific intersections and the effects of shifting traffic to downstream intersections.

The project team obtained geometric, traffic, and crash data for intersections along urban, four- and six-lane corridors in California. These intersections included three-legged, stop-controlled intersections with full movement (no physical turning restrictions) and RIRO operations (curbed or other positive median barrier) as well as the immediate downstream four-legged, stop-controlled or signalized intersections with full movement. The project team conducted a cross-sectional analysis to estimate the effects of turning movement restrictions while controlling for other factors. To select full movement intersections with similar characteristics to the RIRO intersections, the project team used propensity score matching. Analyses focused on safety effects at target stop-controlled intersections (i.e., those with turning movement restrictions) and downstream intersections. The analysis controlled for changes in safety due to differences in traffic volume and differences between intersections with and without turning restrictions.

The aggregate results indicated reductions for all crash types analyzed (i.e., total, all intersection-related, and fatal and injury intersection-related) for urban, three-legged, stop-controlled intersections with RIRO compared to full movement. The reductions were statistically significant at the 95-percent confidence level for all crash types. The crash modification factors (CMFs) for total, all intersection-related, and fatal and injury intersection-related crashes, were 0.547, 0.324, and 0.199, respectively. Potential for crash migration in determining net benefits needs to be considered. Results indicated potential increases at the downstream intersection for most of the crash types analyzed. While many of the increases at downstream intersections were not statistically significant, even at the 90-percent confidence level, a rigorous analysis would include these potential increases in estimating the net benefit conservatively.

The disaggregate analysis sought to identify those conditions under which the strategy was most effective by including interaction terms for variables of interest, including number of lanes on the mainline, traffic volumes on the major and minor road, and design speed. Results indicated that interaction terms were not statistically significant at even an 80-percent confidence level for any the variables of interest. This was consistent for all crash types.

Assuming a hypothetical scenario with a single stop-controlled intersection and a downstream signalized intersection, a 20-year service life, conservative costs, and benefits for fatal and injury crashes, the B/C ratio is 9.6 to 1. With the U.S. Department of Transportation recommended sensitivity analysis, these values could range from 5.4 to 1 up to 13.5 to 1. While these results suggest the strategy can be cost-effective in reducing crashes at a hypothetical stop-controlled intersection, there is a need to analyze potential costs and benefits on a case-by-case basis with site-specific values.

CHAPTER 1. INTRODUCTION

BACKGROUND ON STRATEGY

Improving access management near unsignalized intersections and reducing the frequency and severity of intersection conflicts are two objectives to improve unsignalized intersection safety in the National Cooperative Highway Research Program (NCHRP) *Report 500 Guide, Volume 5: A Guide for Addressing Unsignalized Intersection Collisions*.(1) Restricting or eliminating turning maneuvers is a key element in related strategies.

Turning movement restrictions are access management strategies used to improve the safety of stop-controlled intersections and driveways. Restricted and prohibited turn movements reduce the number of turning conflict points at intersections, which is generally known to reduce crash risk.(2) Transportation agencies commonly use signs, pavement markings, or geometrics to prohibit turning movements. In almost all cases, one or more left-turn movements are prohibited, and right-turning vehicles are allowed to operate as normal. Left-turn movements cross a conflicting direction of traffic and present risk for crashes. Right turns at most stop-controlled intersections are essentially merging movements and do not present the same level of safety risks as left turns.

Turning operations at most stop-controlled intersections can be categorized into one of the three following groups:

- Full movement.
- Left turn from mainline only.
- Right-in-right-out (RIRO).

Full movement implies no turning restrictions; most stop-controlled intersections operate with full movement. Left turn from mainline only prohibits left turns out of the minor road, such as a restricted crossing U-turn intersection. This study did not evaluate the left turn from mainline only strategy due to sample size limitations. RIRO eliminates left turns into and out of the minor road. A positive or curbed median barrier on the mainline is a common strategy for creating a RIRO at minor road stop-controlled intersections. The median physically blocks left turns into and out of the intersecting street. Figure 1 presents a photograph of a stop-controlled intersection with turning movements restricted to RIRO. Refer to the appendix for examples of intersections similar to the ones observed in this study.

As with all access management techniques, agencies must strike a balance between the safety and operational efficiency of intersections and maintaining access to properties along and adjacent to the roadway. While restricting turns is expected to provide a safety improvement in most cases, limited information is available about the quantitative safety effects of these practices and the effects on downstream intersections. This study addressed the need for research into the safety effects of turning movement restrictions at stop-controlled intersections.

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Figure 1. Photo. RIRO stop-control intersection.

BACKGROUND ON STUDY

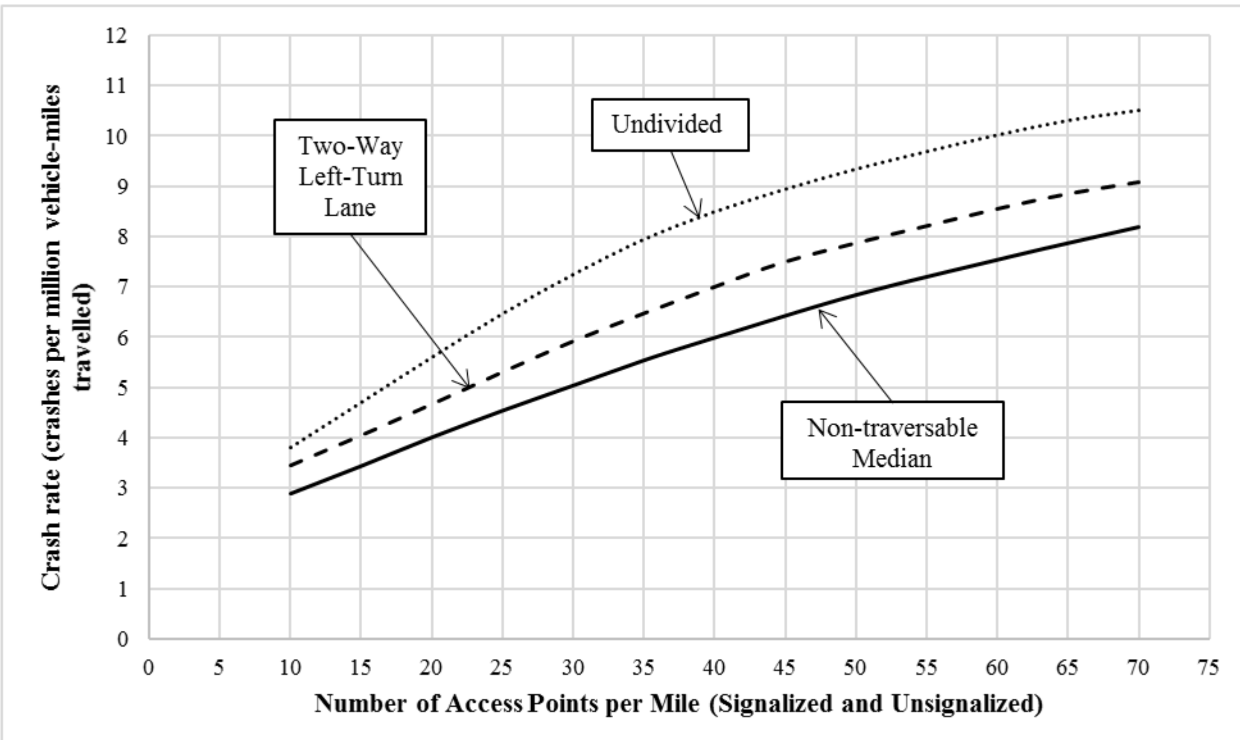
The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable, quantitative estimates of their effectiveness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

LITERATURE REVIEW

The literature review focused on the safety effects of converting full movement to RIRO operations at intersections, which are most commonly implemented with a raised median preventing all left turns. Most or all evaluations to date have examined corridor and segment impacts of installing raised medians rather than the effects of turning restrictions at intersections and downstream intersections. The following is a summary of salient research related to specific strategies.

Research by Schultz, Braley, and Boschert in *Correlating Access Management to Crash Rate, Severity, and Collision Type* indicated that the presence of a raised median corresponded to a reduction of 1.23 crashes per million vehicle miles traveled (MVMT).[3] In addition, raised medians were negatively correlated with right-angle collisions.

Research performed by Gluck, Levinson, and Stover for NCHRP Report 420 also investigated the relationship between median type and crash rates.[4] Figure 2 illustrates the relationship between crash rate and roadway cross-section.



Adapted from Gluck, J., Levinson, H.S., and Stover, V. (1999). *NCHRP Report 420: Impacts of Access Management Techniques*, figure 24, p. 57.

Figure 2. Chart. Relationship between total access points per mile and crash rate.[4]

NCHRP Report 395 compared outcomes from crash prediction models developed by various researchers.[5] A composite finding suggested, in general, a raised median was safer than undivided roadways, especially on roads with above 20,000 vehicles per day.

Eisele and Frawley in *Estimating the Safety and Operational Impact of Raised Medians and Driveway Density: Experiences from Texas and Oklahoma Case Studies* investigated the relationship between access density and crash rate for raised median and nonraised median corridors separately.[6] Both relationships showed positive correlation with crashes, but the trend line was slightly steeper for nonraised than for raised median corridors. The researchers concluded that the reduced slope of the regression line for raised median corridors demonstrated that relatively lower crash rates in corridors with raised medians were due to reduced conflict points.

Hallmark et al. indicated in the *Toolbox to Assess Tradeoffs between Safety, Operations, and Air Quality for Intersection and Access Management Strategies: Final Report* that a FHWA evaluation involving data from seven States suggested raised medians reduced crashes at least 40 percent in urban settings.[(7)]

CHAPTER 2. OBJECTIVE

The project team for this evaluation examined safety impacts of physically restricting turning movements to RIRO from full movement at stop-controlled intersections in California. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Target crash types included the following:

- Total: all crashes within 100 ft of intersection (all types and severities combined).
- Intersection-related: all crashes within 100 ft of intersection defined as “intersection-related” by the reporting officer (all types and severities combined).
- Fatal and injury: all injury crashes within 100 ft of intersection defined as “intersection-related” by the reporting officer (fatal injury, incapacitating injury, non-incapacitating injury, and possible injury).
- Multivehicle: all multiple-vehicle crashes within 100 ft of intersection defined as “intersection-related” by the reporting officer (all types and severities combined). Because all intersection-related crashes within 100 ft of the intersections included multiple vehicles, the project team dropped this category from the remainder of the analysis, as it was redundant.

A further objective was to address the following ways in which effects may vary:

- By lane configuration of intersection (i.e., four mainline lanes and two cross-street lanes versus six mainline lanes and two cross-street lanes).
- By level of traffic volume.
- By design speed on the major route.
- By type of traffic control at downstream intersections (i.e., signalized or minor road stop-control).
- By the presence of turn lanes at downstream intersections.

Evaluation of overall effectiveness included consideration of installation costs and crash savings in terms of the B/C ratio.

Meeting these objectives placed some special requirements on the data collection and analysis tasks, including the following needs:

- Select a sufficiently large sample size of sites with and without physical turning restrictions to detect, with statistical significance, what may be small differences in safety for some crash types after controlling for differences due to factors unrelated to turning restrictions.

- Identify appropriate reference sites without turning restrictions.
- Properly account for changes in safety due to differences in traffic volume and other differences between intersections with and without physical turning restrictions.

CHAPTER 3. STUDY DESIGN

While the current state of the art for developing high-quality crash modification factors (CMFs) employs an empirical Bayes before–after study design, several factors can preclude its use. One factor is the availability of treatment information, including installation date and location for the treatment of interest. For strategies such as restricting turning movements, there is often insufficient information to determine the exact location and timing of the treatment. Using FHWA's *A Guide to Developing Quality CMFs*, the project team determined that a rigorous cross-sectional study design would serve as a suitable alternative.[(8)] The following study design considerations included steps to account for potential biases and sample size considerations in cross-sectional analysis.

ACCOUNTING FOR POTENTIAL ISSUES AND SOURCES OF BIAS

A cross-sectional study design is an observational study used to analyze a representative sample at a specific point in time. The safety effect is estimated by taking the ratio of the average crash frequency for two groups—one with and the other without the feature of interest. In this case, the feature of interest is RIRO operation. For this method to work, the two groups should be similar in all regards except for the feature of interest. In practice, this is difficult to accomplish, and multivariable regression models are typically used to estimate the feature of interest's safety effects while controlling for characteristics that vary among sites.

Multivariable regression models use explanatory variables such as geometric and operational characteristics to predict a response variable, such as frequency of crashes. While these cross-sectional models provide a means to estimate the safety effects of treatments, they are susceptible to biases that should be accounted for during sampling and modeling. The following issues and biases were identified from the *Recommended Protocols for Developing CMFs* and are potentially applicable to this study.[(9)] General issues with safety evaluations are listed below, followed by a list of potential biases specific to cross-sectional studies. The project team made an effort to address all applicable biases.

General Issues

The following are descriptions of general issues:

- *Measure of effectiveness:* Direct measures of safety effectiveness, including crash frequency and severity, are preferred over surrogate measures. This study employed a crash-based analysis to evaluate the safety impacts of turning movement restrictions at stop-controlled intersections.

- *Exposure:* Neither crash frequency nor severity alone provides adequate information to determine the safety effectiveness of a particular design feature. Exposure is an important factor in assessing crash risks. This study uses traffic volumes on the major and minor roads (i.e., total entering volume) of each intersection as explanatory variables.

- *Sample size:* Because crashes are rare and random events, it is necessary to include a sufficient number of sites and/or years with enough crashes in the study sample to develop a valid relationship between the treatment and safety effect. The following section, Sample Size Considerations, presents a full discussion of sample size for this study.

- *Site selection bias:* In highway safety, sites are often selected for treatment based on need. In other words, sites with the highest crash frequency, severity, or potential for improvement are addressed first. When a countermeasure evaluation uses these types of sites exclusively, evaluation results are only applicable to sites with similar safety issues. The project team selected sites for this study based on the presence of the treatment and their geometric characteristics rather than crash experience; however, transportation agencies may implement the treatment based on crash experience. The potential for regression-to-the-mean was a non-issue in this study because the project team employed a cross-sectional analysis, which included data for only the period after treatment. To select suitable reference sites and to mitigate potential site selection bias, the project team used propensity score matching, discussed later in this chapter.

- *Crash data quality:* There is no national standard for crash data reporting. Although many States adopt some or all of the Model Minimum Uniform Crash Criteria data elements, crash data lack uniformity across jurisdictions, and most crash data are susceptible to quality and timeliness issues. It is necessary to account for these types of issues in the study design and analysis. For example, if the reporting threshold varies among States in the study and crashes from those States are aggregated in modeling, then the analysis should account for the difference in thresholds. The data used in this research is from the Highway Safety Information System (HSIS) database, which ensures a higher level of quality control and documentation in each participating State than data obtained directly from State agencies.

Issues Specific to Cross-Sectional Models

The following is a list of issues specific to cross-sectional models:

- *Control of confounding factors:* Confounding factors are those that are significant predictors of the response variable, and associated with the treatment in question. Turning movement restrictions at intersections are often present at high traffic volumes, but they are not a consequence of high volumes. Since traffic volume is also a significant predictor of crashes, it is a potential confounding factor and is accounted for as a variable in the model. It is difficult to control for all potential confounding factors, but these factors were considered and addressed to the extent possible in the study design and evaluation. The project team used propensity score matching, discussed later in this chapter, to select suitable reference sites and to mitigate potential confounding effects.

- *Omitted variable bias:* It is difficult to account for the potential effects of omitted variable bias in an observational cross-sectional study such as this. This study addressed omitted variable bias to the extent possible by carefully considering the roadway and traffic characteristics that should be included in the models. With the rich data in HSIS, the project team tested a wide range of variables in the models and selected suitable variables for final modeling. There is potential for omitted variable bias due to factors such as weather, driver population, and vehicle fleet that are not directly included as variables in the models.

- *Selection of appropriate functional form:* The project team applied generalized linear modeling techniques to calibrate crash prediction models. They specified a log-linear relationship using a negative binomial error structure, following state of the art procedures in modeling crash data. The negative binomial error structure is recognized as more appropriate for crash counts than the normal distribution used in conventional regression modeling. The negative binomial error structure also has advantages over the Poisson distribution in that it allows for overdispersion that is often present in crash data.

- *Correlation among independent variables:* Correlation refers to the degree of association among variables. A high degree of correlation among the predictor variables makes it difficult to reliably estimate the effects of specific predictor variables. The project team examined the correlation matrix to determine the extent of correlation among independent variables and used it to prioritize variables for inclusion.

- *Over-fitting of prediction models:* Over-fitting is related to the concept of diminishing returns. At some point, it is not worth adding independent variables to the model because they do not significantly improve the model fit. Over-fitting also increases the opportunity to introduce inter-correlation between independent variables. The project team considered combinations of predictor variables and employed relative goodness-of-fit measures to penalize models with greater estimated parameters.

- *Low sample mean and sample size:* This study dismissed low sample mean as a potential issue as many sites had experienced one or more crashes during the study period. The study addressed sample size through preliminary sample size estimates (see Sample Size Considerations section) and during early stages of the study and analysis.

- *Temporal and spatial correlation:* Temporal correlation may arise if multiple observations are used for the same site. In this study, three years of data were aggregated into a single observation at each site. As a result, this study dismissed temporal correlation as a potential issue. Spatial correlation is a potential issue. To help account for spatial correlation, the study selected sample corridors from various regions in California to achieve diversity of sites with respect to weather, topography, and driver population.

- *Endogenous independent variables:* Endogeneity occurs when one or more independent variable depend on the dependent variable. For example, transportation agencies may install left-turn lanes due to the frequency of left-turn crashes at an intersection, and thus their presence depends on crash frequency. The potential concern in an observational cross-sectional study is that treatments can be incorrectly associated with higher crashes when compared with sites where the treatments are absent and which may be prone to lower crash frequency. The project team used propensity score matching, discussed later in this chapter, to select suitable reference sites and to mitigate potential endogeneity issues.

SAMPLE SIZE CONSIDERATIONS

For crash-based studies, the total number of crashes is the primary measure of sample size rather than sites or years. However, including a sufficient number of sites and years in the study was necessary to attain an adequate sample of crashes. Further, selecting sites based on features of interest—not crash history—was important to minimize the potential for site selection bias and increase the applicability of the results.

The number of locations required for multivariable regression models depended on a number of factors, including the following:

- Average crash frequency.
- Number of variables desired in a model.
- Level of statistical significance desired in a model.
- Amount of variation in each variable of interest across sample sites.

Determination of whether or not a sample size is adequate can only be made once preliminary modeling is complete. If the variables of interest are not statistically significant, then more data are required to detect statistically significant differences, or it is necessary to accept a lower level of confidence. Estimation of the required sample size for cross-sectional studies is difficult and requires an iterative process, although, through experience and familiarity with specific databases, it is possible to develop an educated starting guess.

Table 1 presents average crashes per site-year for 138 target stop-control intersections by number of lanes and turning movement condition (RIRO or full movement). The 138 sites represented 161 total crashes per year and were reasonably representative of the range of site characteristics for urban, three-leg, minor road stop-controlled intersections.

Table 1. Crashes per site-year from data collection sites.

Turning Movement Condition	Four-Lane Major Crashes/Site-Year (Sites)	Six-Lane Major Crashes/Site-Year (Sites)	Combined Crashes/Site-Year (Sites)
RIRO	0.64 (24)	1.02 (34)	0.86 (58)
Full movement	1.08 (57)	2.16 (23)	1.39 (80)
Combined	0.95 (81)	1.48 (57)	1.09 (138)

Table 2 presents average crashes per site-year for the 109 downstream intersections by number of lanes and turning movement condition at the respective upstream stop-controlled intersection. The 109 sites experienced 463 total crashes per year. While there was no formal stratification of the data by site characteristics during site selection, the project team included sites with a range of traffic volumes and other characteristics among sites to increase the practical applicability of the results. This sample data were likely sufficient to develop reliable cross-sectional models based on experience with similar evaluations.

Table 2. Crashes per site-year from downstream intersections.

Turning Movement Condition at Upstream Intersection	Four-Lane Major Crashes/Site-Year (Sites)	Six-Lane Major Crashes/Site-Year (Sites)	Combined Crashes/Site-Year (Sites)
RIRO	3.92 (21)	7.70 (27)	6.05 (48)
Full movement	2.17 (43)	4.39 (18)	2.83 (61)
Combined	2.74 (64)	6.38 (45)	4.24 (109)

PROPENSITY SCORE MATCHING

In experimental studies, a sample is selected from the reference population and treatment is applied randomly to one group while leaving another group untreated for control purposes. Using this approach, the treatment and control groups are similar, and the only difference is the presence of treatment. This helps to ensure the treatment effect does not include safety effects due to other differences between the two groups.

In observational studies, it is desirable to replicate the random assignment of treatment while accounting for the fact that sites are often selected for treatment based on safety and operational performance measures. Matching treatment and reference sites to have similar characteristics reduces the potential for site selection bias and confounding factors. Selecting reference sites that are geometrically and operationally similar to treatment sites provides a more reliable comparison in cross-sectional studies, and propensity score matching is a rigorous approach to match treatment and reference sites.

This study employed propensity score matching to select reference sites that closely matched the treatment sites in terms of general site characteristics. In this study, physical turning movement restrictions at treatment sites related to substantial geometric and operational differences from nontreatment sites where all turning movements were allowed. Propensity score matching techniques helped account for site selection bias and other differences among sites with and without physical turning movement restrictions.

Propensity score matching is based on regression modeling. The project team developed a regression model to estimate scores (i.e., the probability of treatment or nontreatment) for all treatment and nontreatment sites based on site characteristics. The project team then used propensity scores to select reference sites most comparable with treatment sites for forming the study sample. Detailed discussions of propensity score matching and its application in traffic safety research are available in papers by Rosenbaum and Rubin (1983) and Sasidharan and Donnell (2013).[10,11]

CHAPTER 4. METHODOLOGY

The evaluation used a cross-sectional study design. At its most basic level, the safety effect is estimated by taking the ratio of the average crash frequency for two groups, one with the treatment and the other without the treatment. The two groups of sites should be similar in all regards except for the presence of the treatment. This is difficult to accomplish in practice, and the project team used propensity score matching to match sites with and without treatment and used multivariable regression modeling to control for characteristics that varied among sites.

The project team used multivariable regression to develop the statistical relationships between the dependent variables and a set of predictor variables. In this case, crash frequency was the dependent variable, and the team considered predictor variables, including treatment presence, traffic volume, and other roadway characteristics. The team estimated regression coefficients during the modeling process for each predictor variable. The coefficients represented expected change in crash frequency due to a unit change in the predictor variable with all else being equal.

The project team applied generalized linear modeling techniques to develop the crash prediction models and specified a log-linear relationship using a negative binomial error structure. The negative binomial error structure has advantages over the Poisson distribution in that it allows for overdispersion of the variance that is often present in crash data. One concern was the possibility of site-selection bias if agencies installed turning movement restrictions to address safety issues. The project team used propensity score matching to address potential site selection bias.

After developing a propensity score-based matched dataset, the project team employed the following protocol to develop the multivariable models:

- Step 1: Identify base models with traffic volume only.
- Step 2: Explore other predictor variables.
- Step 3: Select final model.

The project team determined the appropriate form for the base models (Step 1) according to the procedure outlined in Hauer.[(12)] The team added predictor variables to the base models and assessed them one at a time to determine the appropriate functional form and value added. They used various functional forms to assess potential relationships between crash frequency and continuous variables and to determine whether variables were best represented as continuous or indicator variables. The team used the correlation matrix to consider correlations among predictor variables and prioritized correlated variables for inclusion in the final models. Once a variable was included in the model, the project team examined estimated parameters and associated standard errors to determine the following:

- Was the direction of effect (i.e., expected decrease or increase in crashes) in general agreement with expectations? General expectations were based on previous research.

- Did the magnitude of the effect seem reasonable?

- Were the parameters of the model estimated with statistical significance?
- Did the estimated dispersion parameter improve significantly?

CHAPTER 5. DATA COLLECTION

The majority of data for this study was collected under a previous project funded by FHWA, entitled *Safety Evaluation of Access Management Policies and Techniques*.[13] The current study relied on Geographic Information System (GIS) files compiled under the previous effort to identify candidate intersections for this evaluation. The GIS files provided the location and type of turning restriction (i.e., full movement or RIRO) for intersections across California.

The GIS files were enriched with additional data from the HSIS database. The HSIS roadway inventory provided number of lanes, lane width, shoulder width, design speed, average annual daily traffic (AADT), and other geometric characteristics on the mainline roads. The intersection inventory from HSIS supplied routes, county numbers, and mileposts on the mainline of all intersections. The HSIS inventory also provided AADT of the cross street. The project team verified HSIS data using Google® Earth™.

The project team used milepost, county, and route number to identify and link crashes from the HSIS crash data files to each intersection. The team included all crashes that occurred within a 200-ft influence zone from the center of the intersection (i.e., 100 ft upstream and 100 ft downstream). The team used location type information to identify and separate "intersection-related" crashes (loc_typ = "I") and number of vehicles involved with crash severity to develop multiple vehicle and fatal and injury data categories.

The data collection process followed these key steps:

- Step 1: Using the existing intersection GIS files, the attribute tables were exported from ArcGIS into text file format.[14] Latitude and longitude of all intersections were calculated using the "calculate geometry" tool in ArcGIS prior to exporting the attribute table. Data files were imported into MS Excel and separated by traffic control types (i.e., stop control or signalized).

- Step 2: Exported data from the previous step were processed and encoded into Keyhole Markup Language (KML) for Google® Earth™. The project team created separate KML files for stop control and signalized intersections.

- Step 3: KML files were imported into Google® Earth™, and each route was reviewed to select appropriate intersections for this study. Candidate intersections were marked in HSIS intersection inventory files. Stop-controlled sites with full movement or RIRO turning movements were selected as candidates if they at least fit the following criteria:

    - 200 ft from another stop-controlled intersection.
    - 100 ft away from the limits of a turning lane for a signalized intersection.
    - 350 ft from a signalized intersection with no turning lanes.

The team used the Ruler tool in Google® Earth™ for distance measurement.

The feature identifier (FID) number, a unique identifier from ArcGIS and shown in the Google® Earth™ KML files, was populated in the HSIS intersection inventory for candidate sites as a reference key. The team used cross-street names to relate sites across the two datasets. Street names of the upstream and downstream intersections were available for additional verification. Cross-street name for each intersection in the HSIS data file was an essential piece of information for this process. Having cross-street name and verifying it in Google® Earth™ allowed the project team to link and merge information across data files from different sources. This was also why California was the only State examined in this study. The project team considered other States where GIS data were collected. However, either these States did not have an HSIS intersection file to supplement the data or the intersection files did not have data elements to link GIS and HSIS data (e.g., cross-street name).

Figure 3 and figure 4 illustrate the site selection process for an intersection on Route 82 in northern California. This example identifies a stop-controlled intersection with RIRO operation (FID = 8) in Google® Earth™. This intersection is approximately 260 ft from the left-turn lanes at the nearby signalized intersection (FID = 9), and there are no other stop-controlled intersections within 200 ft of this intersection. It met the three criteria listed above, and is located in the HSIS intersection inventory in Figure 4. The cross street name, Rice Way, from Google® Earth™, is shown in Figure 3 and was located in the HSIS intersection inventory in Figure 4. The project team used the nearby intersection (Branham Lane) to confirm the location of interest. Last, the team entered the FID (FID = 8) in the HSIS intersection inventory file.

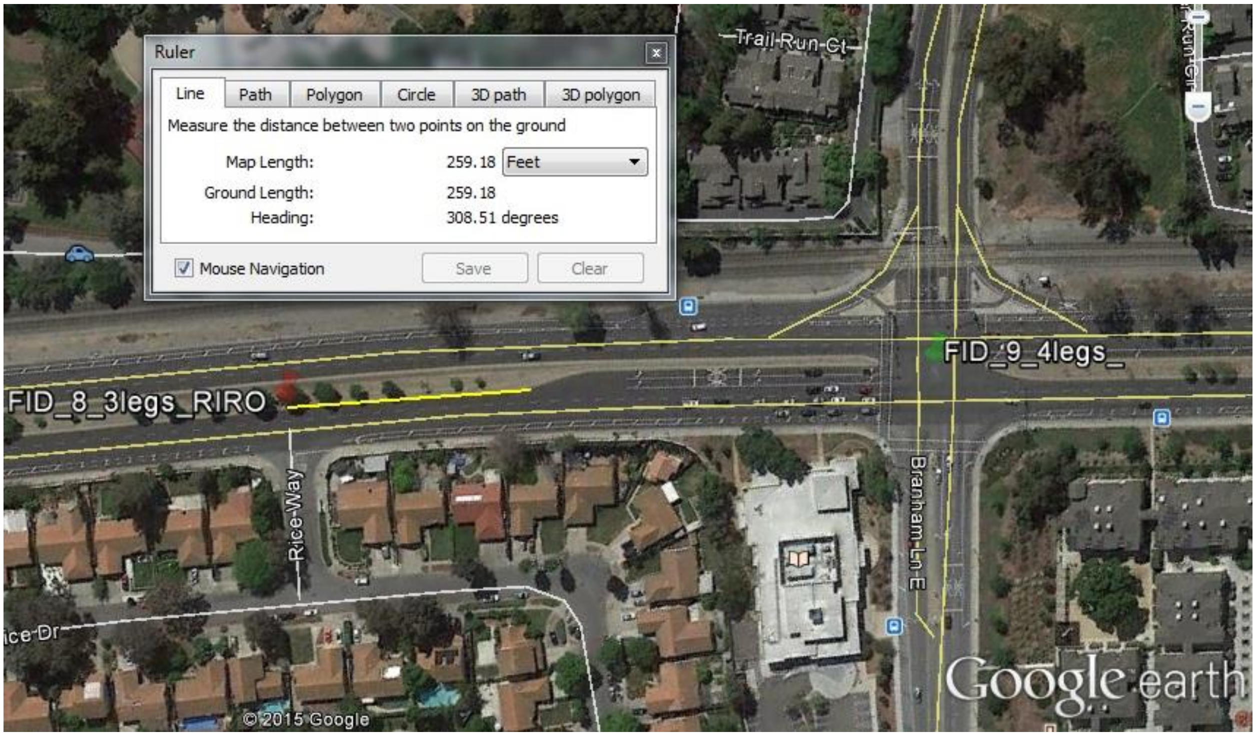


Figure 3. Screenshot. Example intersection selection from Google® Earth™.(15)

int_desc	FID	trf_cntl	milepost	int_prf	county	xstaadt	cntyrte	inty_rte	int_rte	rte_nbr
GAZANIA DR	6	B	1.16		43	101	04082 43 D		.	082
BOUGAINVILLEA DR	7	B	1.32		43	301	04082 43 D		.	082
RICE WAY	8	B	1.481		43	101	04082 43 D		.	082
BRANHAM LN		B	1.631		43	600	04082 43 D		.	082
VALLEY HAVEN WAY	10	B	2.03		43	400	04082 43 D		.	082
SKYWAY DR (SNELL RD)		M	2.133		43	8200	04082 43 D		.	082
SENTER RD		M	2.662		43	2600	04082 43 D		.	082

Source: FHWA, data from HSIS.

Figure 4. Screenshot. HSIS intersection inventory table.

In addition to collecting data for these stop-controlled intersections, the project team collected data from downstream intersections. The goal was to examine possible crash migration from an RIRO location to the nearest location where vehicles can make U-turns. In all cases, the downstream intersection was the next immediate intersection following the parent RIRO or full movement intersection. The project team collected the following elements for the downstream turning locations:

- Type of traffic control (i.e., signalized or minor road stop control). For signalized intersections, it was unknown if a protected phase could facilitate a U-turn.
- Presence of a dedicated turn lane.
- Distance from stop-controlled intersection to downstream turn lane (if applicable).
- Distance from stop-controlled intersection to downstream turning location (where U-turn was permitted).

The project team collected data for 333 candidate stop-controlled intersections and 202 downstream intersections. During preliminary data analysis, the team decided to retain locations with four or six lanes on the mainline and drop all other locations. There were too few RIRO sites along two-lane corridors to draw meaningful conclusions (five intersections in this category). Further, based on literature review, prior studies indicated little if any benefit for implementing RIRO at intersections and driveways where left-turning traffic only crossed one lane. Locations with five or more than six lanes were also dropped because of small sample sizes.

The final dataset included 138 stop-controlled intersections with a mix of RIRO and full movement operations. The downstream intersection dataset included 109 intersections with a mix of stop- and signal-control. The number of downstream intersections was smaller because some three-legged, stop-controlled intersections had the same downstream intersection. This happened when two parent intersections (i.e., three-legged stop-controlled) were located on opposite sides and opposite approaches to a four-legged intersection. When two stop-controlled intersections shared a downstream intersection, the project team confirmed that the type of operation (i.e., RIRO or full movement) was the same for the two parent intersections.

DATA SUMMARY

The project team collected and aggregated three years of data for the analysis. Table 3 and table 4 present a data summary for 138 urban, three-legged, stop-controlled intersections included in the primary analysis. Table 3 presents a summary of 58 locations with RIRO operations using physical barriers, and table 4 presents a summary 80 locations with full movement. Table 5 and table 6 present data summaries for 109 intersections downstream from the primary study intersections. Table 5 presents a summary of 48 intersections downstream from intersections with RIRO operations, and table 6 presents a summary of 61 intersections downstream from intersections with full movement.

For continuous variables (e.g., mainline AADT), the tables present the number of sites as well as the mean, standard deviation, minimum, and maximum value for each variable. For indicator variables (e.g., mainline six-lane indicator), the tables present the number of sites as well as the mean, minimum, and maximum value for each variable. Indicator variables are either 0 or 1, indicating the absence or presence of the characteristic, respectively. The mean value of an indicator variable indicates the proportion of sites with the attribute present (indicator value of 1). For example, the six-lane indicator in table 3 had a mean value of 0.586. This implied that 58.6 percent of locations had six lanes on the mainline (indicator value = 1), and 41.4 percent of locations had four lanes (indicator value = 0). Similarly, the mean value of the signalized indicator in table 5 was 0.771, indicating that 77.1 percent of the sample was signalized intersections.

Table 3. Data summary for urban, three-legged, stop-controlled intersections with RIRO operation.

Variable	Sites	Mean	Std. Dev.	Min	Max
Mainline AADT	58	38,724	11,997	13,433	75,000
Cross street AADT	58	519	510	51	2,600
Mainline six-lane indicator (1 if six lanes, 0 if four lanes)	58	0.586	—	0	1
50+ mph indicator (1 if 50+ mph, 0 otherwise)	58	0.224	—	0	1
Total crashes	58	2.586	2.555	0	9
Intersection-related crashes	58	0.638	0.968	0	4
Fatal and injury, intersection-related crashes	58	0.190	0.438	0	2

—Not applicable.

Table 4. Data summary for urban, three-legged, stop-controlled intersections with full movement.

Variable	Sites	Mean	Std. Dev.	Min	Max
Mainline AADT	80	34,271	11,719	9,940	75,000
Cross street AADT	80	765	759	51	3,650
Mainline six-lane indicator (1 if six lanes, 0 if four lanes)	80	0.288	—	0	1
50+ mph indicator (1 if 50+ mph, 0 otherwise)	80	0.500	—	0	1
Total crashes	80	4.163	3.777	0	17
Intersection-related crashes	80	2.025	2.658	0	11
Fatal and injury, intersection-related crashes	80	1.125	1.618	0	8

—Not applicable.

Table 5. Data summary for downstream intersections of locations with RIRO operation.

Variable	Sites	Mean	Std. Dev.	Min	Max
Mainline AADT	48	39,148	12,723	22,010	75,000
Cross street AADT	48	6,686	9,656	201	56,000
Signalized indicator (1 if signalized, 0 otherwise)	48	0.771	—	0	1
Mainline six-lane indicator (1 if six lanes, 0 if four lanes)	48	0.563	—	0	1
Total crashes	48	18.146	24.163	0	107
Intersection-related crashes	48	6.563	9.079	0	50
Fatal and injury, intersection-related crashes	48	2.771	3.508	0	12

—Not applicable.

Table 6. Data summary for downstream intersections of locations with full movement.

Variable	Sites	Mean	Std. Dev.	Min	Max
Mainline AADT	61	34,573	12,489	8,867	75,000
Cross street AADT	61	3,918	5,459	51	25,390
Signalized indicator (1 if signalized, 0 otherwise)	61	0.557	—	0	1
Mainline six-lane indicator (1 if six lanes, 0 if four lanes)	61	0.295	—	0	1
Total crashes	61	8.475	7.997	0	36
Intersection-related crashes	61	3.213	3.843	0	21
Fatal and injury, intersection-related crashes	61	1.705	1.986	0	8

—Not applicable.

CHAPTER 6. DEVELOPMENT OF CRASH PREDICTION MODELS

This chapter presents crash prediction models. The project team used generalized linear modeling to estimate model coefficients assuming a negative binomial error distribution, consistent with the state of research in developing these models. In specifying a negative binomial error structure, the team estimated the dispersion parameter, *k*, iteratively from the model and the data. For a given dataset, smaller values of *k* indicate relatively better models.

The project team calibrated crash prediction models separately for urban, three-legged, stop-controlled intersections and downstream four-legged, stop-controlled, and signalized intersections. The following sections present the crash prediction models developed. Variable definitions included in the final crash prediction models are as follows:

- *TOTAL* = predicted number of total crashes (all types and severities).
- *TOTAL_INT* = predicted number of total intersection-related crashes.
- *FI_INT* = predicted number of intersection-related fatal and injury crashes.
- *ML_AADT* = AADT on the mainline (two-way, vehicles/day). (Traffic volume estimates were from HSIS, representing AADT for the roadway section as a whole.)
- *XST_AADT* = AADT on the cross street (two-way, vehicles/day). (Traffic volume estimates were from HSIS, representing AADT for the roadway section as a whole.)
- *RIRO* = indicator for RIRO operation (1 if RIRO, 0 otherwise).
- *LANE6* = indicator for number of mainline lanes (1 if six, 0 if four).
- *SPD50PLUS* = indicator for design speed (1 if ≥50 mph on mainline, 0 otherwise).

CRASH PREDICTION MODELS

Total Crashes

Figure 5 presents the functional form of the crash prediction model, and table 7 presents the model parameters for total crashes.

$$TOTAL = ML\_AADT^{\beta_1} \times XST\_AADT^{\beta_2} \times e^{(\beta_3 \times RIRO + \beta_4 \times LANE6 + \beta_6)}$$

Figure 5. Equation. Model for total crashes.

Table 7. Model parameters for total crashes.

Variable	Coefficient	Estimated Value	Standard Error
Mainline AADT	β_1	0.834	0.232
Cross street AADT	β_2	0.285	0.078
RIRO operation	β_3	–0.604	0.156
Mainline with six lanes	β_4	0.355	0.163
Intercept term	β_6	–9.220	2.437
Dispersion parameter (*k*)	—	0.364	0.094

—Not applicable.

Intersection-Related Crashes

Figure 6 presents the functional form of the crash prediction model, and table 8 presents the model parameters for intersection-related crashes.

$$TOTAL\_INT = ML\_AADT^{\beta_1} \times XST\_AADT^{\beta_2} \times e^{(\beta_3 \times RIRO + \beta_4 \times LANE6 + \beta_5 \times SPD50PLUS + \beta_6)}$$

Figure 6. Equation. Model for intersection-related crashes, all severities.

Table 8. Model parameters for total intersection-related crashes.

Variable	Coefficient	Estimated Value	Standard Error
Mainline AADT	β_1	0.850	0.329
Cross street AADT	β_2	0.493	0.113
RIRO operation	β_3	–1.127	0.252
Mainline with six lanes	β_4	0.458	0.231
50 mph or higher design speed	β_5	0.442	0.219
Intercept term	β_6	–11.751	3.436
Dispersion parameter (*k*)	—	0.500	0.170

—Not applicable.

Fatal and Injury, Intersection-Related Crashes

Figure 7 presents the functional form of the crash prediction model, and table 9 presents the model parameters for fatal and injury, intersection-related crashes.

$$FI\_INT = ML\_AADT^{\beta_1} \times XST\_AADT^{\beta_2} \times e^{(\beta_3 \times RIRO + \beta_5 \times SPD50PLUS + \beta_6)}$$

Figure 7. Equation. Model for fatal and injury, intersection-related crashes.

Table 9. Model parameters for fatal and injury, intersection-related crashes.

Variable	Coefficient	Estimated Value	Standard Error
Mainline AADT	β_1	0.957	0.379
Cross street AADT	β_2	0.413	0.132
RIRO operation	β_3	–1.616	0.361
50 mph or higher design speed	β_5	0.539	0.267
Intercept term	β_6	–12.821	3.983
Dispersion parameter (*k*)	—	0.407	0.220

—Not applicable.

The team also developed crash prediction models for the immediate U-turn location downstream from the intersection of interest. The team considered five additional predictor variables beyond those considered in developing crash prediction models for the upstream "parent" full movement and RIRO intersections. Specifically, the team considered an indicator for the operation at the parent intersection (full movement or RIRO), an indicator for the traffic control (stop-controlled or signalized), an interaction term between these two indicators, an indicator for the presence of turn lanes, and the distance to the parent intersection of interest. While several of these variables were not statistically significant at the 90-percent confidence level, the team included the terms in the final models for predictive purposes. Specifically, the inclusion of these variables can help users differentiate between scenarios. The model development process revealed that including these variables did not statistically affect the indicator for RIRO operations. As such, the inclusion of these variables does not impact the recommended CMFs. The remainder of this section presents the models and associated model parameters. Definitions of variables included in the final crash prediction models are as follows:

- $TOTAL_{DS}$ = predicted number of total crashes (all types and severities) at downstream intersections.
- $TOTAL\_INT_{DS}$ = predicted number of total intersection-related crashes (coded as intersection-related) at downstream intersections.
- FI_INT_{DS} = predicted number of intersection-related fatal and injury crashes (coded as intersection-related) at downstream intersections.
- $MLAADT_{DS}$ = AADT on the mainline at downstream intersections (two-way, vehicles/day).
- $XSTAADT_{DS}$ = AADT on the cross street at downstream intersections (two-way, vehicles/day).
- *PRIRO* = indicator for RIRO operation at upstream "parent" intersection of interest (1 if RIRO, 0 otherwise).
- *SIGNAL* = indicator for signal control at downstream intersection (1 if signalized downstream intersection, 0 otherwise).
- *RIROSIG* = interaction term between PRIRO and SIGNAL (= PRIRO × SIGNAL).

- *TRNLN* = indicator for the presence of turn lane(s) at downstream intersection, located on the same approach as intersection of interest (1 if turn lane, 0 otherwise).

- *TRNDIST* = distance from the stop-controlled intersection of interest to its downstream intersection (immediate U-turn location).

- *LANE6* = indicator for number of lanes on the mainline (1 if six, 0 if four).

- *SPD50PLUS* = indicator for design speed (1 if ≥50 mph on mainline, 0 otherwise).

Total Crashes at Downstream Intersections

Figure 8 presents the functional form of the crash prediction model, and table 10 presents the model parameters for total crashes at the downstream intersections.

$$TOTAL_{DS} = MLAADT_{DS}^{\beta_1} \times XSTAADT_{DS}^{\beta_2} \times e^{(\beta_3 \times \mathrm{PRIRO} + \beta_4 \times SIGNAL + \beta_5 \times \mathrm{RIROSIG} + \beta_6 \times TRNLN + \beta_7 \times TRNDIST + \beta_8 \times LANE6 + \beta_9 \times SPD50PLUS + \beta_{10})}$$

Figure 8. Equation. Model for total crashes at downstream intersections.

Table 10. Model parameters for total crashes at downstream intersections.

Variable	Coefficient	Estimated Value	Standard Error
Mainline AADT	β_1	0.918	0.268
Cross street AADT	β_2	0.254	0.078
RIRO operation at upstream intersection	β_3	0.494	0.328
Signal control	β_4	0.742	0.271
Interaction between RIRO and Signal	β_5	–0.402	0.373
Presence of turning lane(s)	β_6	0.107	0.265
Distance to turning point	β_7	–3.68E–04	2.42E–04
Mainline with six lanes	β_8	0.284	0.185
50 mph or higher design speed	β_9	0.168	0.181
Intercept term	β_{10}	–10.057	2.712
Dispersion parameter (*k*)	—	0.503	0.087

—Not applicable.

Total Intersection-Related Crashes at Downstream Intersections

Figure 9 presents the functional form of the crash prediction model, and table 11 presents the model parameters for total intersection-related crashes at the downstream intersections.

$$TOTAL\_INT_{DS} = MLAADT_{DS}^{\beta_1} \times XSTAADT_{DS}^{\beta_2} \times e^{(\beta_3 \times PRIRO + \beta_4 \times SIGNAL + \beta_5 \times \text{RIROSIG} + \beta_6 \times TRNLN + \beta_7 \times TURNDIST + \beta_8 \times LANE6 + \beta_9 \times SPD50PLUS + \beta_{10})}$$

Figure 9. Equation. Model for total intersection-related crashes at downstream intersections.

Table 11. Model parameters for total intersection-related crashes at downstream intersections.

Variable	Coefficient	Estimated Value	Standard Error
Mainline AADT	β_1	0.780	0.319
Cross street AADT	β_2	0.413	0.093
RIRO operation at upstream intersection	β_3	0.938	0.390
Signal control	β_4	0.471	0.333
Interaction between RIRO and Signal	β_5	–0.917	0.447
Presence of turning lanes	β_6	0.096	0.313
Distance to turning point	β_7	–3.62E–04	2.75E–04
Mainline with six lanes	β_8	0.141	0.212
50 mph or higher design speed	β_9	0.245	0.217
Intercept term	β_{10}	–10.627	3.254
Dispersion parameter (*k*)	—	0.563	0.119

—Not applicable.

Fatal and Injury Intersection-Related Crashes at Downstream Intersections

Figure 10 presents the functional form of the crash prediction model, and table 12 presents the model parameters for fatal and injury intersection-related crashes at the downstream intersections.

$$TOTAL_{DS} = MLAADT_{DS}^{\beta_1} \times XSTAADT_{DS}^{\beta_2} \times e^{(\beta_3 \times \text{PRIRO} + \beta_4 \times SIGNAL + \beta_5 \times \text{RIROSIG} + \beta_6 \times TRNLN + \beta_7 \times TRNDIST + \beta_8 \times \text{LANE6} + \beta_9 \times SPD50PLUS + \beta_{10})}$$

Figure 10. Equation. Model for fatal and injury, intersection-related crashes at downstream intersections.

Table 12. Model parameters for fatal and injury intersection-related crashes at downstream intersections.

Variable	Coefficient	Estimated Value	Standard Error
Mainline AADT	β_1	0.770	0.362
Cross street AADT	β_2	0.383	0.101
RIRO operation at upstream intersection	β_3	0.446	0.451
Signal control	β_4	0.332	0.374
Interaction between RIRO and Signal	β_5	–0.509	0.513
Presence of turning lane(s)	β_6	0.104	0.352
Distance to turning point	β_7	–2.42E–04	2.96E–04
Mainline with six lanes	β_8	–0.138	0.231
50 mph or higher design speed	β_9	0.056	0.236
Intercept term	β_{10}	–10.645	3.707
Dispersion parameter (k)	—	0.515	0.152

—Not applicable.

CHAPTER 7. CROSS-SECTIONAL EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 13 presents estimated CMFs and related standard errors for each target crash type at the stop-controlled intersections with RIRO compared to intersections with full movement. As above, following are the target crash types:

- Total: all crashes within 100 ft of intersection.
- Intersection-related: all crashes within 100 ft of intersection defined as "intersection-related."
- Fatal and injury: all injury crashes within 100 ft of intersection defined as "intersection-related."

Table 13. Results for urban, three-legged, stop-controlled intersections with RIRO compared to full movement.

Variable	Total	Intersection-Related	Fatal & Injury
Observed crashes per site-year with RIRO	0.86	0.21	0.06
Observed crashes per site-year with full movement	1.39	0.68	0.38
Estimate of CMF	0.55*	0.32*	0.20*
Standard error of CMF	0.09	0.08	0.07

*Statistically significant results at the 95-percent confidence level.

The project team estimated CMFs and standard errors based on the model coefficients in table 7 to table 9. Figure 11 presents the formula for estimating CMF from a regression model where β was the estimated coefficient from the regression model for the variable of interest, X was the condition without treatment, and Y was the condition with treatment. In this study, the variable of interest was RIRO, which is a binary variable where 1 indicates "with condition" (i.e., RIRO), and 0 indicates "without condition" (i.e., full movement). As an example, consider the model estimates from table 7, where the estimated coefficient for RIRO was –0.604. The total crash CMF for converting full movement to RIRO was exp (–0.604 * (1 – 0)) = 0.55.

$$CMF = \exp(\beta * (Y - X))$$

Figure 11. Equation. Formula for estimating CMF from regression model.

Figure 12 presents the formula for estimating the standard error of the CMF from a regression model. Again, β was the estimated coefficient from the regression model for the variable of interest, X was the condition without treatment, and Y was the condition with treatment. (Note: s was the standard error of the estimated coefficient from the regression model for the variable of interest.) Continuing with the previous example, consider the model estimates from table 7 where the estimated coefficient for RIRO was –0.604, and the standard error of the coefficient was 0.156. The standard error of the total crash CMF for converting full movement to RIRO was 0.09.

$$SE(CMF) = \frac{exp\big((\beta + s) * (Y - X)\big) - exp\big((\beta - s) * (Y - X)\big)}{2}$$

Figure 12. Equation. Formula for estimating standard error of CMF from regression model.

The aggregate results indicated reductions for all crash types analyzed (i.e., total, all intersection-related, and fatal and injury intersection-related) at the stop-controlled intersections with RIRO compared to intersections with full movement. The reductions were statistically significant at the 95-percent confidence level for all crash types. The CMF for total, all intersection-related, and fatal and injury intersection-related crashes were 0.55, 0.32, and 0.20, respectively.

Crash migration is a potential issue related to the physical restriction of turning movements at a given access point. This occurs when crashes at a treated site are shifted to another site. While RIRO operations eliminate left turns at the subject location, U-turn movements and related crashes have potential to increase at the next intersections upstream and downstream that allow U-turns. As such, at a full movement signalized intersection within a corridor, there could be an increase in U-turn movements from both directions along the mainline if the stop-controlled intersections are converted to RIRO along the corridor. To account for this in this analysis, only U-turns at one intersection (the downstream intersection) were paired with the RIRO intersection because U-turn movements at the upstream intersection were paired with another RIRO intersection, and the effect was counted. This avoided double counting U-turns and overestimating the effect.

Figure 13 illustrates the relocation of direct left turns at a parent full movement, stop-controlled intersection to a downstream intersection when the parent intersection was converted to RIRO. To estimate the change in safety performance, the combined safety performance of the full movement stop-controlled intersection and downstream intersection need to be compared with the combined safety performance of the RIRO stop-controlled intersection and downstream intersection. Table 13 provides CMFs for estimating the change in safety from converting full movement to RIRO at the parent stop-controlled intersection. The remainder of this section provides the CMFs needed to estimate change in safety performance at the downstream intersection.

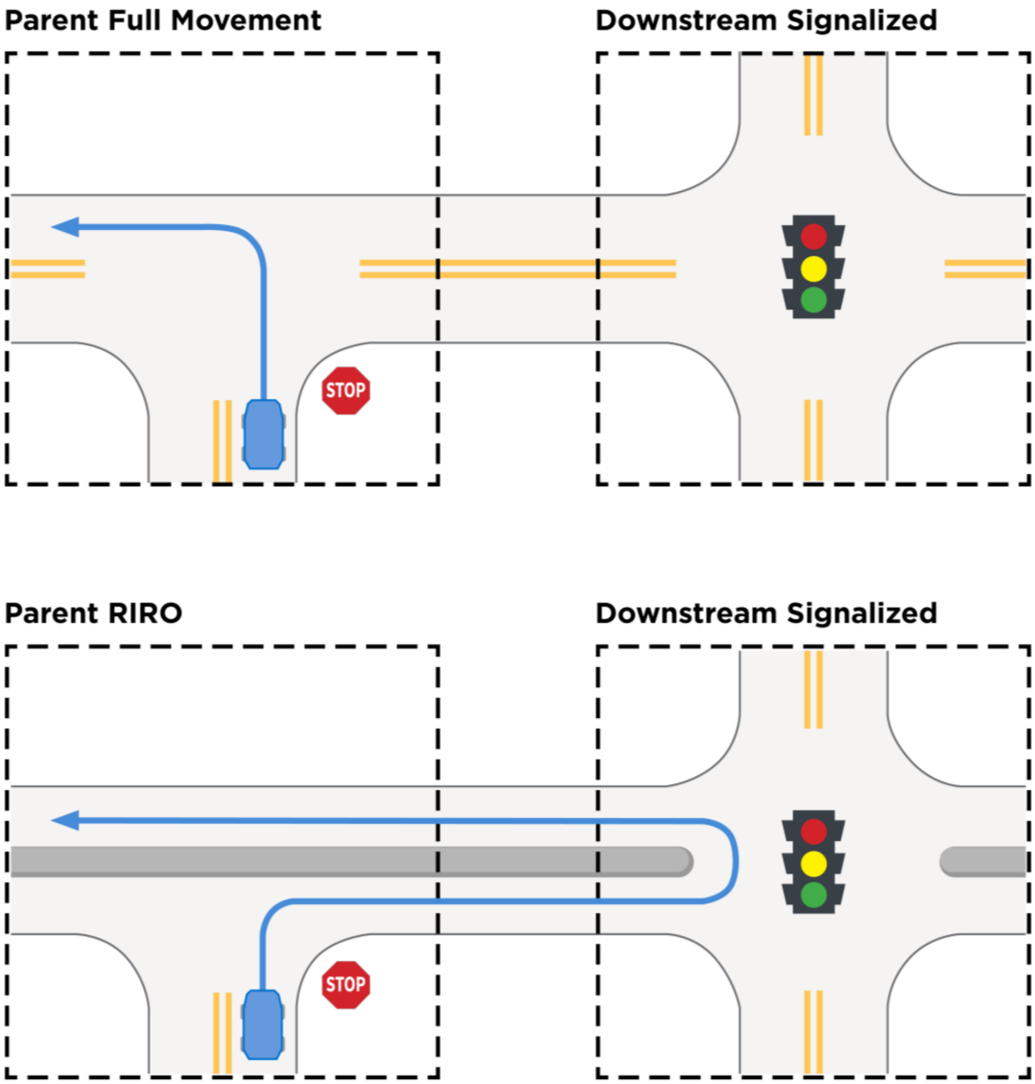


Figure 13. Graphic. Illustration of upstream and downstream full movement intersections compared to upstream RIRO and downstream full movement intersections.

The project team considered the potential change in crashes at downstream locations. Specifically, the project team identified the nearest downstream intersection where U-turning was permitted and compared crashes at parent RIRO stop-controlled intersections with parent full movement stop-controlled intersections. The downstream intersections comprised both signalized and stop-controlled intersections. For downstream signalized intersections, the signal phasing was unknown and may include permissive, permissive-protected, and protected left-turn phasing. In this analysis, the team used an interaction term between the RIRO indicator for the upstream intersection and the signal control indicator for the downstream intersection. This revealed differences in crash migration effects by traffic control type (i.e., signal vs. stop control) at the downstream U-turn location. The project team computed CMFs from the estimated model coefficients in table 10 to table 12 using the equation in figure 14.

$$CMF = e^{(\beta_3 + \beta_5 \times RIROSIG)}$$

Figure 14. Equation. Formula for estimating CMF from regression model with interaction term.

Figure 15 presents the equation to compute the standard error of the CMF.(16)

$$SE(CMF) = \sqrt{VAR(\beta_3) + RIROSIG^2 \times VAR(\beta_5) + 2 \times RIROSIG \times COV(\beta_3, \beta_5)}$$

Figure 15. Equation. Formula for estimating standard error of CMF from regression model with interaction term.

Where:

- β_3 = model coefficient for RIRO operation at the upstream intersection of interest (table 10–table 12).
- β_5 = model coefficient for the interaction term between RIRO operation at the upstream intersection of interest and the signal control at the downstream intersection (table 10–table 12).
- *RIROSIG* = interaction term (1 if RIRO upstream and signalized downstream intersection; 0 otherwise).
- $VAR(\beta_3)$ = variance of β_3 (from variance-covariance matrix of estimated coefficients).
- $VAR(\beta_5)$ = variance of β_5 (from variance-covariance matrix of estimated coefficients).
- $COV(\beta_3, \beta_5)$ = covariance of β_3 and β_5 (from variance-covariance matrix of estimated coefficients).

Table 14 and table 15 present the estimated CMFs and related standard errors for each target crash type and traffic control type combination at the downstream intersections. The CMFs represent the change in crashes at the immediate downstream full movement intersection from RIRO locations compared to an immediate downstream full movement intersection from full movement locations. Analysts should apply the downstream CMF for each upstream intersection. In other words, the CMFs represent the safety effect of each intersection conversion from full movement to RIRO. For example, if there were three full movement intersections converted to RIRO immediately upstream of a signalized intersection and the CMF for total crashes at the downstream signal was 1.10 for a single conversion, then the combined CMF for total crashes at the downstream signalized intersection was 1.10 * 1.10 * 1.10 = 1.33.

Table 14 presents the results for downstream intersections with signal control. Reductions were not statistically significant even at the 90-percent confidence level; however, there was potential for increased total and intersection-related crashes at downstream signalized intersections. CMFs for total, all intersection-related, and fatal and injury intersection-related crashes were 1.10, 1.02, and 0.94, respectively. A rigorous analysis would include the potential increases, even though these were not statistically significant, in estimating the net benefit conservatively.

Table 15 presents the results for downstream intersections with stop-control. Increases were statistically significant at the 90-percent confidence level for two of the three CMFs, one of which was also statistically significant at the 95-percent confidence level. All three CMFs indicated potential for increased total, intersection-related, and fatal and injury intersection-related crashes at downstream stop-controlled intersections. CMFs for total, all intersection-related, and fatal and injury intersection-related crashes were 1.64, 2.55, and 1.56, respectively. A rigorous analysis would include the potential increases, even those that were not statistically significant, in estimating the net benefit conservatively.

Comparing CMFs, results indicated small potential changes for all crash types at downstream signalized intersections relative to downstream stop-controlled intersections. Further, CMFs for downstream signalized intersections were not statistically significant at the 90-percent confidence level, while two of the three CMFs for downstream stop-controlled intersections were statistically significant at the 90-percent confidence level.

Table 14. Results for urban signalized intersections downstream from stop-controlled intersections with RIRO compared to full movement.

Variable	Total	Intersection-Related	Fatal and Injury
Estimate of CMF (parent RIRO = 1 and downstream SIGNAL = 1)	1.10	1.02	0.94
Standard error of CMF (parent RIRO = 1 and downstream SIGNAL = 1)	0.20	0.24	0.26

Table 15. Results for urban stop-controlled intersections downstream from stop-controlled intersections with RIRO compared to full movement.

Variable	Total	Intersection-Related	Fatal and Injury
Estimate of CMF (parent RIRO = 1 and downstream SIGNAL = 0)	1.64*	2.55**	1.56
Standard error of CMF (parent RIRO = 1 and downstream SIGNAL = 0)	0.33	0.39	0.45

*Statistically significant result at the 90-percent confidence level.
**Statistically significant result at the 95-percent confidence level.

DISAGGREGATE ANALYSIS

The disaggregate analysis sought to identify those conditions under which the strategy is most effective. The project team considered several variables in the disaggregate analysis, including major and minor road traffic volume, number of mainline lanes, and design speed. The multivariable regression models included interaction terms to investigate the potential differential effects of RIRO with respect to the interacted variable. For example, the interaction term for major road traffic volume and RIRO was the product of the two variables. A statistically significant interaction term indicated an apparent differential effect of RIRO across varied traffic volumes.

Results indicated that interaction terms were not statistically significant at even an 80-percent confidence level for any of these interactions between RIRO and major road traffic volume, minor road traffic volume, design speed, and number of lanes on the mainline. This was consistent for all crash types.

Based on the disaggregate results, it did not appear that RIRO operations have differing effects for different levels of traffic on both mainline and cross-street, design speed, or number of lanes on the mainline.

CHAPTER 8. ECONOMIC ANALYSIS

The project team conducted an economic analysis of a hypothetical scenario to estimate the cost-effectiveness of converting full movement, stop-sontrolled intersections to RIRO operations using physical barriers. The team estimated the treatment cost based on the construction and maintenance costs associated with physical barriers. The team determined net benefits by considering the change in fatal and injury crashes at the hypothetical stop-controlled intersection as well as the next downstream median opening where drivers may make a U-turn. While this economic analysis focused on potential safety benefits in relation to installation and maintenance costs, other factors to consider included impacts to traffic operations (e.g., travel time and delay) and economic impacts to adjacent businesses.

For this analysis, the project team used sites with physical median barriers to create RIRO operations. Other agencies might have used other means to implement RIRO operations, such as cable barrier, rigid barrier, or with signs only. For estimating treatment costs, assumptions included an average median width of 4 ft at an average cost of $6 per square foot.(17) (Note: the median may be 6 ft wide for a portion of the length between full movement intersections, with narrower sections at the ends to facilitate turning lanes.) Given these assumptions, the implementation cost was approximately $24 per linear foot (or $126,720 per mile). For cost estimation purposes, the project team assumed a distance of 1,210 ft, which represented the average distance between the centers of signalized intersections evaluated in this study, minus 100 ft to account for the intersection area. Given these assumptions, the average cost per installation between signalized intersections was approximately $26,500. Analysts should adjust this cost accordingly, based on the scenario of interest and typical costs in their area as necessary.

The project team assumed the useful service life for safety benefits was 20 yr. Based on Michigan and Ohio data, the annual maintenance costs per lane-mile for area mowing, curb sweeping, and curb and gutter repairs were less than $60 annually. Given the relatively low cost for these services, the team assumed these costs were negligible compared to the installation costs over the service life.(18)

FHWA Office of Safety Research and Development suggested using the Office of Management and Budget *Circular A-4* as a resource for the real discount rate of seven percent to calculate the present value B/C of the treatment over the service life.(19) With this information, the project team computed the capital recovery factor as 10.59.

For the benefit calculations, the project team used the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type as a base.(20) FHWA developed these costs based on 2001 crash costs, and the unit cost (in 2001 U.S. dollars) for a fatal and injury crash was $158,177. At the time of analysis, this was updated to 2015 U.S. dollars by applying the ratio of the U.S. Department of Transportation (USDOT) 2015 value of a statistical life of $9.4 million to the 2001 value of $3.8 million.(20,21) Applying this ratio of 2.47 to the unit cost resulted in an aggregate 2015 unit cost of $391,280 for a fatal and injury crash.

To estimate the safety benefits of implementing RIRO operations, the project team analyzed two hypothetical sections: one with a single stop-controlled intersection leading to a signalized intersection and another more complex corridor example with multiple intersections. The team calculated the net change in crashes by adding the expected change in crashes at RIRO intersections to the expected change in crashes at the downstream intersections. In some cases, there was an expected increase in crashes at downstream intersections from conversion of upstream full movement stop-controlled intersections to RIRO intersections.

This section illustrates the proper application of applicable CMFs with hypothetical examples. Analysts should conduct a similar economic analysis with site-specific conditions and data to estimate the safety performance and B/C ratio for their specific scenario of interest.

EXAMPLE OF SINGLE INTERSECTION CONVERSION

The first example is a simple case of converting a single, full movement, three-legged, stop-controlled intersection to RIRO where the downstream intersection is signalized. Figure 13 illustrates this scenario. For the purpose of this analysis, the three-legged, stop-controlled intersection had an average crash frequency of 3.0 fatal and injury crashes per year before treatment, and the downstream signalized intersection had an average crash frequency of 5.0 fatal and injury crashes per year before treatment.

From table 13, the CMF for converting full movement stop-controlled intersections to RIRO was 0.20 for fatal and injury crashes. From table 14, the CMF for the effect at downstream signalized intersections was 0.94 for fatal and injury crashes, which was not statistically significant at 90-percent confidence level. While the CMF for the downstream intersection is included here for completeness, a conservative analysis could ignore the effects at the downstream signal because the CMF was less than 1.0, indicating a reduction in fatal and injury crashes.

Applying these CMFs to the average annual crashes before treatment yielded a reduction of 2.4 fatal and injury crashes per year (i.e., 3.0 * (1 – 0.20)) at the parent stop-controlled intersection and a reduction 0.3 crashes per year (i.e., 5.0 * (1 – 0.94)) at the downstream signalized intersection. The net crash reduction was approximately 2.7 fatal and injury crashes per year (i.e., 2.4 + 0.3). A conservative estimate of the crash reduction is 2.4 fatal and injury crashes per year, ignoring the potential reduction in crashes at the downstream signalized intersection.

The project team calculated annual economic benefits by multiplying the conservative crash reduction per year by the average cost of a fatal and injury crash. The team calculated the B/C ratio of 9.6 to 1 as the ratio of the present value of benefits to the present value of all costs. USDOT recommended a sensitivity analysis be conducted assuming values of a statistical life of 0.55 and 1.38 times the recommended 2015 value.(21) These factors can be applied directly to the estimated B/C ratios to get a range of from 5.4 to 1 to 13.5 to 1. Results of this hypothetical example suggested the RIRO strategy, with conservative assumptions in cost, service life, and value of a statistical life, can be cost effective for reducing fatal and injury crashes at similar stop-controlled intersections; however, there is a need to consider potential costs and benefits with site-specific values on a case-by-case basis.

EXAMPLE OF MULTIPLE INTERSECTION CONVERSION

The project team examined a more complex example with multiple conversions from full movement to RIRO along a corridor. Figure 16 illustrates this example, which proposed a section of a corridor between two four-legged intersections, one signalized and one stop-controlled. The side of the road leading to the four-legged signal has two three-legged, stop-controlled intersections. There is one three-legged, stop-controlled intersection on the other side of the road leading to the full movement, four-legged, stop-controlled intersection. The analyst would like to estimate change in safety performance by installing a median, effectively converting the three-legged stop-controlled intersections to RIRO.

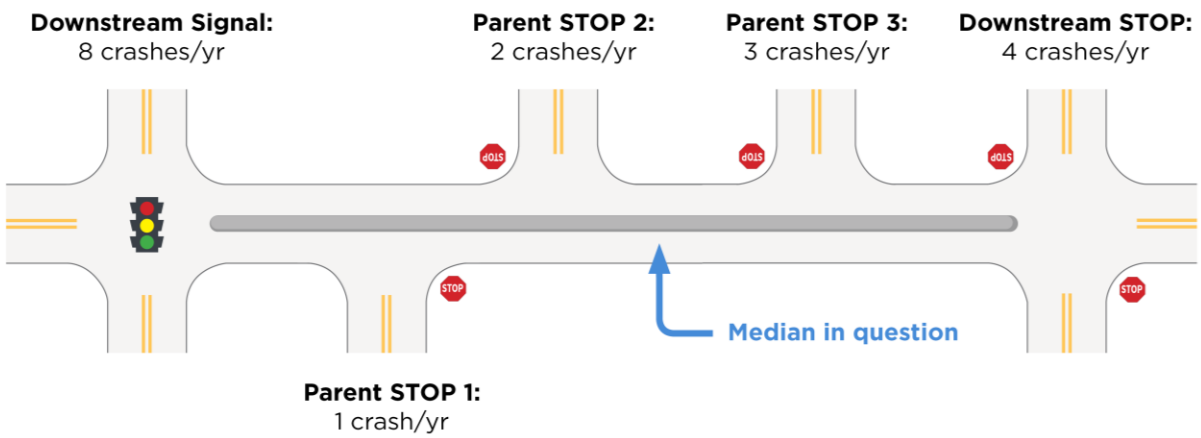


Figure 16. Graphic. Illustration of corridor with multiple intersections converted from full movement to RIRO.

From table 13, the CMF for converting full movement stop-controlled intersections to RIRO is 0.55 for total crashes. From table 14, the CMF for the effect at downstream signalized intersections was 1.10 for total crashes. From table 15, the CMF for the effect at downstream stop-controlled intersections was 1.64 for total crashes. To estimate the safety effect at a downstream intersection, an analyst must apply the applicable CMF once for each upstream intersection. In this example, there are two three-legged, stop-controlled intersections upstream of the signalized intersection, and the CMF for the effect at the signalized intersection is 1.10. The CMF is applied once for each upstream intersection, resulting in a combined CMF of 1.21 (i.e., 1.10 * 1.10).

Table 16 shows the average total crash frequency per year prior to treatment, applicable CMFs, estimated crashes per year after treatment (i.e., CMF * crashes per year before), and estimated change in crashes per year (i.e., estimated crashes per year after treatment minus average crashes per year before treatment) at each intersection.

Table 16. Applying CMFs to a corridor scenario.

Intersection	Average Crashes per Year Before Treatment	CMF	Estimated Crashes per Year After Treatment	Estimated Change in Crashes per Year
STOP 1—upstream from four-legged STOP	1.0	0.55	0.55	–0.45
STOP 2—upstream from four-legged signal	2.0	0.55	1.10	–0.90
STOP 3—upstream from four-legged signal	3.0	0.55	1.65	–1.35
Downstream four-legged STOP	4.0	1.64	6.56	+2.56
Downstream four-legged signal	8.0	1.21*	9.68	+1.68
Total	18.0	N/A	19.54	+1.54

*CMF multiplied twice (i.e., 1.10 * 1.10 = 1.21) to reflect two upstream intersections.

As shown Table 16, the net effect of installing a median to implement RIRO in this corridor section was an increase of 1.54 total crashes per year across all sites. This treatment is not justified due to the estimated increase in crashes, and therefore there is no need to conduct further analysis to estimate the B/C ratio.

SUMMARY

The hypothetical scenarios presented in this section illustrate the range of potential results from converting full movement, three-legged, stop-controlled intersections to RIRO. In some cases, it was cost-beneficial to convert full movement to RIRO intersections. In other cases, the increase in crashes at downstream locations outweighed the benefits at the parent intersection converted from full movement to RIRO. Analysts should conduct an economic analysis with site-specific conditions and data to estimate the safety performance and B/C ratio for the scenario of interest. In general, the B/C ratio for this treatment depends primarily on the magnitude of crashes at the parent intersection(s) and the downstream intersection(s). Specifically, conversion from full movement to RIRO will generally result in safety benefits when there is a demonstrated safety issue at the parent intersections and relatively low crash history at the downstream full movement intersections.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous cross-sectional evaluation of the safety effectiveness, as measured by crash frequency, of physical turning movement restrictions at urban, three-legged, stop-controlled intersections. The study compared RIRO to full movement access using data from California to examine the effects on total, intersection-related, and fatal and injury intersection-related crashes. Based on the aggregate results, table 17 presents recommended CMFs for various crash types for urban, three-legged, stop-controlled intersections with RIRO compared to full movement. Aggregate results indicated reductions for all crash types analyzed, and all reductions were statistically significant at the 95-percent confidence level.

Table 17. Recommended CMFs for urban, three-legged, stop-controlled intersections with RIRO compared to full movement.

Variable	Total	All Intersection-Related	Fatal and Injury
Estimate of CMF	0.55*	0.32*	0.20*
Standard error of CMF	0.09	0.08	0.07

*Statistically significant results at the 95-percent confidence.

While results indicated crash reductions at stop-controlled intersections with RIRO compared to full movement, there is a need to consider the potential for crash migration in determining the net benefits. Table 18 and table 19 present recommended CMFs for various crash types for signalized and stop-controlled intersections, respectively, downstream from urban, three-legged, stop-controlled intersections with RIRO compared to full movement. CMFs in table 18 and table 19 apply to the immediate full movement downstream intersection, and analysts should apply the downstream CMF once for each upstream intersection converted from full movement to RIRO. For example, if there are three full movement intersections converted to RIRO immediately upstream of a signalized intersection, and the CMF for total crashes at the downstream signal is 1.10 for a single conversion, then the combined CMF for total crashes at the downstream signalized intersection is 1.10 * 1.10 * 1.10 = 1.33.

Table 18. Recommended CMFs for urban signalized intersections downstream from stop-controlled intersections with RIRO compared to full movement.

Variable	Total	All Intersection-Related	Fatal and Injury
Estimate of CMF (signalized)	1.10	1.02	0.94
Standard error of CMF (signalized)	0.20	0.24	0.26

Note: apply CMFs once for each upstream intersection converted from full movement to RIRO.

Table 19. Recommended CMFs for urban stop-controlled intersections downstream from stop-controlled intersections with RIRO compared to full movement.

Variable	Total	Intersection-Related	Fatal and Injury
Estimate of CMF (stop-controlled)	1.64*	2.55**	1.56
Standard error of CMF (stop-controlled)	0.33	0.39	0.45

Note: apply CMFs once for each upstream intersection converted from full movement to RIRO.
*Statistically significant result at 90-percent confidence level.
**Statistically significant result at 95-percent confidence level.

Differences in crash migration effects depend on the downstream traffic control type. CMFs for downstream locations with signal control were close to 1.0, and estimates were not statistically significant at 90-percent confidence level. As such, there was relatively low chance of increased crashes for downstream signalized intersections. Conversely, results indicated likely increases at downstream stop-control intersections for all crash types analyzed. Increases were statistically significant at 90- and 95-percent confidence levels for total and total intersection-related crashes, respectively.

The disaggregate analysis sought to identify those conditions under which the strategy is most effective. Variables of interest included number of lanes on the mainline and cross street, traffic volumes, and design speed. For major road traffic volume, minor road traffic volume, and design speed, the disaggregate analysis indicated no statistically significant differences in effects for various levels of these variables.

The B/C ratio for converting a hypothetical stop-controlled intersection from full movement to RIRO, estimated with conservative cost and service life assumptions, and considering the change in fatal and injury crashes with the potential for crash migration at a downstream signalized intersection, was 9.6 to 1. With the USDOT recommended sensitivity analysis, these values could range from 5.4 to 1 to 13.5 to 1. The economic analysis is based on a single hypothetical stop-controlled intersection and a downstream signalized intersection. RIRO operation improved B/C when the target stop-controlled intersections had relatively high safety risk compared to downstream intersections, particularly downstream stop-controlled intersections. While these results suggest the strategy can be cost-effective in reducing crashes at stop-controlled intersections, there is a need to analyze potential costs and benefits on a case-by-case basis with site-specific values.

This study estimated the safety effectiveness of physical turning movement restrictions at urban, three-legged, stop-controlled intersections. The study compared RIRO to full movement access using data from California to examine the effects for total, intersection-related, and fatal and injury intersection-related crashes. Future research needs include the opportunity to evaluate similar data from other States, examine the safety effects related to other crash types such as pedestrian crashes, and expand the analysis to include other facility types such as two-lane roads.

APPENDIX. EXAMPLE INTERSECTIONS

This appendix presents images of three types of intersections considered in this study. Figure 17 displays an example of a three-legged, stop-controlled intersection with full turning movements (i.e., no restrictions).

Figure 17. Photo. Example three-legged, stop-controlled, full movement intersection.

Figure 18 displays an example of an urban, three-legged, stop-controlled intersection with RIRO operations.

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Figure 18. Photo. Example urban, three-legged, stop-controlled RIRO intersection.

Figure 19 displays an example of an urban, four-legged, signalized intersection downstream from a RIRO parent intersection.

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Figure 19. Photo. Example four-legged, signalized intersection downstream from RIRO parent intersection.

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