Safety Effects of Turning Movement Restrictions at Stop-controlled Intersections

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5th Urban Street Symposium
May 21 – 24, 2017
Raleigh, NC

ABSTRACT

The physical right-in-right-out (RIRO) turning movement restrictions at stop-controlled intersections was one of the strategies selected for safety evaluation under FHWA's Development of Crash Modification Factors (DCMF) program. This study evaluated the safety effects of converting full movement intersections to RIRO as measured by the change in crash frequency. The project team obtained geometric, traffic, and crash data for urban, three-legged, stop-controlled intersections with full movement and RIRO restrictions, as well as the downstream four-legged, stop-controlled or signalized intersection with full movement, from California. A cross-sectional analysis provided estimates of the effects of turning movement restrictions while controlling for other differences between sites with RIRO and full movement. The aggregate results indicate reductions for total, intersection-related, and fatal and injury intersection-related crashes for stop-controlled intersections with RIRO compared to full movement. The reductions are statistically significant at the 95-percent confidence level for all crash types. Based on the disaggregate results, it does not appear that RIRO restrictions have different effects for different levels of traffic, design speed, or number of lanes. The analysis also examined for the potential for crash migration in determining the net benefits. The results indicate potential crash increases at downstream intersections, but many of the 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, there is a need to analyze potential costs and benefits on a case-by-case basis with site-specific values.

INTRODUCTION

Turning movement restrictions are a type of access management strategy 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.(1) 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, which presents a risk for crashes. Right turns at most stop-controlled intersections are essentially weaving movements and do not present the same level of safety risks as left turns.

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

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

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. Right-in-right-out (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 Google Street View™ image of a stop-controlled intersection with RIRO turning movement restriction followed by a downstream signalized intersection where U-turns may occur (i.e., to facilitate the prohibited left turn movement at the RIRO stop-controlled intersection). Refer to Appendix A for further examples of intersections 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, there is limited information available about the quantitative safety effects of these practices and the effects on downstream intersections. This study serves to address the need for research into the safety effects of turning movement restrictions at stop-controlled intersections.

Figure 1. RIRO stop-control intersection with positive median barrier screenshot from Google Street View™.(2)

LITERATURE REVIEW

The literature review focused on the safety effects of RIRO restrictions, 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 provides a summary of the salient research related to specific strategies.

The research by Schultz, Braley, and Boschert in *Correlating Access Management to Crash Rate, Severity, and Collision Type* indicated 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) NCHRP Report 395 compared different outcomes from a number of crash prediction models developed by different researchers.(5) A composite finding suggested in general a raised median is safer than undivided roadways, especially on roads with above 20,000 vehicles per day. Eisele and Frawley investigated the relationship between access density and crash rate for raised median and non-raised median corridors separately.(6) Both relationships were positively correlated, but the trend was slightly steeper for non-raised median corridors than raised median corridors. The researchers concluded that the reduced slope of the regression line for raised median corridors demonstrates there are relatively lower crash rates in corridors with raised medians due to the reduced conflict points. A study with data from seven States by Hallmark et al. suggested raised medians reduced crashes at least 40-percent in urban settings.(7)

RESEARCH OBJECTIVE

This research examined the 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 & Injury: all injury crashes within 100 ft of intersection defined as 'intersection-related' by the reporting officer (K, A, B, and C injuries on KABCO scale).
- Multi-vehicle: all multiple-vehicle crashes within 100 ft of intersection defined as 'intersection-related' by the reporting officer (all types and severities combined). Note all 'intersection-related' crashes within 100 ft of the intersections included multiple vehicles, so the project team dropped this category from the remainder of the analysis, as it is 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 the type of traffic control at downstream intersections (i.e., signalized or minor road stop-control).
- By the presence of turn lanes at downstream intersections.

The evaluation of overall effectiveness included the consideration of the installation costs and crash savings in terms of the benefit-cost ratio.

METHODOLOGY

The evaluation used a cross-sectional study design. At the 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 other characteristics that vary among sites.

The project team used multivariable, negative binomial 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 represent the expected change in crash frequency due to a unit change in the predictor variable with all else being equal. 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. 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).(8,9)

DATA COLLECTION

The majority of data for this study was collected under a previous project funded by the FHWA entitled *Safety Evaluation of Access Management Policies and Techniques*.(10) 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 milepost 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”). They used number of vehicles involved and crash severity to develop multiple vehicle and fatal and injury data categories. 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 a RIRO location to the nearest location where vehicles 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 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 sites with physical RIRO restrictions along two-lane corridors to draw meaningful conclusions (five intersections in this category). Further, based on the literature review, prior studies indicate very little, if any, benefit of implementing RIRO at intersections and driveways where left-turning traffic only crosses one lane. Locations with five lanes 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 physical RIRO restriction and full movement. The downstream intersection dataset included 109 intersections with a mix of stop- and signal-control. The number of downstream intersections is smaller because some three-legged, stop-controlled intersections have the same downstream intersection. This happens when two parent intersections (i.e., three-legged stop-controlled) are located on opposite sides and opposite approaches to a four-legged intersection. When two stop-controlled intersections share a downstream intersection, the project team confirmed the type of restriction (i.e., RIRO or full movement) is the same for the two parent intersections.

Data Characteristics and Summary

The project team collected and aggregated three years of data for the analysis. Table 1 and Table 2 present a data summary for 138 urban, three-legged, stop-controlled intersections included in the primary analysis. Table 1 presents a summary of 58 locations with physical RIRO restriction and Table 2 presents a summary 80 locations with full movement. Table 3 and Table 4 present a data summary for 109 intersections downstream from the primary study intersections. Table 3 presents a summary of 48 intersections downstream from intersections with RIRO restriction and Table 4 presents a summary of 61 intersections downstream from intersections with full movement. 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 1 has a mean value of 0.586. This implies that 58.6 percent of locations have six lanes on the mainline (indicator value = 1) and 41.4 percent of locations have four lanes (indicator value = 0). Similarly, the mean value of the signalized indicator in Table 3 is 0.771, indicating that 77.1 percent of the sample is signalized intersections.

Table 1. Data summary for urban, three-legged, stop-controlled intersections with RIRO restriction.

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 6-lane indicator (1 if 6 lanes, 0 if 4 lanes)	58	0.586	0.497	0	1
50+ mph indicator (1 if 50+ mph, 0 otherwise)	58	0.224	0.421	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

Table 2. 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 6-lane indicator (1 if 6 lanes, 0 if 4 lanes)	80	0.288	0.455	0	1
50+ mph indicator (1 if 50+ mph, 0 otherwise)	80	0.500	0.503	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

Table 3. Data summary for downstream intersections of locations with RIRO restriction.

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	0.425	0	1
Mainline 6-lane indicator (1 if 6 lanes, 0 if 4 lanes)	48	0.563	0.501	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

Table 4. 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	0.501	0	1
Mainline 6-lane indicator (1 if 6 lanes, 0 if 4 lanes)	61	0.295	0.460	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

SAFETY PERFORMANCE FUNCTION DEVELOPMENT

This section presents the crash prediction 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. The 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). Note traffic volume estimates are from HSIS, representing the AADT for the roadway section as a whole.
- XST_AADT = AADT on the cross street (two-way, vehicles/day). Note traffic volume estimates are from HSIS, representing the AADT for the roadway section as a whole.
- RIRO = indicator for right-in-right-out restriction (1 if there is restriction, 0 otherwise).
- LANE6 = indicator for number of lanes on the mainline (1 if six lanes, 0 if four lanes).
- SPD50PLUS = indicator for design speed (1 if 50+ mph on mainline, 0 otherwise).

ANALYSIS RESULTS AND DISCUSSIONS

Table 5 presents the estimated CMFs and related standard errors for each target crash type at the stop-controlled intersections with RIRO compared to intersections with full movement. The aggregate results indicate reductions for all crash types analyzed: total, all intersection-related, and fatal and injury intersection-related. The reductions are 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 are 0.55, 0.32, and 0.20, respectively.

Table 5. 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

Note: * indicates statistically significant results at the 95-percent confidence level

Crash migration is a potential issue related to the physical restriction of turning movements at a given access point. This occurs when the crashes at a treated site are shifted to another site. While RIRO turning restrictions eliminate left turns at the subject location, there is potential to increase U-turn movements and related crashes at the next intersections upstream and downstream that allow U-turns.

Figure 2 illustrates the relocation of direct left turns at a parent full movement stop-controlled intersection to a downstream intersection when the parent intersection is converted to RIRO. To estimate the change in safety performance, there is a need to compare the combined safety performance of the full movement stop-controlled intersection and downstream intersection with the combined safety performance of the RIRO stop-controlled intersection and downstream intersection.

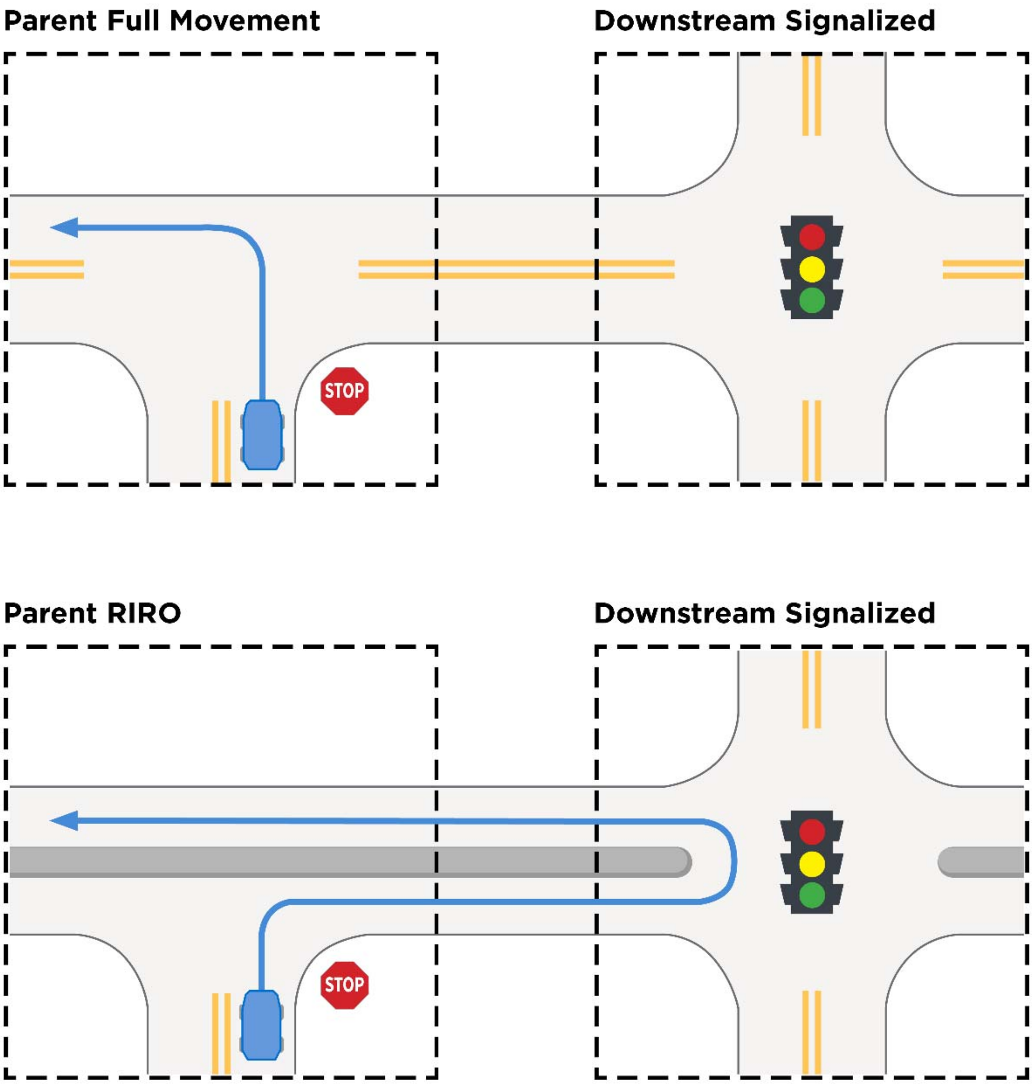

Figure 2. Illustration of upstream and downstream full movement intersections compared to upstream RIRO and downstream full movement intersections.

The project team considered the potential change in crashes at downstream locations. Specifically, the project team identified the nearest downstream intersection where U-turning is 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 is 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. Table 6 and Table 7 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.

Table 6 presents the results for downstream intersections with signal control. The reductions are not statistically significant even at the 90-percent confidence level; however, there is potential for increased total and intersection-related crashes at downstream signalized intersections. The CMFs for total, all intersection-related, and fatal and injury intersection-related crashes are 1.10, 1.02, and 0.94, respectively. A conservative analysis would include the potential increases (i.e., those not statistically significant) in the estimation of the net benefit.

Table 7 presents the results for downstream intersections with stop-control. The reductions are statistically significant at the 90-percent confidence level for two of the three CMFs, one of which is also statistically significant at the 95-percent confidence level. All three CMFs indicate the potential for increased total, intersection-related, and fatal and injury intersection-related crashes at downstream stop-controlled intersections. The CMFs for total, all intersection-related, and fatal and injury intersection-related crashes are 1.64, 2.55, and 1.56, respectively. A conservative analysis would include the potential increases (i.e., those not statistically significant) in the estimation of the net benefit.

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

Table 6. Results for urban signalized intersections downstream from stop-controlled intersections with RIRO compared to full movement.

Variable	**Total**	**Intersection - Related**	**Fatal & 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 7. Results for urban stop-controlled intersections downstream from stop-controlled intersections with RIRO compared to full movement.

Variable	**Total**	**Intersection - Related**	**Fatal & 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

Note: * indicates statistically significant result at the 95-percent confidence level
** indicates statistically significant result at the 90-percent confidence level

The project team considered several variables in the disaggregate analysis, including major and minor road traffic volume, number of mainline lanes, and design speed. Based on the disaggregate results, it does not appear that RIRO restrictions have different effects for different levels of traffic on both mainline and cross-street, design speed, or number of lanes on the mainline.

Economic Analysis

The project team conducted an economic analysis of a hypothetical scenario to estimate the cost-effectiveness of implementing physical RIRO turning movement restrictions at stop-controlled intersections. The team estimated the treatment cost based on the construction and maintenance costs associated with physical RIRO restrictions. The team determined the 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 focuses on potential safety benefits in relation to installation and maintenance costs, other factors to consider include impacts to traffic operations (e.g., travel time and delay) and economic impacts to adjacent businesses. The hypothetical scenario analysis illustrate the range of potential results from converting full movement, three-legged, stop-controlled intersections to RIRO. In some cases, it is cost-beneficial to convert full movement to RIRO intersections. In other cases, the increase in crashes at downstream locations outweighs 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 is mostly dependent on the magnitude of crashes at the parent intersection(s) and the downstream intersection(s). Specifically, the 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.

SUMMARY AND CONCLUSION

The objective of this study was to undertake an 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. The aggregate results indicate reductions for all crash types analyzed at urban, three-legged, stop-controlled intersections with RIRO compared to full movement. All reductions are statistically significant at the 95-percent confidence level.

While the results indicate crash reductions at stop-controlled intersections with RIRO compared to full movement, the analysis of downstream intersections indicates potential crash increases at immediate downstream U-turn locations of RIRO intersections. There are differences in crash migration effects depending on the downstream traffic control type. The CMFs for downstream locations with signal control are close to 1.0 and the estimates are not statistically significant at 90 percent confidence level. As such, there is relatively low chance of increased crashes for downstream signalized intersections. Conversely, the results indicate likely increases at downstream stop-control intersections for all crash types analyzed. The increases are statistically significant at 90 and 95 percent confidence levels for total and total intersection-related crashes, respectively. The disaggregate analysis indicated no statistically significant differences in effects for major road traffic volume, minor road traffic volume, and design speed.

The economic analysis 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.

The study relied on 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.

ACKNOWLEDGEMENTS

This report was prepared by VHB for the Federal Highway Administration, Office of Safety Research and Development under Contract DTFH61-13-D-00001. The FHWA Contracting Officer's program and Task Manager for this project was Roya Amjadi.

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