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Safety Evaluation of Turning Movement Restrictions at Stop-Controlled Intersections

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This document is a technical summary of the Federal Highway Administration report *Safety Effects of Turning Movement Restrictions at Stop-Controlled Intersections* (FHWA-17-064).

Objective

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and to promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in broad applications of new strategies for 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.

This study evaluated the safety effects of converting three-legged, full movement intersections to right-in/right-out (RIRO) operations using physical barriers. The intent of this strategy is to reduce the frequency and severity of crashes by eliminating left turns into and out of target intersections, which are 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 information is available to quantify the safety effects of restricting left turns at specific intersections and the effects of shifting traffic to downstream intersections.

Introduction

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 of several related strategies.

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 are generally known to reduce crash risk.[2] RIRO eliminates left turns into and out of the minor road. A positive or curbed median barrier on the mainline is a common strategy, creating an 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 RIRO operations.

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 their effects on downstream intersections. The full report serves to address the need for research into the safety effects of turning movement restrictions at stop-controlled intersections.

A literature review focused on the safety effects of RIRO operations, 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 treated and adjacent full movement intersections.

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.

Figure 1. Photo. RIRO stop-controlled intersection.

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In NCHRP Report 420, Gluck, Levinson, and Stover also investigated the relationship between median type and crash rates.[4]

NCHRP Report 395 compared outcomes from a number of crash prediction models developed by researchers.[5] A composite finding suggested that, in general, a raised median is safer than undivided roadways, especially on roads with more than 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 were positively correlated, but the trend line was slightly steeper for nonraised median corridors than raised median corridors. The researchers concluded that the reduced slope of the regression line for raised median corridors demonstrated there were relatively low crash rates in corridors with raised medians 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 an FHWA evaluation involving data from seven States suggested raised medians reduced crashes at least 40 percent in urban settings.[7]

Methodology

This research examined the safety impacts of restricting turning movements to RIRO from full movements 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 an intersection (all types and severities combined).
- Intersection-related: as termed by the reporting officer, all crashes within 100 ft of an intersection (all types and severities combined).
- Fatal and injury: all injury crashes defined as "intersection-related" (fatal, incapacitating, non-incapacitating, and possible injuries).
- Multivehicle: all multivehicle crashes defined as "intersection-related" (all types and severities combined). (Note: all "intersection-related" crashes included multiple vehicles; therefore, 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 might have varied:

- Lane configuration of intersection (i.e., four mainline lanes and two cross-street lanes versus six mainline lanes and two cross-street lanes).
- Level of traffic volume.
- Design speed on the major route.
- Type of traffic control at downstream intersections (i.e., signalized or minor road stop control).
- Presence of turn lanes at downstream intersections.

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

For strategies such as restricting turning movements, there is often insufficient information to determine the exact location and timing of the treatment, which precludes the use of an empirical Bayes before–after study design. 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] A cross-sectional study design is a type of observational study used to analyze a representative sample at a specific point in time. Using this method, researchers estimate the safety effect by taking the ratio of the average crash frequency for two groups—one with the feature of interest and the other without the feature of interest. In this case, the feature of interest was RIRO operations. For this method to work, the two groups should be similar in all regards except for the feature of interest.

Finding two groups of subjects that fit this criterion is difficult to accomplish in practice. The project team adopted multivariate 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 several predictor variables, including treatment presence, traffic volume, and other roadway characteristics. The project 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.

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.

The full report contains a detailed explanation of the methodology, including a description of how the estimate of safety effects for target crashes was calculated.

Results

Results are presented in two parts. The first part contains aggregate results, and the second part is based on a disaggregate analysis that sought to identify those conditions under which the strategy is most effective.

Aggregate Analysis

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 operations compared to intersections with full movement (table 1). Reductions were statistically significant at the 95-percent confidence level for all crash types. Crash modification factors (CMFs) 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 restricted turning movements at a given access point. This occurs when crashes at a treated site shift to another site. While RIRO operations eliminate left turns at the subject location, U-turn movements and related crashes potentially increase at the next intersection downstream that allows 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.

Table 2 and table 3 present the estimated CMFs and related standard errors for each target crash type and traffic control type combination at the downstream intersections. 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.

Disaggregate Analysis

The disaggregate analysis sought to identify those conditions under which the strategy was 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.

Table 1. Results for urban, three-legged, stop-controlled intersections with RIRO compared to full movement.

Variable	Total	Intersection-Related	Fatal and 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

*Indicates statistically significant results at the 95-percent confidence level.

Table 2. Results for urban signal control 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; downstream SIGNAL = 1)	1.10	1.02	0.94
Standard error of CMF (parent RIRO = 1; downstream SIGNAL = 1)	0.20	0.24	0.26

Table 3. 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; downstream SIGNAL = 0)	1.64*	2.55**	1.56
Standard error of CMF (parent RIRO = 1; downstream SIGNAL = 0)	0.33	0.39	0.45

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

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 different traffic volumes.

The 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 had differing effects for different levels of traffic on both mainline and cross street, design speed, or number of lanes on the mainline.

Economic Analysis

For this analysis, the project team used sites with physical barriers to provide the 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, the project team's assumptions included an average median width of 4 ft at an average cost of $6 per sq ft.[9] (Note: the median may be 6 ft wide for a portion of the length between full movement intersections with narrow sections at the ends to facilitate turning lanes.)

Given these assumptions, implementation cost was approximately $24 per linear ft (or $126,720 per mi). 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.

The analysis assumed the useful service life for safety benefits was 20 years. Based on Michigan and Ohio data, 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 analysis assumed these costs were negligible compared to the installation costs over the service life.[10]

The 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 7 percent to calculate the present value benefits and costs of the treatment over the service life.[11] With this information, the analysis computed the capital recovery factor as 10.59.

For benefit calculations, the project team used the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type as a base.[12] FHWA developed these costs based on 2001 crash costs, and the unit cost (in $U.S. 2001) for fatal and injury crashes was $158,177. At the time of analysis, this was updated to 2015 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.[12,13] Applying this ratio of 2.47 to the unit cost for fatal and injury crashes resulted in an aggregate 2015 unit cost of $391,280.

To estimate the safety benefits of implementing RIRO operations, the project team analyzed two hypothetical sections: (1) a single stop-controlled intersection leading to a signalized intersection, and (2) a 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.

The project team calculated the annual economic benefits by multiplying the crash reduction per site per year by the average cost of a fatal and injury crash. The team calculated the B/C ratio of 9.6:1 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.[13] These factors can be applied directly to the estimated B/C ratios to get a range from 5.4:1 to 13.5:1. Results of this hypothetical example suggest the RIRO strategy, with reasonable 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.

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 turning movement restrictions at stop-controlled intersections. The study compared RIRO to full movement access using California data to examine effects for specific crash types: total, intersection-related, and fatal and injury intersection-related crashes. Based on the aggregate results, table 4 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.

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 net benefits. Table 5 and table 6 present the recommended CMFs for various crash types for downstream intersections from urban, three-legged, stop-controlled intersections with RIRO compared to full movement. Table 5 presents results for downstream intersections with signal control. Changes 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. Table 6 presents the results for downstream intersections with stop control. Increases were statistically significant at the 90-percent confidence level for total crashes and statistically significant at the 95-percent confidence level for intersection-related crashes. All three CMFs indicated potential for increased total, intersection-related, and fatal and injury intersection-related crashes at downstream stop-controlled intersections.

The disaggregate analysis sought to identify those conditions under which the strategy was most effective.

Table 4. 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

*Indicates statistically significant results at the 95-percent confidence level.

Table 5. 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	1.10	1.02	0.94
Standard error of CMF	0.20	0.24	0.26

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

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

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

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

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 potential for crash migration at a downstream signalized intersection, was 9.6:1. With USDOT recommended sensitivity analysis, these values could range from 5.4:1 to 13.5:1. The economic analysis was based on a single hypothetical stop-controlled intersection and a downstream signalized intersection. The RIRO operation was more cost beneficial 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, potential costs and benefits need to be analyzed on a case-by-case basis with site-specific values.

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