Developing Crash Modification Factors for Mini-Roundabouts

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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 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' Strategic Highway Safety Plan. ELCSI-PFS studies provide a crash modification factor (CMF) and benefit–cost economic analysis for each targeted safety strategy identified as a priority by member States of the PFS.

This report documents the evaluated safety effectiveness of mini-roundabout (MR) installations at two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC) locations. This study focused on MR safety effectiveness using data such as dimensions, number of lanes, median types and widths, and number of legs at various sites in Washington, Michigan, and Maryland. The analysis found a statistically significant crash reductions of 39 percent in multivehicle crashes at MRs converted from AWSC in all three States.

These study results may be of interest to roadway safety professionals, State and local engineers, and planners responsible for the design and operation of facilities that may benefit from MR installations.

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16. Abstract
This study evaluated the safety effectiveness of mini-roundabout (MR) installations at two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC) locations. Based on a longitudinal design including comparison sites, the database included three States: Washington, Michigan, and Maryland. Safety data were compiled for locations of known MR installations where the date of installation and prior intersection condition were known. Suitable comparison locations were included. The study included 15 MR locations from Washington, 6 from Michigan, and 6 from Maryland. Crash data from 2003 through 2019 were available from Washington, data from 2013 through 2019 from Michigan, and data from 2015 through 2019 from Maryland. A fully Bayesian evaluation based on the Washington crash data estimated crash reductions for MR converted from TWSC ranging from 31 to 42 percent for various crash types, which were statistically significant. The study found a statistically significant reduction of 39 percent in multivehicle crashes at MR converted from AWSC intersections from an additional analysis based on the complete database from all three States. This study also produced benefit–cost ratios of 2.88 and 2.87 for MR conversions from TWSC and AWSC, respectively, when only safety benefits were considered, whereas the ratio was 13.41 for AWSC intersections when operational benefits were also considered. These results indicate economic feasibility of MR installations.

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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for 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
AWSC	all-way stop-control (controlled)
B/C	benefit–cost
CMF	crash modification factor
DCMF	Development of Crash Modification Factors
DOT	department of transportation
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FB	fully Bayesian
FHWA	Federal Highway Administration
FI	fatal and injury
GIS	geographic information system
GLM	generalized linear model
GLMM	generalized linear mixed model
HSIS	Highway Safety Information System
ITS-CG	interrupted time series design and analysis with comparison groups
KE	kinetic energy
MCMC	Markov chain Monte Carlo
MR	mini-roundabout
NCHRP	National Cooperative Highway Research Program
OR	odds ratio
PDO	property damage only
PIA	personal injury accident
PS	propensity score
PSL	posted speed limit
Std Dev	standard deviation
Std Err	standard error
TWSC	two-way stop-control (controlled)
vpd	vehicles per day

EXECUTIVE SUMMARY

The Federal Highway Administration's (FHWA) Development of Crash Modification Factors (DCMF) Program was established in 2012 to address highway safety research needs and evaluate new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes (FHWA 2022a).

The ultimate goal of the FHWA DCMF Program "is to save lives by identifying new safety strategies that effectively reduce crashes and promote strategies for nationwide installation by providing measures of their safety effectiveness" (e.g., crash modification factors (CMFs) and benefit–cost (B/C) ratios) through research (FHWA 2022a). State departments of transportation (DOTs) and other transportation agencies need to have objective measures of the countermeasures' safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements.

Forty-one State DOTs are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS) and provide technical feedback on high-priority research needs for safety improvements to the DCMF Program. These States implement new and unproven safety improvements to facilitate ELCSI-PFS evaluations and ELCSI-PFS functions under the DCMF.

The ELCSI-PFS Technical Advisory Committee selected evaluating the safety effectiveness of mini-roundabouts (MRs) as one of ELCSI-PFS' priorities. This report documents the evaluation of the safety effectiveness of MRs in the United States.

More specifically, this study evaluated the safety effectiveness of MR installations at two-way stop-controlled and all-way stop-controlled locations. Databases were developed and analyzed representing three States: Washington, Michigan, and Maryland. Suitable comparison locations were included to control for covarying extraneous factors. Site features were collected for analysis, including dimensions, number of lanes, median types and widths, number of legs, and so on, before and after MR installation, as well as annual average daily traffic where available. The study included 15 MR locations from Washington, 6 from Michigan, and 6 from Maryland. Crash data from 2003 through 2019 were available from Washington, from 2013 through 2019 from Michigan, and from 2015 through 2019 from Maryland.

This research developed CMFs that indicated crash reductions in general, but some of the results were statistically insignificant. An additional, analysis of severe crash outcomes indicated a statistically significant reduction in risk of injury or death. B/C ratios were developed accordingly. Practitioners can use these results for decisionmaking in their project development and safety planning processes.

CHAPTER 1. INTRODUCTION TO SAFETY EVALUATION OF MINI-ROUNDABOUTS

Mini-roundabouts (MRs) are small-diameter roundabouts (50- to 90-ft radii) with traversable islands (central island and splitter islands). MRs use less space than regular-sized roundabouts while offering most of the benefits. They are best suited for locations with slow operational speeds and where site constraints would preclude the use of larger roundabouts. As a particular type of roundabout, MRs are expected to improve traffic operations with a minimal impact on capacity—or even to increase capacity under certain conditions—and reduce frequency and severity of crashes, most likely by curbing right-angle crashes, typical at stop-controlled and signalized intersections.

While MRs are frequently used in European countries, their use is just emerging in the United States. A previous evaluation by the Federal Highway Administration (FHWA 2015) demonstrated that conversion from intersections controlled by all-way stop-controlled (AWSC) or two-way stop-controlled (TWSC) improved intersection operating efficiency and reduced congestion, and that a formal safety evaluation study based on actual crash data is challenging, partly due to the scarcity of locations and data. The limited number of crashes at MR sites with multiple years of crash data can provide significant challenges in developing crash modification factors (CMFs) for MRs. For assessing safety benefits of MRs, proper accounts for those different pretreatment conditions are needed.

REVIEW OF LITERATURE

MRs are a simpler version of traditional roundabouts. They feature a single lane and smaller diameters, ranging from 45 to 80 ft (Robinson et al. 2000). The key element of MRs is that their islands are traversable (central island and splitter islands). As a result, MRs use less space than regular-sized roundabouts, while still retaining most operational benefits and potentially safety as well. As a result, the cost of retrofitting an existing intersection with an MR is significantly lower than implementing traditional roundabouts (Jurewicz et al. 2013).

While MRs are frequently used in European countries, only a few locations in the United States have had MRs for more than a decade, with wide MR use expanding just in the last decade.

CHARACTERISTICS, ADVANTAGES, AND DISADVANTAGES OF MRs

MRs offer a low-speed, low-noise intersection option that requires little regular maintenance (Rodegerdts, Scarbrough, and Bansen 2010). As mentioned in the preceding section, the defining feature of a MR is a small and traversable central island, as well as traversable split islands that can accommodate large vehicles driving over them but are uncomfortable for small vehicles to mount (i.e., raised but traversable) (Zhang 2015; Adnan, Adem, and Osman 2014). One factor engineers should keep in mind when designing the central mini-island is that it should not cause problems for winter maintenance. With this issue in mind, stamped epoxy or concrete are the preferred materials used as the surface material for central islands (Walker and Pittam 1989).

According to recent research, the major advantages of MRs are as follows: higher capacity than stop-control; better fit into existing intersection right of way; improved intersection operating efficiency and safety; and low cost ($25,000 to $50,000 per intersection, assuming only pavement replacement under the central and splitter islands) (Chandler et al. 2013; Zhang 2015).

Given all their benefits, MRs have the same disadvantages as traditional roundabouts, which are mostly general issues pertaining to accommodating pedestrians and cyclists (Delbosc et al. 2017). Bodé and Maunsell (2006) recommend not placing MRs at intersections with known large pedestrian volumes. However, cyclists are considered "just as vulnerable" on roundabouts as on any other crossroad system. Additionally, MRs offer no protection for vulnerable users against drunk and reckless drivers because of the lack of nontraversable physical barriers compared with traditional roundabouts.

Sawers (2009) presents an examination of successful and failed cases of MR applications in the United Kingdom, discussing geometric design, safety, and other aspects for potential applications in the United States. In his examination of conflict points, Sawers included statistics for crash types, pointing out a significant difference between three-legged and four-legged MRs: Clearly a larger proportion of right-angle crashes occur at four-legged locations.

SUITABILITY OF MRs

MRs have been used at urban junctions since their introduction in Europe in the early 1970s and produce some traffic calming effects (Kennedy, Hall, and Barnard 1998; Rodegerdts, Scarbrough, and Bansen 2010). They are suitable for intersections on two-lane or three-lane high-volume collector roads with comparable traffic volumes from major and minor approaches and with a total entering daily traffic volume value no more than approximately 15,000 vehicles, low truck volumes, and a posted speed limit (PSL) of 35 mph or less (Rodegerdts, Scarbrough, and Bansen 2010; Robinson et al. 2000; Kennedy, Hall, and Barnard 1998). As a particular type of roundabout, MRs are expected to improve traffic operations with a minimal impact on capacity and reduce the frequency and severity of crashes, most likely by curbing right-angle crashes, which are typical at stop-controlled and signalized intersections.

OPERATIONAL EVALUATIONS OF MRs

The literature shows a clear pattern of operational benefits of MRs. FHWA conducted a field and safety evaluation of five existing MRs and before-and-after operational evaluation of 15 MRs (Georgia, Maryland, Michigan, Minnesota, New York, Washington, and Virginia) (FHWA 2015). This evaluation demonstrated that conversion from intersections controlled by AWSC or TWSC improved intersection operating efficiency and reduced congestion.

A study in South Australia found a 62-percent drop in 85th percentile speeds through intersections with MRs (Zito and Taylor 1996). A study by Rodegerdts, Scarbrough, and Bansen (2010) found that MRs help reduce vehicle approach speeds. Delbosc et al. (2017) recorded driver and pedestrian behavior in 40 MRs and found that speed limit compliance increased after the installation.

SAFETY EVALUATIONS OF MRs

MRs are expected to enhance safety for drivers and bicyclists by providing more time to make decisions, act, and react by reducing the number of directions a driver needs to monitor for conflicting traffic. One can also argue that safety improves because of a reduced need to judge gaps accurately in fast traffic. Crosswalks are provided for bicyclist and pedestrians. These benefits, combined with the lower impact angles due to the nature of MRs, should lead to lower impact kinetic energy (KE) in the event of a crash, resulting in "safer" crashes if they do occur (Candappa 2015). Candappa (2015) conducted a treatment control study that evaluated the behavior pattern and compliance of 533 vehicles. Results indicated that the KE generated by a typical crash at the control site was deemed higher than that generated at either treated site, thus implying that safety benefits of vulnerable road users (pedestrians and cyclists) exist at MRs.

Cross-Sectional Studies

A few cross-sectional studies can be found in the MR literature. Kennedy, Hall, and Barnard (1998) studied crash risk in the United Kingdom based on a national stratified sample of 200 three-legged and 100 four-legged urban MRs on 30-mph single carriageway roads (311 sites, 2,100 personal injury accidents (PIAs), 1986–1992) with an objective to develop relationships between crash frequency and traffic flow, road features, layout, geometry, land use, and other variables. Extensive data collection was conducted at these junctions, including 12-h vehicle and pedestrian counts and a geometric survey. Crash records were obtained for all reported PIAs occurring at the junctions from 1986 to 1992. The crashes were categorized based on frequencies, severities, and rates by type of central island and by region, crash group, road user involvement, and number of casualties per accident. Generalized linear modeling was used to quantify such relationships for different types of accidents. This study found that the average PIA frequency at four-legged sites was about 50 percent higher than at three-legged sites (0.92 PIAs per year). The study also found that the severity of crashes at MRs was reduced compared with two-way-stop junctions and signalized junctions. Reductions were found for pedestrian crashes as well—about half the number found at two-way-stop junctions and traffic signals. Bicycle and motorcycle crash involvement rates were found to be higher at MRs than those involving cars and light trucks.

However, relative crash involvement rates for bicycles at MRs were higher than for two-way-stop junctions (Kennedy, Hall, and Barnard 1998). Rates of motorcycle crashes remained the same for both types of intersections. The flush or mountable central island was found to pose higher risk of single vehicle crashes at four-legged MRs. The type of central island did not matter for the rest of the crash rates. The increasing proportion of two-wheelers increased the effect of crashes involving vehicles entering, circulating, and merging at three-legged MRs. Speed variables and deflection (vehicle path curvature) variables were not significant to crash rates. Researchers argued that appropriate angular displacement variables could be used in future studies to replace vehicle path curvature variables. Lastly, the research found that visibility affected a number of different crash groups, and that crashes increased with longer sight distances, with all other things being equal.

In their 1989 cross-sectional study, Walker and Pittam (1989) stated that PIAs within 20 m of MRs occurred at an average frequency of 0.61 PIA per junction per year for three-legged sites and 0.88 PIA per junction per year for four-legged sites. The corresponding crash rates per 100 million vehicle inflows were 10 and 17, respectively. Crash severity (the percentage of fatal and serious crashes) was between 16 and 18 percent for the MRs. These results are similar to the severities of other urban junctions (small roundabouts: 18 percent; traffic signals: 20 percent) but are less than 27 percent for urban conventional roundabouts. The average crash frequencies and rates for MRs were similar to those for rural T-junctions (0.5 PIA per junction per year and 17 PIAs per 100 million vehicles) but were considerably lower than those for other types of roundabouts and for traffic signals. This result might be explained in terms of the likely similarity in the aggregate traffic flows and the balance of flows within the junctions between MRs and rural T-junctions, and the dissimilarity of these flows between MRs and the other junctions (Walker and Pittam 1989).

Before–After Studies

The majority of research efforts assessing MRs use a before–after design. These works are mostly based in European countries, particularly in the United Kingdom, and span over several decades.

Green (1977) evaluated safety change in a before–after design in 1977. Results indicated a significant reduction of between 28 and 37 percent for all injury crashes and 46 percent reduction in fatal and serious injury crashes when TWSC intersections were converted to small roundabouts or MRs. This study evaluated 150 junctions that were converted to MRs. Considered separately, 132 of these junctions were previously governed by 30 or 40 mph speed limits with TWSC, traffic signals, or roundabouts. The average lengths of the before and after periods were 3.4 and 2.5 yr, respectively.

Another safety study was conducted at 20 MRs in greater London by Lalani (1975). This study showed that vehicle crashes within 50 m of the MR declined 29.5 percent, and pedestrian crashes within 50 m declined 37.5 percent. Total injury crashes declined 30.3 percent after construction of a MR, which was statistically significant at the 90-percent confidence level (Waddell and Albertson 2005). The injury crash data in this study were limited to the period from January 1970 to May 1975. Lalani (1975) did not provide information on crashes at each site but gave the total number of crashes during the before and after periods for different categories of roundabout sites.

Ibrahim and Metcalfe (1993) studied the effect of replacing TWSC intersections by MRs and installing new MRs at six groups of sites (each collected and analyzed in separate studies) by observing rates of crashes during the before and after periods and using two Bayesian methods. The first method assumed a constant treatment effect on all six groups and involved combining studies chronologically. The second method allowed for variation of treatment effect between groups and is based on a Bayesian hierarchical framework. They concluded that a policy of replacing TWSC intersections by MRs is likely (chances of 90 percent) to lead to a reduction in crashes of at least 13 percent (1.3 standard deviations (Std Devs) below the pessimistic mean), and the best estimate of the benefit was a reduction in crashes of between 23 and 28 percent. However, there was evidence that some groups of sites benefitted more than others. Except for one study, all the analyzed studies reported a reduction in crash rate after MRs were installed at a group of sites.

Another before–after study on a single MR at the Village of Dimondale (Dimondale, MI), conducted by Waddell and Albertson (2005) considered all crashes that occurred within 300 ft of the intersection. Five crashes were reported in the 3 yr both before and after the installation period, with only a $733 reduction in the cost of crashes (due only to a shift in injury classes). The authors could not claim any significant benefits to the conversion of the TWSC intersection to a MR (Waddell and Albertson 2005).

In another study based in the United Kingdom, MRs were found to improve the safety at three-legged intersections. Reportedly, crash rate reductions of approximately 30 percent were found compared with signalized intersections (Bodé and Maunsell 2006). The estimated rate is similar to that of priority T-junctions. The severity of crashes (percentage of fatal and serious crashes to all injury crashes) at three-legged MR sites was found to be lower than at three-legged signaled junctions and considerably lower than at 30-mph T-junctions, which can be attributed to the operational effect of the design (i.e., reduced speeds).

A study by Brilon (2011) in Germany found a 29-percent reduction in crash rate following a conversion of 13 unsignalized intersections to MRs. Only personal injury crashes and damage-only crashes were included in the study to calculate the crash rate and crash cost rates, since only data for these types of crashes were available. The before–after study reported a reduction in crash rate (crashes per motor vehicle) from 0.79 to 0.56, and the crash cost rate (euros per 1,000 vehicles) was reduced from 9.47 to 3.91. Based on this study, MRs were recommended at urban areas with a PSL of less than 50 km/h and maximum number of vehicles 20,000 per day. However, the authors did not recommend the use of MRs outside urban areas.

Delbosc et al. (2017) analyzed crash records 3 yr before and after the installation of 40 MRs in Australia, along with a case study of two adjacent MRs installed in 2016. The crash comparison clearly suggested a crash reduction associated with the MR installation. Crashes were reduced by 78.9 percent, with the number of serious crashes reduced from six to zero. The “cross traffic” and “right far” crashes virtually disappeared after the installation of MRs. The change was also found to have an increased yielding rate to pedestrians, which might have resulted in a decreased number of crashes. Additionally, driver behavior was recorded through a questionnaire survey (32 respondents, 16 pedestrians, and 16 residents) to assess community acceptance. The MRs were shown to improve the perception of safety by offering a safer driving and walking experience at the intersection than before the installation. Based on the results, the authors recommended MRs at locations with significant bus or heavy vehicle traffic, or in grid-based local road networks. However, authors argue that MRs might not be appropriate in areas with high cyclist movements on local roads.

Finally, a recent evaluation in the United States has indicated decreases in total crashes and fatal and injury (FI) crashes (CMFs of 0.83 and 0.41, respectively) for MR conversions from TWSC or one-way stop-controlled intersections (Pulugurtha, Mishra, and Mathew 2021). However, this study also reported a statistically significant increase in property damage only (PDO) crashes for these types of conversions (CMF of 1.09). Moreover, this study indicated large crash increases when AWSC intersections were converted to MRs. The corresponding CMFs increases for total, FI, and PDO crashes are 3.25, 1.74, and 3.84, respectively.

CHAPTER SUMMARY

Past safety evaluations of MRs clearly suggest that safety benefits are present. Most safety evaluations of MRs based on crash data have been performed abroad, especially in Europe. Results are consistent over several decades and from multiple countries, suggesting that the treatment offers benefits independent of the country in which it is applied. Highlights from the literature review findings are given as follows.

Some studies have found that MRs provide an increased perception of safety among users. Regarding operational benefits, several observations have been documented: a drop in 85th percentile speeds; a reduction in the number of conflict points; and more time to make decisions, act, and react, thus, reducing the number of directions a driver needs monitor for conflicting traffic and reducing the need for drivers to judge gaps accurately in fast traffic (Zito and Taylor 1996; Sawers 2009; Rodegerdts, Scarbrough, and Bansen 2010).

Studies have found that replacing TWSC intersections with MRs is linked to crash reductions by at least 13 percent and up to 79 percent (Ibrahim and Metcalfe 1993; Delbosc et al. 2017). The best estimate of the benefit range provided by Ibrahim and Metcalfe (1993) is between 23 and 28 percent and has been confirmed by later works. For example, a similar estimate was obtained from a study in Germany that found a 29-percent reduction in crash rate by converting 13 unsignalized intersections to MRs (Brilon 2011). Similarly, MRs in the United Kingdom were found to be linked to improved safety at three-legged intersections with reported crash rate reductions of approximately 30 percent compared with signalized intersections (Bodé and Maunsell 2006).

An Australian study found that MRs provide similar benefits as traditional roundabouts (Jurewicz et al. 2013). One United States-based study, however, found no change in crash numbers after MR installation, whereas another indicated large increases for AWSC conversions to MRs (Waddell and Albertson 2005; Pulugurtha, Mishra, and Mathew 2021).

CHAPTER 2. STUDY DESIGN AND METHODOLOGY

The study design for this evaluation needed to account for multiple features and overcome the particular challenges anticipated from a safety evaluation of MRs, as described in chapter 1. A proper study design can significantly maximize the chances of obtaining meaningful, quality results. Generally speaking, safety studies rely on observational data because randomization is not possible, and true experiments, such as randomized control group experiments where injury or death is a potential outcome, are not feasible or ethical. This study is no exception. However, a good observational study should be consistent with key elements of control group experiments to the extent possible. Building a dataset that represents both treated and nontreated sites is one such key element, as well as an account of key confounding variables. This study followed a quasi-experimental design by using a nonequivalent comparison group or a control series design (Campbell and Stanley 1966; Campbell and Ross 1968). However, in the case of evaluating the safety potential of MR installations, the researchers deemed obtaining a large before–after dataset representing multiple jurisdictions to be the biggest challenge after reviewing potential data sources. The selection of jurisdictions was driven mostly by the potential to produce a dataset large enough for a robust safety analysis. However, due to the effort needed for developing a before–after study, the number of jurisdictions that can be included was limited by budget and schedule.

A safety evaluation in the face of limited study locations could benefit from incorporating existing knowledge about safety performance of roundabout and stop-controlled intersections into the evaluation. This strategy was considered because of its potential to produce more precise CMF estimates. However, this approach's validity greatly depends on the transferability of that knowledge of roundabout safety in general to MR designs. Although potential differences in safety performance are expected, this approach takes advantage of any similarities between MRs and other roundabout types. The National Cooperative Highway Research Program (NCHRP) *Report 572* offers various functional forms of roundabout intersection designs where the only independent variable is annual average daily traffic (AADT) and where the crashes increase with additional legs (three to five) and additional circulatory lanes (one to four) (Rodegerdts et al. 2007). On the other hand, functional forms from various jurisdictions already in possession of crash prediction models for AWSC and TWSC intersections (e.g., studies by Gates et al. 2018 and Walker et al. 2020) could be potentially incorporated. These crash prediction models and their parameter estimates imply probability distributions of crashes for the before–after conditions that can be incorporated as inputs in the analysis that would produce MR CMFs. The Bayesian framework—described in more detail in the Data Analysis Methods section—offers a way of incorporating past results while producing new updated information (i.e., CMFs in this case) by integrating new data with information from past research.

STUDY DESIGN

Longitudinal study designs (e.g., before–after) are preferred when developing CMFs because of their ability to effectively account for site-to-site variability and biases due to omitted variables. Such a design can be strengthened if a reference group or a comparison group is available that can control for covarying extraneous variables.

This study intended to establish the safety effectiveness of MRs using TWSC or AWSC intersections as the basis of comparison. The design of the evaluation is a before–after design with a comparison group; thus, having the dates of conversion to MR at the study locations was relevant for data collection. However, the small number of MR facilities in the United States was a limiting factor, combined with the fact that most of these installations are relatively recent. As a result, the research team decided to include MR installations and safety data in the study, with special emphasis on the jurisdictional location. The need to identify a robust set of baseline condition sites (TWSC or AWSC intersections) with comparable features to the MR sites in the study was clear in the early stages of the study. The research team identified MR implementations in multiple States and requested data for the before and after periods when available.

Another FHWA guidance was to consider the possibility of incorporating operational assessments into the evaluation, such as metrics that can be obtained from external vendors. In response to this guidance, the research team investigated the feasibility of obtaining operational and safety data for the main analysis but ultimately could not secure a sufficently large operational dataset to pair with the safety data. However, later in this reseach, the researchers derived rough operational benefits of MR installations from past studies to estimate B/C ratios.

The unit of analysis for the study was determined as an intersection-year, given that the analysis will explicitly model the conversions to MR. The safety performance evaluations included the following general data types:

- Location (such as city and State) of each intersection.
- Years that the intersection type (MR, TWSC, or AWSC) design has been in place.
- Geometric characteristics of the intersection (such as number of legs, number of lanes, lane widths, channelization, advanced signage, pedestrian and bike facilities, island radius, median types, and so on).
- Sufficient number of crashes for the period of analysis.
- Crash types and severities.
- Date and time of crashes.
- Traffic volume data (AADTs for both major and minor approaches).

Study Design: Interrupted Time Series Design with Comparison Groups

The research team implemented an interrupted time series design and analysis with comparison groups (ITS-CG) to cope with the small number of treatment (MR) sites.

ITS-CG is a quasi-experimental method that can minimize the threat of confounding (Campbell and Stanley 1966; Campbell and Ross 1968). An interrupted time series design and an ITS-CG are study designs often used in social science to determine the impact of an intervention. As stated in the report from Campbell and Ross (1968), “In the Interrupted Time-Series, the ‘causal’ variable is examined as an event or change occurring at a single time, specified independently of inspection of the data.” Here the causal variable (intervention) is a deployment of an MR. These study designs require crashes to be aggregated monthly or yearly at each site. ITS-CG has been applied to before–after data to evaluate the impact of the intervention treatment on the crash frequency (Wagenaar and Maybee 1986; Wagenaar 1986). Comparison groups are added to control for extraneous variables and strengthen the study design. In ITS-CG, a treatment group is also compared to the comparison group that had not undergone the treatment but was selected to be as similar as possible to the treatment group to better isolate the effect of the treatment.

The next section of the report describes the database preparation for the evaluation.

DATABASE DESIGN AND MANAGEMENT

Locations of interest included sites that have MR installations, with entering volumes in excess of 800 vehicles per hour, and potentially low speed applications. Those characteristics are most likely found in arterials, minor arterials, and collector roads, which will be the focus of this evaluation. The key data element would be locations with MRs, preferably with known dates of installation, and the type of traffic control present before the MR installation. In addition to MR locations, a suite of appropriate locations was needed to form a comparison group. The purpose of a comparison group is to provide a reference of the natural fluctuations in safety for MR viable but untreated sites, so that any changes in safety found for the treated locations can be assessed against the normally expected changes had no MR been installed.

To develop the intended CMFs for MRs, explicit consideration of different factors was needed, including land use, traffic control device before the MR installation, speed limit, and traffic volume, among other factors. Table 1 shows a list of data elements necessary for this evaluation.

Table 1. Data elements for MR evaluation.

Category	Elements
Crash characteristics	• State, county, city, and milepost (measure). • Latitude and longitude. • Date (weekday, month, year). • Time (nighttime, daytime). • Crash contributing factor (fixed object, speed). • Crash type (single vehicle, multivehicle). • Crash severity (fatal, severe injury). • Driver impairment and distraction. • Vehicle type (passenger, truck).
MR characteristics	• Traffic control device before and after MR installation. • MR diameter. • Alignment (curves, angle of intersection). • Speed limit. • Signage. • Number of lanes. • Pavement markings. • Lane width.
Approach roads characteristics	• Area type (rural, urban). • Number of lanes. • Lane width. • Median width and type. • Alignment (curves, angle of intersection). • Signs and signals. • Shoulders.
Traffic operations	• Traffic volume for facility. • Daily hourly volume profile for these locations.

Data Management Extraction and Integration

The data management stage of the process involved collecting and revising data, supplementing the data where appropriate, concatenating variables across multiple sources, and preparing the data for statistical analyses. In response to actual data availability, the research team refined the final datasets through a data integration process explained in this section. The research team used geographic information systems (Esri™ 2019) software to prepare, filter, and combine data from multiple sources and geolocations (typically in shapefile format). GIS tools allow the manipulation, combination, and display of data for different types of attributes, including crashes, road infrastructure, traffic volume, census tract, land use, and other types. The starting point of this process is the locations with known MR installations. The research team then located nearby sites that could potentially become comparison sites. This potential was judged by the roadway character (rural/urban), surrounding land use (residential/commercial/industrial), facility type (major or minor arterial/collector), number of lanes in the main road, and relative proximity to each MR site. After reviewing all candidate sites, the research team selected a set of three comparison sites per MR site, and geometry variables were collected for each study location (both MR and comparison). Geolocated crash data and traffic volumes were obtained where available and linked to the geolocation of each study site using GIS tools. In instances for which the data obtained were not geolocated, the research team did the corresponding linkage using other languages and appropriate tools, such as Sequential Query Language queries on Access and R-statistical language (The R Foundation 2021), or additional manual extraction (mostly for traffic volume data), such as spreadsheets or other tabular data.

AADT Imputation

The research team found challenges in obtaining AADT data for all sites and all periods in the study, especially for those located in lower functional classes. Needing to cover almost two decades (due to different dates of installation), the research team often performed AADT data extraction using AADT maps and GIS layers available from various sources online to obtain the needed AADT figures. Inevitably, multiple periods of analysis were unavailable, prompting the research team to apply imputation methods to estimate the missing values where that was feasible from a trend (i.e., for sites with more than 1 yr of AADT available, or for locations where other nearby locations had sufficient AADT data available).

Using imputed values instead of measured ones always carries an inherent risk. However, the alternative is to drop the sites and periods without measures of exposure, which would further reduce an already limited dataset. Even published AADTs are not always necessarily derived from actual counts and are often estimated, especially for lower functional classes. A common practice is to perform actual counts at a subset of locations to produce their AADTs, whereas AADTs for a sizable proportion of sites are estimated using the counts from similar sites. Because of the inherent inaccuracy of AADTs, the research team ascertained that the benefit of implementing imputation—avoiding the need to drop study locations—outweighed the uncertainty of using imputation, which could be comparable to the uncertainty already given in AADT values. Although using imputation was not expected to add significantly to the existing uncertainty of the AADTs, the research team recognized that the extent of that uncertainty and its shift due to imputation was unknown.

Data Balancing

Although other States were initially considered for this evaluation, the research team ultimately gathered safety data from Washington, Michigan, and Maryland. The research team collected three comparison sites for each treated site; ratios of 3:1 or 4:1 for comparison and treated sites have been recommended to maximize statistical power (Linden and Samuels 2013). The selection of comparison sites required consideration of several factors and approaches to establish the degree of similarity between treated sites and comparison sites.

Given the relatively small size of the samples in each study State, the research team deemed a propensity score (PS) analysis might not be robust enough to select comparison sites with similar characteristics as the treated sites because regression models might not have enough data to identify a set of covariates to balance. For this reason, the researchers selected the comparison sites using a systematic approach based on the roadway geometric and land use data available during data collection. Locations with the same number of legs, adjacent land use, and functional class, and in the same city or jurisdiction, were preferred when sites were selected for the comparison group, as illustrated in figure 1 for one location in Washington using publicly available satellite imagery (Google 2019).

Original map © 2019 Google® Earth™. Modified by FHWA (see Acknowledgments).

Figure 1. Map. Treated and comparison sites in Federal Way, WA (Google 2019).

Although the research team considers proximity between treated and comparison sites to be desirable, too much proximity is a potential issue because the safety performance of both sites could be mutually influential (e.g., between two adjacent intersections). Therefore, the research team used a threshold of 0.5 mi to include additional rules of inclusion. In case a comparison site was closer than 0.5 mi, either it should not be on the same roadway as the treated site, or there should be another intersection in between the two sites.

DATA ELEMENTS AND SOURCES

The research team obtained detailed information for about 120 MRs from different sources. The identified MRs were located in 30 States, including Washington, Arizona, Oregon, Pennsylvania, Rhode Island, Texas, and Vermont. Most of these States, however, were found to have only one MR each.

In the initial stages, the MR information obtained from various sources included the following:

- Location (e.g., city, State) of each improvement deployment.
- Year(s) of installation.
- The traffic control device before the MR installation.
- Number of legs.
- Intersection name and coordinates.

While the research team collected the geometric and signage characteristics directly, traffic and crash data were procured either directly from online resources or through communications with the corresponding State DOTs.

In contrast, the research team used various criteria and tools to identify and collect detailed information related to the comparison sites, once a subset of treated sites was reduced to a manageable number of sites and States.

Although the research team received detailed information of MRs from 30 States, due to the incremental effort required for data collection in multiple States, the research team estimated that the budget and schedule would allow using up to 4 States with at least 6 MRs each. The research team narrowed down the search to nearly 60 MRs in 6 States. Nineteen MRs were identified in Washington, six in Michigan, six in Maryland, and six in North Carolina, which were the States of most interest from a sample-size standpoint. At FHWA's request, other locations were considered (i.e., Georgia, Minnesota, and Missouri), but ultimately many of these States were discarded due to either determining they were traditional roundabouts, a small number of MR locations identified, the small number of available periods after the installation date (i.e., Minnesota), and/or the increased complexity of managing data collection for an increasing number of States. The final database consisted of three States: Washington, Michigan, and Maryland.

MR installment years range from 2006 to 2019 across the three States selected for this study. Most of the potential sites were converted from either TWSC at four-legged or three-legged intersections. In contrast, a few sites were converted from AWSC intersections. The research team evaluated the location (land uses) of potential sites, which include residential, commercial, and mixed land uses.

The research team also found out about a number of recent or planned installations across the country (e.g., in the cities of Elizabethtown, KY; Takoma Park, MD; and McLean, VA) that would be useful in the economic analysis.

Since the research team selected three similar comparison sites for each MR location, the research team defined evaluation groups consisting of the subsets of data from each MR location and its three comparison sites.

CRASH DATA

The research team collected crash data from various sources. The data include online sources such as an online data repository for Maryland (Maryland.gov 2022), and various jurisdiction-specific sites for Washington and Michigan (King County 2022; Michigan DOT 2022), including GIS layers with traffic and crashes, as well as direct contact to the respective DOTs. After collecting crash data, the team used ArcGIS® (Esri 2019) tools to obtain crashes that occurred on the MRs and control sites. A buffer of 250 ft and intersection-related fields were used to extract crashes that occurred at or near the sites of interest.

For each location, the research team obtained 17 yr of crash data (2003–2019) for Washington, 7 yr of crash data (2013–2019) for Michigan, and 5 yr of crash data (2015–2019) for Maryland. Additionally, the research team compiled safety and exposure data and the geometry, for each period of analysis.

TRAFFIC DATA

Traffic data are key to explaining changes in crash frequencies and should be accounted for in the safety evaluation of MRs. The research team procured the AADT at treated and control locations for at least 3 yr before and 3 yr after the MR installation. Since some of the MRs had very early installation dates, and because their location was at low classification roadways, the research team could not obtain the AADT for all the periods at the sites under evaluation. Thus, the performed model-based imputation of AADT was at the locations for which sufficient data were available, either from other periods or from other nearby locations with similar characteristics, such as land use and road class.

DATA ANALYSIS METHODS

The empirical analyses in this study were conducted using the statistical methods appropriate to the characteristics of the assembled datasets. The research team used Fully Bayesian (FB) analyses and generalized linear mixed-model (GLMM) variants (binomial mixed) to obtain the safety-effectiveness estimates of interest, given the ITS-CG design.

Modeling Framework for FB Analysis of Before–After Designs with Comparison Groups

The FB analysis of safety effectiveness of MR in this study builds on the basic modeling framework from previous research, utilizing an ITS-CG design as a study design (Park, Park, and Lomax 2010; Park, Carlson, and Pike 2019). The research team employed Poisson-gamma mixture models to model crash counts. Poisson-gamma mixture models are equivalent to negative binomial distributions for observed crash frequencies. The modeling framework of Poisson-gamma mixture models for a FB before–after evaluation with comparison groups is presented as follows.

Let y_{it} denote an observation at site i (i=1, …, I) during time (year) t (t=1, …, T). That is, y_{it} is the number of crashes that occurred in year t at site i. Let K be the number of covariates and $X_{it}=(1, X_{1it}, \ldots, X_{Kit})$ be a (K+1)-dimensional vector of covariates.

Let $\boldsymbol{\beta}$=(β_0, β_1, …, β_K)′ denote the (K+1)-dimensional column vector of the regression coefficients for the crash count. Let υ_{it} denote a vector of yearly random effects corresponding to site i and year t, explaining extra-Poisson variability. Suppose that conditional on υ_{it} and $\beta \in RK+1$, the crash count at site i in year t, y_{it}, follows a Poisson distribution with mean μ_{it}, where the parameter μ_{it} is itself parameterized as the product of υ_{it} and the exponential of the product of X_{it} and $\boldsymbol{\beta}$.

The y_{it} values are independent, given the μ_{it} values. υ_{it} follows the gamma distribution with parameters η and $1/\eta$.

The marginal distribution of y_{it} is given as a negative binomial distribution with mean λ_{it} and variance $\lambda_{it}[1+\lambda_{it}/\eta]$, where $\lambda_{it}=\mu_{it}/\upsilon_{it}$. The Poisson-gamma mixture model allows for intrasite correlation among crash counts from the same site as well as overdispersion.

Let the elements of the covariate vector X_{it} include indicator variables for treatment and time, an indicator variable for $t>t_0$, an interaction term between treatment and time, an interaction term between treatment and the indicator for $t>t_0$, and variables for intersection characteristics.

Then this model can be viewed as a change-point model, which assumes that, at the time of implementation, there is a possible change in the level with respect to time at treatment sites that might be attributable to the implementation of the countermeasure. Specifically, the coefficient for the interaction between the treatment indicator and the indicator for $t>t_0$ represents a possible "jump" or "drop" effect of the countermeasure on crashes at the treatment site. The comparison group also has the imaginary before and after periods defined the same as those for the matching treatment group, although no treatment is applied to sites in the comparison group. For each group and period, the model can be rewritten in terms of mean crash count versus time.

An FB analysis of the model as described requires the (second-level) prior distributions for the parameters, β_0, β_1, β_2,…, β_K as well as η, to be chosen. Estimation of model parameters is performed using Markov chain Monte Carlo (MCMC) methods (Gilks et al. 1996).

We assume a normal prior distribution for β, with parameters m_k and σ^2_k and a gamma prior distribution for η with parameters c_0 and d_0.

Once the posterior samples for model parameters and the true average crash frequencies (μ_{it}) for the treatment and comparison groups per period are obtained, the following steps can be followed to estimate the index (θ) of safety effectiveness (CMF) of MR.

Steps for Implementing FB Before–After Evaluations with Multiple Comparison Groups

The steps for implementation are as follows:

1. Specify the hyperparameter values, (c_0, C_0, r_0, R_0) for prior distribution of model parameters.
2. Obtain the draws of model parameters and the expected annual crash frequency for each site (i) and year (t) by MCMC.

3. Obtain posterior distributions of crash frequencies during the before period for the treatment group (μ_{TB}), during the after period for the treatment group (μ_{TA}), during the before period for the comparison group (μ_{CB}), and during the after period for the comparison group (μ_{CA}) by taking an average of the expected crash frequencies over the appropriate years and the sites.
4. Obtain a posterior distribution of the ratios of the expected crash frequencies before and after periods for the comparison group (comparison ratio) for the *g*th comparison group by the ratio $R_{c(g)}=\mu_{CA(g)}/\mu_{CB(g)}$.
5. Step 5. Obtain a posterior distribution of the predicted frequencies that would have occurred without treatment in the after period for the *g*th treatment group as: $\pi_{(g)}=\mu_{TB(g)}R_{C(g)}$.
6. Step 6. Obtain a posterior distribution of the index of effectiveness (of the countermeasure) for the crashes as the ratio of the sum of all $\mu_{TA(g)}$ to the sum of all $\pi_{(g)}$.
7. Step 7. Obtain the point estimates for β_k and θ as the sample means of corresponding posterior distributions.
8. Step 8. Obtain the uncertainty estimates for β_k and θ as the sample Std Dev of corresponding posterior distributions.
9. Step 9. Construct the 95 percent (or 90 percent) credible intervals of β_k and θ using the 2.5th (or 5th) percentiles and the 97.5th (or 95th) percentiles of the corresponding posterior distributions. If the credible interval contains the value 1, then no significant effect has been observed. The credible interval placed below 1 (i.e., the upper limit of the interval is less than 1) implies that the countermeasure has a significant positive effect (i.e., a reduction in crashes) on safety. The credible interval placed above 1 (i.e., the lower limit of the interval is greater than 1) implies that the countermeasure has a significant negative effect (i.e., an increase in crashes) on safety.

The FB approach addresses the regression-to-the-mean problem by focusing on estimation of the *expected* number of crashes for both before and after periods without directly using the *observed* crash count in the comparison. In the FB approach, the uncertainty in model parameters is incorporated into the final CMF estimate.

Generalized Linear Regression Analysis with PS Weighting

To increase statistical power, the research team performed some analyses using generalized linear regression models to aggregate locations from the three States, as well as to include locations for which the longitudinal data did not include the date of change to MR, locations that otherwise needed to be discarded in the ITS-CG analyses. While allowing the estimation to include such locations, generalized linear model (GLM)-based analysis also allowed for accounts of yearly trends, and changes in yearly trends by type of location (MR and comparison), grouping at two different levels (by evaluation group and by specific location within evaluation group), as well as other influential factors. The analyses were consistent with predictive methods described in the *Highway Safety Manual* (American Association of State Highway and Transportation Officials (AASHTO) 2010). The models included an error term that describes the variability between the mean response and the observations.

In the context of safety statistical modeling, the effect of a countermeasure is generally estimated by comparing the expected crash frequency or crash probability at treated sites to the expected crash frequency or probability when the treatment is absent. In the current evaluation, the data structure permits the focus on these contrasts to consider before and after periods for each MR conversion, while controlling for the corresponding change at the set of three comparison sites within the evaluation group. Although this approach can account for regression to the mean, this type of comparison could still be fraught with safety changes in other safety-influential covariates if not properly accounted for properly. For example, if sites with the countermeasure carry more traffic than those without the countermeasure, then the sites with the countermeasure would tend to experience more crashes merely because of their increased exposure to crash risk, despite the presence of the countermeasure. This effect should be explicitly controlled for in the analysis before estimation of the effect of the countermeasure under study. Similar to the FB approach, using GLMs allows for an account of such potential key differences explicitly in the set of parameter estimates while developing CMFs from a subset of parameters.

PS weighting was used in the GLM analysis balancing for representation on the overlap distribution of sites, as defined by Li, Morgan, and Zaslavsky (2018). Under this framework, weights are developed based on a PS analysis of the data, so that the contrasts reflect a population of sites approximately equally likely to be in either the treated or comparison groups.

Binomial Mixed Models for Estimating Severity CMFs Through Severe Crash Risk

The research team used binomial mixed models on data with two levels of aggregation (i.e., evaluation group, and study site), to assess the change in safety linked to the MR conversion at the treated sites. In this instance, the distribution of a response variable *Y* indicating the number of successful observations (i.e., fatal crashes) from a binomial set of trials (i.e., number of crashes in each period for that location in the study) can be modeled as a function of independent variables *X* and appropriate adjustments for the two nested grouping levels as a binomial variable (figure 2).

$$P\left(Y = y_i \middle| \boldsymbol{X}_i, MR\_CO\_ID_i, Eval\_group_j\right) = \binom{n_i}{y_i} \cdot p^{y_i} \cdot (1-p)^{n_i - y_i} \cdot k\left(MR\_CO\_ID_i, Eval\_Group_j\right)$$

Figure 2. Equation. Conditional probability of y value, given explanatory variables and site characteristics.

Where:

P = probability of Y taking value y_i, given the ith realization of a vector of explanatory variables X and *MR_CO_ID* (defined as the identification number for the site study) and evaluation group (*Eval_Group*) random effects.
Y = count of observed successes, given n trials.
y_i = a particular value in the domain of random count variable Y.
$MR\_CO\_Id_i$ = random effect for the ith *MR_CO_ID* in the dataset.
$Eval\_Group_j$ = random effect for the jth *Eval_Group* in the dataset.
n_i = reference number of trials for which Y is observed.
p = probability of a crash.
k = multiplicative random function of *MR_CO_ID* and *Eval_Group* capturing binomial overdispersion in the data through crossed-random-effects variability.

For a crash corridor i, the logit of p_i can be expressed as in figure 3.

$$g(p_i) = \ln\left(\frac{p_i}{1 - p_i}\right) = \boldsymbol{\beta}' \cdot \boldsymbol{X}_i + MR\_CO\_ID_i + Eval\_Group_j$$

Figure 3. Equation. Binomial-lognormal mixed-model parameterization.

Where:

$g(p_i)$ = logit function of p_i.

p_i = probability of crash at ith *MR_CO_ID*.

$\boldsymbol{X}$ = vector of independent variables (including key variable in evaluation and other safety-influential covariates).

$\boldsymbol{\beta}$ = vector of regression coefficients.

The mixed-effects model approach allows an explicit account for possible correlations between multiple realizations of the outcome variable at a common MR_CO_ID and at nearby locations within a given Eval_Group. From each model, the research team estimated rate parameters, which were used to estimate the odds ratios (ORs) (when combined with the different levels of the independent variables). An OR is a direct estimate of a CMF and is expressed as the expected increase or decrease in crash risk of one level of treatment (MR intersection) relative to a base level (TWSC or AWSC). An OR greater than 1.0 indicates that the change in that condition increases risk, and a ratio less than 1.0 indicates a decrease in risk.

CHAPTER SUMMARY

This chapter describes the study design, database structure, statistical methodologies, analysis methods, and tools that the research team used in performing the safety evaluations in this study. The chapter discusses the methodological features associated with the evaluations and the critical steps to develop a database suitable for statistical analysis.

Finally, this chapter outlines statistical analysis methods to assess the safety effectiveness of MR installations (FB analysis of before–after designs with comparison groups) and contrasts in crash risk between MR and either TWSC or AWSC (via binomial mixed-effects regression models, as specified in figure 2 and figure 3) to support developing the CMFs of interest.

CHAPTER 3. DATA COLLECTION AND INTEGRATION

The research team identified several data sources to meet the needs of the MR safety evaluations in this study. As described in chapter 2, the research team focused on balancing the sites from treated and comparison locations, and, when selecting the latter, obtaining data from additional comparison locations to substitute less suitable locations for the comparison group when necessary.

CRASH AND TRAFFIC VOLUME DATA COLLECTION

The research team obtained crash data from Washington, Michigan, and Maryland. Washington crash data covered 17 yr (2003–2019), Michigan crash data covered 7 yr (2013–2019), and Maryland crash data covered 5 yr (2015–2019). The team further determined that MRs were installed in Washington between 2006 and 2019, in Michigan between 2015 and 2018, and in Maryland between 2000 and 2013. The research team ideally intended to use at least 3 yr before and after installation, but this number was not feasible for all locations and States, given the ranges of data representation. However, the methods of analysis described in chapter 2 can be adapted to have before and after periods of different lengths.

Anticipated Effect Size and Data Needs

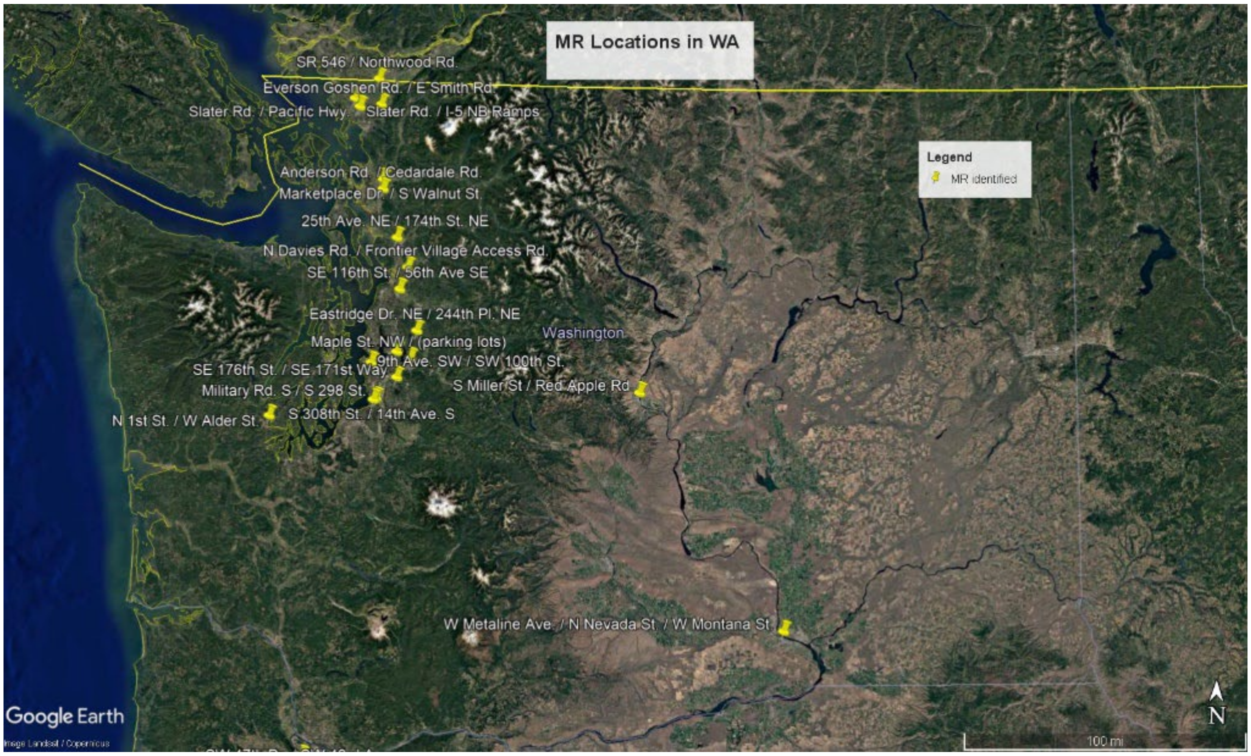
From the literature review, various international studies have quantified the safety benefit of MRs compared with TWSC intersections. Crash reduction effect estimates range from 25 to 37 percent (Brilon 2011; Green 1977; Ibrahim and Metcalfe 1993; Bodé and Maunsell 2006). The study by Ibrahim and Metcalfe (1993) found a benefit had a sample of 88 MRs. Given the preliminary exploration of the available data in the United States, the research team considered that such a large sample size may not be available for this study. However, the team anticipated that a smaller sample might yield meaningful results, given the relatively large safety effect expected of at least 25 percent and up to 37 percent of crash reductions from those studies, as well as the use of statistical methods capable of handling small sample sizes.

Treated and MR Sites

For some study locations, satellite and street-level imagery did not offer sufficient detail to determine the geometric features of interest, especially in the periods before MR conversions. Additionally, due to limited availability of AADT data at locations from lower functional classes, the research team had to use imputation based on AADT history of similar locations, as explained in chapter 2. After a few locations without AADT data were removed from the study, the final number of MRs in the evaluation was 27, representing three States: Washington, Michigan, and Maryland.

The research team determined that a substantial number of candidates for this study were located in Washington. A screening of data in March 2020 revealed 19 sites that could be potentially used. These sites include 11 MRs that were converted from either TWSC or STOP on minor roadways and 1 converted from AWSC, leaving 7 sites with an unknown before condition.

A map with these locations is shown in figure 4. Additionally, the research team confirmed that Highway Safety Information System (HSIS) data dictionaries indicated no intersection file available for Washington (HSIS 2022). For those reasons, the research team contacted the Washington DOT directly to request crash data.



Original map © 2019 Google® Earth™. Modified by FHWA (see Acknowledgments).

Figure 4. Map. MR locations in Washington (Google 2019).

Initially, the research team searched data availability in the HSIS (2022) database from Washington and found safety data available up to 2018 but not at locations out of the State-maintained highway system.

The research team was able to collect information for six sites in four different cities in Maryland, leaving seven sites with an unknown before condition (table 2). Among the sites obtained, two were converted from TWSC, one from a STOP on a minor roadway, and three from AWSC.

Table 2. Identified sites in Maryland.

City	Location	Year Completed	Land Use	Before Control
Columbia	Golden Straw Ln. and Davis Rd.	2000	Residential/urban	TWSC
Bel Air	S. Tollgate Rd. and W. MacPhail Rd.	2012	Residential/urban	TWSC
Baltimore	Canterbury Rd. and W. 39th St.	2013	University/urban	TWSC
Baltimore	Guilford Ave. and 22nd St.	2012	Residential/urban	AWSC
Baltimore	Guilford Ave. and E. 24th St.	2012	Residential/urban	AWSC
Stevensville	Thompson Creek Rd. and U.S. 50 eastbound ramps	2007	Commercial/urban	AWSC

CHARACTERISTICS OF SELECTED MR LOCATIONS

A comparable group of MRs was installed at locations with either TWSC or AWSC (table 3).

Table 3. Traffic control type before MR installation.

State	AWSC	TWSC	Unclear	Total
Maryland	3	3	0	6
Michigan	6	0	0	6
Washington	0	9	6	15
Total	9	12	6	27

Similarly, table 4 shows the number of sites of analysis available at comparison sites.

Table 4. Traffic control type at comparison sites.

State	AWSC	TWSC	Total
Maryland	9	9	18
Michigan	17	0	17
Washington	12	35	47
Total	38	44	82

The research team collected other site characteristics that would potentially be accounted for in the statistical contrast between the MRs and comparison sites. These characteristics included land use, proximity to school zones, the presence of the bus stop, bike lanes, crosswalks, median type, and signs and markings, among others. Most of the MRs and comparison sites were in urban areas and in residential locations, and some sites were at commercial and mixed land use locations. Furthermore, most of the MRs and their comparison sites were located away from school zones, did not have crosswalks, and did not have pedestrian crossing signs (table 5).

Table 5. Other characteristics of treated and comparison sites.

State	Within School Zone		Crosswalk Present		Pedestrian Crossing Signs	
	No	Yes	No	Yes	No	Yes
Maryland	22	2	11	14	11	13
Michigan	23	0	23	0	23	0
Washington	59	3	44	19	45	19
Total	104	5	78	33	79	32

If a site had at least one period for a given condition (such as having crosswalks or not having them), they are counted in the corresponding cell. As a result, the totals for the two columns under each variable in table 5 do not necessarily add up to the same value, because sites that had a change for a feature (e.g., crosswalk present) are counted under both the Yes and No columns.

Table 6, table 7, and table 8 show summary statistics of the assembled databases. Table 6 shows that the average total entering volumes (i.e., both average major and average minor AADT combined) for the sites in Washington are approximately 7,800 vehicles per day (vpd).

Table 6. Descriptive statistics—Washington data.

Variable	Mean	Std Dev	Median	Minimum	Maximum
Year	2011	4.9	2011	2003	2019
MR.Install date	2014.03	3.82	2014	2006	2019
MajAADT (vpd)	5,588.71	3,128.41	5,602	642.87	1,5138
MinAADT (vpd)	2,222.36	1,628.96	1,707.21	240	9,555
Approaches	3.81	0.4	4	3	4
lanes_maj (approach)	2.1	0.43	2	2	3
lanes_min (approach)	1.94	0.44	2	1	3
spd_maj (mph)	30.19	6.37	30	20	50
spd_min (mph)	27.5	6.1	25	15	35
diagonal_length (ft)	75.4	17.14	71.5	43	125.08
maj_ln width (ft)	12.2	2.02	12	10	15
min_ln width (ft)	12.3	2.84	12	9	15
MR_diameter (ft)	70.35	12.2	63.31	58.36	97.2

MR.Install date = MR installation date; MajAADT = major AADT; MinAADT = minor AADT; lanes_maj = major lanes; lanes_min = minor lanes; spd_maj = speed limit on the major approaches; spd_min = speed limit on the minor approaches; diagonal_length = diagonal length; maj_ln width = major line width; min_ln width = minor line width; MR_diameter = MR diameter.

The diagonal length (diagonal_length) variable was collected to capture the overall footprint of the intersection, regardless of whether it was a roundabout or comparison site. This variable was considered as an alternative to the diameter in the model selection, as described in the Panel Analysis on Multistate Data section.

Table 7 shows that the average amount of entering traffic (approximately 7,700 vpd) in the Michigan dataset is comparable to that observed for Washington.

Table 7. Descriptive statistics—Michigan data.

Variable	Mean	Std Dev	Median	Minimum	Maximum
Year	2016	2.01	2016	2013	2019
MR.Install date	2016.74	1.08	2017	2015	2018
MajAADT (vpd)	4,206.49	2,292.63	3,341	253	7,598
MinAADT (vpd)	3,566.95	2,135.23	3,062	439	8,397
Approaches	4	0	4	4	4
lanes_maj	2.09	0.41	2	2	4
lanes_min	2.09	0.41	2	2	4
spd_maj (mph)	46.96	3.84	45	35	55
spd_min (mph)	43.7	5.77	45	25	55
diagonal_length (ft)	83.47	12.02	83.11	61.5	108
maj_ln width (ft)	11.91	1.62	12	10	15
min_ln width (ft)	11.78	1.75	11	10	15
MR_diameter (ft)	87.97	7.97	88.02	69.32	98.98

Similarly, table 8 shows the statistics for Maryland data, which had an average entering volume of approximately 7,500 vpd, which was comparable with the other two States.

Table 8. Descriptive statistics—Maryland data.

Variable	Mean	Std Dev	Median	Minimum	Maximum
Year	2017	1.42	2017	2015	2019
MR.Install date	2011.33	1.98	2012	2007	2013
MajAADT (vpd)	4,964.06	3,978.39	3,727.5	877	14,375
MinAADT (vpd)	2,640.98	2,600.72	1,470.25	329	10,052
Approaches	4	0	4	4	4
lanes_maj	2.08	0.4	2	2	4
lanes_min	2	0.29	2	1	3
spd_maj (mph)	28.12	4.54	25	25	40
spd_min (mph)	26.25	3.62	25	15	35
diagonal_length (ft)	67.91	10.8	65.5	55	93
maj_ln width (ft)	12.96	1.60	13	11	15
min_ln width (ft)	12.68	1.90	12	10	15
MR_diameter (ft)	60.79	17.4	62.03	39.06	88.42

Finally, table 9, table 10, and table 11 show crash statistics for the three States. The statistics were generated for yearly periods of analysis so that the statistics would correspond to crashes per year.

Table 9. Crash descriptive statistics—Washington data (crashes per year).

Crash Type	Mean	Std Dev	Minimum	Maximum
Total	0.57	1.18	0	11
FI	0.17	0.52	0	5
PDO	0.39	0.9	0	7
MV_Total	0.51	1.1	0	11
MV_FI	0.15	0.49	0	5
MV_PDO	0.36	0.86	0	7
Total_Ped_&_Bicycle	0.01	0.1	0	1
Total_Bus_&_Truck	0.03	0.18	0	2

MV_Total = multivehicle total; MV_FI = multivehicle FI; MV_PDO = multivehicle PDO; Total_Ped_&_Bicycle = total pedestrian and bicycle; Total_Bus_&_Truck = total bus and truck.

Table 10. Crash descriptive statistics—Michigan data (crashes per year).

Crash Type	Mean	Std Dev	Minimum	Maximum
Total	2.57	3.39	0	24
FI	0.48	0.84	0	4
PDO	2.08	3.12	0	23
MV_Total	2.43	3.3	0	24
MV_FI	0.46	0.79	0	4
MV_PDO	1.98	3.04	0	23
Total_Ped_&_Bicycle	0	0	0	0
Total_Bus_&_Truck	0.08	0.27	0	1

Table 11. Crash descriptive statistics—Maryland data (crashes per year).

Crash Type	Mean	Std Dev	Minimum	Maximum
Total	0.72	1.01	0	5
FI	0.16	0.45	0	2
PDO	0.57	0.81	0	4
MV_Total	0.58	0.93	0	5
MV_FI	0.13	0.41	0	2
MV_PDO	0.45	0.78	0	4
Total_Ped_&_Bicycle	0.03	0.18	0	1

The crash statistics show that the frequency of pedestrian/bicycle and bus/truck crashes is small, and, thus, no meaningful analysis of these crashes could be supported.

CHAPTER SUMMARY

This chapter documents the data collection and assembled database for this study. Various summary statistics are presented for the three databases developed: Washington, Michigan, and Maryland. The next chapter describes the statistical evaluations of these datasets and the derived CMF estimates.

CHAPTER 4. SAFETY-EFFECTIVENESS EVALUATIONS

This chapter describes the statistical analysis and presents the results of the safety-effectiveness evaluations of MR installations, including estimated CMFs of interest.

As described in chapter 3, the research team assembled a three-State database for the statistical evaluation. The research team conducted multiple types of analyses on the ITS-CG data structure. First, FB evaluations were done for Washington for each crash type separately, and second, a GLMM estimation was done on all the panel data from three States combined, to maximize the size of the dataset and thus boost the statistical power of the estimation.

WASHINGTON RASH ANALYSIS

The research team conducted the safety evaluation of MR in Washington by FB before–after analysis with comparison groups. Because the literature suggested that the safety effects associated with MR implementation significantly vary with previous intersection control types (whether TWSC or AWSC) (Green 1977, Ibrahim and Metcalfe 1993, Pulugurtha, Mishra, and Mathew 2021), the team considered CMFs for MR for TWSC and AWSC separately.

The Washington data contained 15 MR sites. The yearly crash data were obtained at each of the 15 sites for 2003 to 2019. The implementation year when the MR was installed at each site varies between 2006 and 2019. Table 12 gives the number of sites in Washington for each implementation year. As can be seen from table 12, the base condition for the before period is missing (no old photo existed for those sites) for 6 out of 15 MRs in the database, and those sites were excluded from the before–after evaluation. The remaining nine sites all had TWSC as the before condition. Consequently, CMF was developed based on before–after analysis of those nine sites with TWSC as the before condition.

Table 12. Number of MR sites and comparison sites in Washington for each implementation year.

Implementation Year	Number of MR Sites	Number of MR Sites with a Known Before Condition (TWSC)	Number of Comparison Sites
2006	2	—	6
2012	2	2	6
2013	2	1	6
2014	3	2	9
2015	—	—	2
2016	1	1	3
2017	2	1	6
2018	1	—	3
2019	2	2	6
Total	15	9	47

—No data.

The treatment group for MR (with TWSC as the before condition) in Washington consists of crashes from intersections where MRs were installed during 2012, 2013, 2014, 2016, 2017, and 2019. The year with the installation of MR is included in the after period.

The team fitted a Poisson-gamma mixture model with a change point as described in chapter 2, to total, FI, PDO, multivehicle total (MV_Total), multivehicle FI (MV_FI), and multivehicle PDO (MV_PDO) crashes. This model included appropriate indicator functions for site type (specifying whether a segment is a treatment site or a comparison site) and period (specifying whether the site belongs to the before or the after period) as well as time trend for each site type and other covariates. Exposure was accounted for by the variables logAADT_Maj and logAADT_Min (log of major approach AADT and log of minor approach AADT, respectively). Additionally, the following variables were included as model covariates:

- Approaches—Number of approaches.
- PedCross01—Whether there is a pedestrian crossing sign: 1 = yes; 0 = no.
- SchoolZone01—Whether there is a school zone within 250 ft: 1 = yes; 0 = no.
- diag1—Length of the first diagonal in feet.
- diag2—Length of the second diagonal in feet.
- spd_maj—Speed limit on the major approaches.

The research team followed the steps for implementing FB before–after evaluations with six comparison groups (corresponding to implementation years 2012, 2013, 2014, 2016, 2017, and 2019 with G=6) as presented in chapter 2. To manage the issue of a limited sample size, the team incorporated prior knowledge obtained from previous studies documented in the CMF Clearinghouse on the safety effects of roundabouts into the analysis through a prior distribution (FHWA 2022b). For the prior distribution of β_5 in the analysis, the research team used an informative prior distribution derived based on the CMFs for roundabouts provided on the CMF Clearinghouse website as well as previous studies (Kennedy, Hall, and Barnard 1998; Green 1977; Walker and Pitnam 1989; Lalani 1975; Ibrahim and Metcalfe 1993) on MRs to compensate for the small sample size. Previous studies on MRs indicated crash reductions of roughly 30 to 79 percent, which would correspond to CMF value of 0.21–0.7 (Green 1977; Lalani 1975;). The CMF Clearinghouse provides the following CMFs for roundabouts: 0.42 (with adjusted standard error (Std Err) 0.13 and unadjusted Std Err 0.07) for conversion of stop-controlled intersection into single-lane roundabout, 0.56 (with adjusted Std Err 0.1 and unadjusted Std Err 0.05) for convert unsignalized intersection to roundabout, and 0.53 (with unadjusted Std Err 0.061) for conversion of intersection into single-lane roundabout. Because the CMF will be roughly on the same scale as $exp(\beta_5)$, the normal distribution with a mean of −0.8 (for total, PDO, MV_Total, and MV_PDO crashes) or −0.9 (for FI and MV_FI crashes), and Std Dev of 0.1 was used for the prior distribution for β_5. For the prior distributions of the other regression coefficients, however, proper but diffuse priors, such as a normal distribution with mean of 0 (or other nonzero constant for β_0) and Std Dev of 1, were used to reflect the lack of precise knowledge on the parameters a priori. The inferences on the parameters of interest were made based on the samples from the posterior distribution obtained by the MCMC algorithm coded in MATLAB® (MathWorks 2022).

Table 13, table 15, table 17, table 19, table 21, and table 23 summarize the results from the FB analysis based on 5,000 posterior samples collected for 100,000 iterations by subsampling every

10th sample after discarding the first 50,000 draws. The estimated CMF and index of effectiveness were obtained by accounting for the changes in unmeasured factors between the before and the after period using the comparison ratio following steps 4–6 described in the section, Steps for Implementing FB Before–After Evaluations with Multiple Comparison Groups, in chapter 2. The corresponding uncertainty estimates for each table for the estimated CMF, the posterior Std Dev, and 95 percent (or 90 percent) credible interval are provided in table 14, table 16, table 18, table 20, table 22, and table 24. The results indicate that there have been statistically significant reductions in total, FI, PDO, MV_Total, and MV_PDO crashes after conversion to MRs from TWSC intersections. Reductions for total and PDO crashes were statistically significant with 95 percent probability, and reductions for FI, MV_Total, and MV_PDO crashes were significant with 90 percent probability.

Table 13. Results for FB evaluation of total crashes for MR sites with TWSC as the before condition in Washington.

Regression Coefficients	Variable	Estimate	Uncertainty Estimates	Lower Limit of 95-percent Credible Interval	Upper Limit of 95-percent Credible Interval
β_0	Intercept	−4.5163	1.3567	−7.0911	−1.7200
β_1	Trt	−0.9762	0.7097	−2.4647	0.4220
β_2	Time	0.0872	0.0214	0.0449	0.1316
β_3	Trt×time	0.1168	0.0271	0.0660	0.1704
β_4	After	−0.2386	0.2212	−0.6715	0.1885
β_5	Trt×After	−0.7595	0.0968	−0.9539	−0.5757
β_6	logAADT_Maj	0.7959	0.3893	0.1077	1.5535
β_7	logAADT_Min	0.0538	0.3269	−0.6154	0.7182
β_8	Approaches	−2.9383	0.6861	−4.3563	−1.6534
β_9	PedCross01	−0.9240	0.6339	−2.1438	0.3774
β_{10}	SchoolZone01	2.8451	0.9931	1.1580	4.9494
β_{11}	diag1	0.0190	0.0117	−0.0027	0.0429
β_{12}	diag2	0.0181	0.0115	−0.0033	0.0412
β_{13}	spd_maj	0.1189	0.0364	0.0537	0.2014

Table 14. MR CMF and uncertainty estimates for table 13.

CMF	Estimate
CMF_{TWSC} ($\hat{\theta}$)	0.6330
Std Dev	0.1512
95-percent credible interval	(0.3807, 0.9713)
90-percent credible interval	(0.4157, 0.8956)
$100\,(1-\hat{\theta})$ (percent reduction)	36.70

$\hat{\theta}$ = the estimated CMF, per FB procedure described in chapter 2.
Std Dev = the posterior standard deviation for θ.
$100\,(1-\hat{\theta})$ = the estimated percent crash reduction.
CMF_{TWSC} = CMF of MR with TWSC as the before condition.

Table 15. Results for FB evaluation of FI crashes for MR sites with TWSC as the before condition in Washington.

Regression Coefficients	Variable	Estimate	Uncertainty Estimates	Lower Limit of 95-percent Credible Interval	Upper Limit of 95-percent Credible Interval
β_0	Intercept	−2.8003	0.9452	4.7607	−0.9262
β_1	Trt	−0.7077	0.5305	−1.8295	0.2539
β_2	Time	0.0501	0.0302	−0.0130	0.1083
β_3	Trt×time	0.1040	0.0392	0.0298	0.1866
β_4	After	−0.2396	0.2950	−0.7931	0.3188
β_5	Trt×After	−0.8979	0.0919	−1.0778	−0.7112
β_6	logAADT_Maj	−0.2411	0.2932	−0.8118	0.3621
β_7	logAADT_Min	0.3922	0.2729	−0.1747	0.9115
β_8	Approaches	−2.1133	0.4149	−3.0429	−1.3591
β_9	PedCross01	−0.9540	0.6402	−2.3349	0.2295
β_{10}	SchoolZone01	1.9136	0.6919	0.5683	3.3282
β_{11}	diag1	0.0163	0.0102	−0.0050	0.0343
β_{12}	diag2	0.0145	0.0110	−0.0056	0.0368
β_{13}	spd_maj	0.1420	0.0281	0.0862	0.2020

Table 16. MR CMF and uncertainty estimates for table 15.

CMF	Estimate
CMF_{TWSC} ($\hat{\theta}$)	0.5773
Std Dev	0.2114
95-percent credible interval	(0.2616, 1.0672)
90-percent credible interval	(0.3019, 0.9577)
$100\,(1-\hat{\theta})$ (percent reduction)	42.27

Table 17. Results for FB evaluation of PDO crashes for MR sites with TWSC as the before condition in Washington.

Regression Coefficients	Variable	Estimate	Uncertainty Estimates	Lower Limit of 95-percent Credible Interval	Upper Limit of 95-percent Credible Interval
β_0	Intercept	−8.6456	1.0573	−10.7568	−6.5717
β_1	Trt	−0.5725	0.5237	−1.6307	0.4614
β_2	Time	0.0954	0.0242	0.0505	0.1400
β_3	Trt×time	0.0980	0.0265	0.0458	0.1478
β_4	After	−0.1331	0.2349	−0.5985	0.3055
β_5	Trt×After	−0.7514	0.0936	−0.9369	−0.5572
β_6	logAADT_Maj	0.7636	0.3338	0.1845	1.4837
β_7	logAADT_Min	0.0371	0.3029	−0.5959	0.5899
β_8	Approaches	−1.6871	0.4411	−2.7441	−0.9767
β_9	PedCross01	−0.8500	0.5291	−1.9080	0.2061
β_{10}	SchoolZone01	1.5275	0.7161	0.2429	3.0469
β_{11}	diag1	0.0186	0.0094	−0.0013	0.0390
β_{12}	diag2	0.0149	0.0095	−0.0049	0.0338
β_{13}	spd_maj	0.0983	0.0299	0.0414	0.1660

Table 18. MR CMF and uncertainty estimates for table 17.

CMF	Estimate
CMF_{TWSC} ($\hat{\theta}$)	0.5977
Std Dev	0.1462
95-percent credible interval	(0.3540, 0.9341)
90-percent credible interval	(0.3884, 0.8623)
$100\left(1-\hat{\theta}\right)$(percent reduction)	40.23

Table 19. Results for FB evaluation of MV_Total crashes for MR sites with TWSC as the before condition in Washington.

Regression Coefficients	Variable	Estimate	Uncertainty Estimates	Lower Limit of 95-percent Credible Interval	Upper Limit of 95-percent Credible Interval
β_0	Intercept	−4.4562	1.1626	−6.6909	−2.0749
β_1	Trt	−0.8073	0.5840	−1.9630	0.3981
β_2	Time	0.0762	0.0212	0.0365	0.1195
β_3	Trt×time	0.1276	0.0264	0.0788	0.1805
β_4	After	−0.1216	0.2140	−0.5489	0.2882
β_5	Trt×After	−0.7704	0.0892	−0.9608	−0.6053
β_6	logAADT_Maj	0.5168	0.3619	−0.1162	1.3486
β_7	logAADT_Min	0.0999	0.2891	−0.5420	0.6598
β_8	Approaches	−2.4914	0.5983	−3.8241	−1.5337
β_9	PedCross01	−0.6885	0.5559	−1.7534	0.4606
β_{10}	SchoolZone01	1.8898	0.7850	0.4563	3.7072
β_{11}	diag1	0.0173	0.0090	−0.0018	0.0348
β_{12}	diag2	0.0191	0.0097	0.0014	0.0407
β_{13}	spd_maj	0.1172	0.0303	0.0630	0.1852

Table 20. MR CMF and uncertainty estimates for table 19.

CMF	Estimate
CMF_{TWSC} ($\hat{\theta}$)	0.6802
Std Dev	0.1621
95-percent credible interval	(0.4073, 1.0458)
90-percent credible interval	(0.4422, 0.9698)
$100\,(1-\hat{\theta})$ (percent reduction)	31.98

Table 21. Results for FB evaluation of MV_FI crashes for MR sites with TWSC as the before condition in Washington.

Regression Coefficients	Variable	Estimate	Uncertainty Estimates	Lower Limit of 95-percent Credible Interval	Upper Limit of 95-percent Credible Interval
β_0	Intercept	−2.6538	0.9399	−4.3873	−0.7207
β_1	Trt	−0.7655	0.5424	−1.8407	0.2512
β_2	Time	0.0465	0.0305	−0.0146	0.1058
β_3	Trt×time	0.1122	0.0416	0.0383	0.1994
β_4	After	−0.2441	0.3133	−0.8660	0.3521
β_5	Trt×After	−0.8962	0.0933	−1.0919	−0.7143
β_6	logAADT_Maj	−0.1564	0.2987	−0.7235	0.4781
β_7	logAADT_Min	0.3267	0.2851	−0.2633	0.8655
β_8	Approaches	−2.3596	0.4333	−3.3062	−1.5895
β_9	PedCross01	−0.7024	0.7151	−2.1196	0.7363
β_{10}	SchoolZone01	1.7498	0.7138	0.3416	3.1752
β_{11}	diag1	0.0126	0.0110	−0.0096	0.0320
β_{12}	diag2	0.0179	0.0115	−0.0041	0.0422
β_{13}	spd_maj	0.1519	0.0316	0.0907	0.2180

Table 22. MR CMF and uncertainty estimates for table 21.

CMF	Estimate
CMF_{TWSC} ($\hat{\theta}$)	0.5980
Std Dev	0.2328
95-percent credible interval	(0.2556, 1.1408)
90-percent credible interval	(0.2966, 1.0174)
$100\,(1-\hat{\theta})$ (percent reduction)	40.20

Table 23. Results for FB evaluation of MV_PDO crashes for MR sites with TWSC as the before condition in Washington.

Regression Coefficients	Variable	Estimate	Uncertainty Estimates	Lower Limit of 95-percent Credible Interval	Upper Limit of 95-percent Credible Interval
β_0	Intercept	−8.4140	1.0395	−10.4963	−6.3436
β_1	Trt	−0.5982	0.5203	−1.7023	0.4434
β_2	Time	0.0888	0.0261	0.0390	0.1420
β_3	Trt×time	0.1111	0.0278	0.0566	0.1650
β_4	After	0.0007	0.2489	−0.4946	0.5091
β_5	Trt×After	−0.7682	0.0922	−0.9496	−0.5922
β_6	logAADT_Maj	0.6021	0.3265	−0.0057	1.3292
β_7	logAADT_Min	0.1487	0.3101	−0.4929	0.7527
β_8	Approaches	−1.7576	0.4620	−2.7889	−0.9891
β_9	PedCross01	−0.4764	0.5472	−1.5742	0.5816
β_{10}	SchoolZone01	1.0436	0.7363	−0.3949	2.5529
β_{11}	diag1	0.0207	0.0097	0.0014	0.0398
β_{12}	diag2	0.0138	0.0105	−0.0105	0.0319
β_{13}	spd_maj	0.1085	0.0347	0.0526	0.1909

Table 24. MR CMF and uncertainty estimates for table 23.

CMF	Estimate
CMF_{TWSC} ($\hat{\theta}$)	0.6389
Std Dev	0.1610
95-percent credible interval	(0.3648, 1.0109)
90-percent credible interval	(0.4091, 0.921)
$100\,(1-\hat{\theta})$ (percent reduction)	36.11

CONSOLIDATED RESULTS

Table 25 presents consolidated results for estimations in the CMFs and percent crash reductions. Again, it can be seen from the table that CMFs for MR converted from TWSC intersections are statistically significant for total, FI, PDO, MV_Total, and MV_PDO crashes.

Table 25. CMFs for MR converted from TWSC for different crash types.

	Total	FI	PDO	MV_Total	MV_FI	MV_PDO
CMF_{TWSC}	**0.6330****	**0.5773***	**0.5977****	**0.6802***	0.5980	**0.6389***
Std Dev	0.1512	0.2114	0.1462	0.1621	0.2328	0.1610
95-percent credible interval	(0.3807, 0.9713)	(0.2616, 1.0672)	(0.3540, 0.9341)	(0.4073, 1.0458)	(0.2556, 1.1408)	(0.3648, 1.0109)
90-percent credible interval	(0.4157, 0.8956)	(0.3019, 0.9577)	(0.3884, 0.8623)	(0.4422, 0.9698)	(0.2966, 1.0174)	(0.4091, 0.921)
Crash reduction (percent)	**36.70****	**42.27***	**40.23****	**31.98***	40.20	**36.11***

*Statistically significant results at 90-percent level.
**Statistically significant results at 95-percent level.
Std Dev = the posterior standard deviation (uncertainty estimate) for CMF.

The next section summarizes an analysis effort based on the complete multistate dataset as an alternative approach to deal with the small sample issue.

PANEL ANALYSIS ON MULTISTATE DATA

The research team conducted the next round of safety evaluations of MR in the multistate panel data. Similar to the FB analysis, an explicit account for the longitudinal structure and comparison groups was used to assess the change in crash frequency at MR installations, given the prior traffic control types at those locations.

The research team performed a panel analysis, including all data for the MR intersection operation compared with the other control types available, namely TWSC and AWSC. The response variables in these analyses were the same as presented in the FB analysis. All estimations in these models were performed using GLMMs.

Particular challenges for these analyses included the multiple dates of installation of the MRs, the availability of data from additional MR sites whose prior condition could not be confirmed or represented in the dataset (in Washington and Maryland), and the availability of additional comparison sites initially collected to be matched and contrasted with an MR but whose MR location had to be removed from the dataset due to unavailable traffic volume data. The data from unmatched locations could only be used in this analysis of the complete multistate panel data. The research team developed overlap PS weights so that the analysis results would be indicative of the overlap population between the treated and comparison sites.

The model estimates for the multistate panel data are shown in table 26.

Table 26. Model estimates from panel multistate data by crash type.

Parameter	Total, Estimate (Std Err)	FI, Estimate (Std Err)	PDO, Estimate (Std Err)	MV_Total, Estimate (Std Err)	MV_FI, Estimate (Std Err)	MV_PDO, Estimate (Std Err)
(Intercept)	−6.453 (1.914)‡	−8.332 (2.453)‡	−5.886 (1.91)†	−7.829 (2.511)†	−7.1139 (2.5638)†	−6.103 (1.988)†
log(MajAADTfc + MinAADTfc)	0.3112 (0.2158)	—	0.243 (0.2162)	0.4104 (0.2858)	0.1972 (0.289)	0.2569 (0.225)
log(MajAADTfc)	—	0.3335 (0.3878)	—	—	—	—
log(MinAADTfc)	—	0.0709 (0.3355)	—	—	—	—
MinAADTfc	—	—	—	−4.701E-5 (9.425E-5)	—	—
I(TR_CTRL = MR)	−0.0184 (0.3046)	−0.2211 (0.6503)	−0.0266 (0.3473)	−0.0311 (0.3712)	0.1214 (0.6492)	−0.3758 (0.3757)
I(TR_CTRL = AWSC)	0.1336 (0.2741)	0.3086 (0.5405)	0.1086 (0.3028)	0.3826 (0.3552)	0.5924 (0.5471)	0.0392 (0.3191)
I(TR_CTRL =TWSC)	−0.0895 (0.2555)	0.1322 (0.4851)	−0.3289 (0.2901)	−0.2593 (0.328)	0.2245 (0.5143)	−0.458 (0.3023)
MR_diameter	−0.0076 (0.0038)*	−0.0907 (0.0396)*	−0.0091 (0.0042)*	−0.0101 (0.005)*	−0.0894 (0.0388)*	−0.0064 (0.0045)
spd_maj	0.086 (0.0168)‡	0.0818 (0.0202)‡	0.0823 (0.0162)‡	0.1084 (0.0199)‡	0.083 (0.0189)‡	0.0845 (0.0166)‡
spd_min	—	—	—	−0.0396 (0.0193)*	—	—
lane_min	—	—	—	0.4413 (0.3195)	—	—
rel.yr	0.0639 (0.0091)‡	0.0388 (0.0166)*	0.0752 (0.0108)‡	0.0652 (0.0092)‡	0.0338 (0.018)§	0.081 (0.0112)‡
MR_diameter: MinAADTfc	3.9E-6 (6.4E-7)‡	—	4.2E-6 (7.0E-7)‡	4.4E-6 (8.8E-7)‡	0.0118 (0.0047)*	4.22E-6 (7.2E-7)‡
log(MinAADTfc): MR_diameter	—	0.0122 (0.0048)*	—	—	—	—

—Not applicable.
§Significant at the 90.0-percent confidence level.
*Significant at the 95.0-percent confidence level.
†Significant at the 99.0-percent confidence level.
‡Significant at the 99.9-percent confidence level.
MajAADTfc = Major AADT; MinAADTfc = Minor AADT; TR = Treatment; CTRL = control; rel.yr = relative year.

Next, the research team estimated the corresponding CMFs by contrasting the MR estimate to the estimates for the other two traffic control types at average values for the roundabout diameter and minor AADT, as the effects of the countermeasures on these variables were found to be interrelated. Table 27 shows the resulting CMFs for conversions of TWSC intersections to MR.

Table 27. CMFs for TWSC-to-MR conversion from panel multistate data.

Crash Type	Estimate	Std Err	*z* Value	*p* Value	Significance
Total	1.1015	0.0967	0.1859	0.6030	—
FI	0.6855	−0.3776	0.3497	0.2803	—
PDO	1.3000	0.2624	0.2140	0.2202	—
MV_Total	1.1552	0.1443	0.2034	0.4782	—
MV_FI	0.7833	−0.2442	0.3730	0.5127	—
MV_PDO	1.2676	0.2372	0.2236	0.2888	—

—Not applicable.

As can be seen in table 27, none of the estimates for TWSC-to-MR conversions was statistically significant in the multistate data. Similar to table 27, table 28 shows the CMFs corresponding to AWSC intersections converted to MRs from the multistate data.

Table 28. CMFs for AWSC-to-MR conversion from panel multistate data.

Crash Type	Estimate	Std Err	*z* Value	*p* Value	Significance
Total	0.8813	−0.1263	0.1852	0.4952	—
FI	0.5746	−0.5541	0.4157	0.1825	—
PDO	0.8393	−0.1751	0.1990	0.3788	—
MV_Total	0.6080	−0.4976	0.2455	0.0427	*
MV_FI	0.5422	−0.6122	0.4072	0.1327	—
MV_PDO	0.7710	−0.2600	0.2105	0.2168	—

—Not applicable.
*Significant at the 95.0-percent confidence level.

All estimates in table 28 are smaller than 1, suggesting there are crash reductions for this type of conversion. However, only for MV_Total crashes was this result statistically significant.

CHAPTER SUMMARY

This chapter documents the statistical evaluations and steps taken to develop CMFs from the three-State safety data available for this study. The analysis developed FB for Washington and GLMM statistical models for crash frequencies for the multistate joint database. The CMFs for MR converted from TWSC intersections were statistically significant for total, FI, PDO, MV_Total, and MV_PDO crashes. The CMF estimates showed directions with intuitive interpretations and reasonable magnitudes. In the multistate database, only a CMF estimate from AWSC to MR conversions yielded statistically significant results.

The next chapter documents an economic analysis that considers the results in the evaluations documented in this chapter.

CHAPTER 5. ECONOMIC ANALYSIS

The research team conducted an economic analysis to estimate B/C ratios for the evaluated MR installations at TWSC locations using the statistically significant severity shift factors developed from the multistate database. The research team adopted the procedures recommended in FHWA's technical document, *Crash Costs for Highway Safety Analysis* (Harmon, Bahar, and Gross 2018).

BENEFITS AND COSTS ESTIMATES

To perform a B/C analysis, the research team took results from the analyses documented in chapter 4, in combination with additional information on costs and other benefits of MR installations.

The research team estimated MR installation costs based on various sources. A Transportation Research Board webinar showed a range of MR installations in Michigan for 2017 that was between $840,000 and $900,000 (Gillum 2017). According to another source, the installation cost for the MRs ranges between $250,000 and $465,000 in Texas (Melton and Shumard 2019). Finally, according to a 2010 FHWA technical summary (Rodegerdts, Scarbrough, and Bansen, 2010), MR construction costs widely depends on the extent of modification to the location necessary for the conversion and the materials used in the construction. The cost estimates offered in 2010 by the FHWA report ranged from $50,000 up to $250,000. For the economic evaluation, the research team adopted the value of $300,000 in 2020 to represent a national average.

For the benefit side, the research team assumed comparable maintenance costs for AWSC and TWSC intersections, unlike traditional roundabouts that have landscape in the center and splitter islands. Regarding the benefit of reduced congestion, this analysis used the average national average of congestion hourly cost per driver of $13.9, as can be extracted from a congestion scorecard recently reported by a private company (INRIX 2018). Simulation studies on AWSC-to-MR conversion suggest significant delay reductions for AWSC configurations, even when operations are near to their saturation levels (Zhang 2012). Assuming such an operation to be a conservative estimate for AWSC, but not for TWSC, the yearly benefit is a reduction of about 3 delay h per driver. When converting this delay estimate to yearly values, the research team made the following conservative assumptions: Because the simulation analyses are performed for peak hour conditions, it was assumed that only half of the drivers would experience any delay, and that the peak hour estimate represents 50 percent of the total delay of an average day.

Economic Effectiveness of MR Installation at TWSC

The safety benefit of MR installation is derived from the estimated reductions in total crash frequency for TWSC conversions (table 25) A statistical life value of $11.6 million is the most current value used by U.S. DOT (Putnam and Coes 2021). The total yearly benefit (safety only) for MR installation at TWSC locations was estimated as $86,290 in 2020 dollars. In contrast, the assumed 2020 cost of construction was $300,000. For a useful life of 10 yr and no salvage value at the end of that period, the B/C ratio for the MR installation is estimated as 2.88.

Economic Effectiveness of MR Installation at AWSC

The safety benefit of AWSC conversion was estimated as the monetary value of reduction in MV_Total crash frequencies for AWSC conversions (per table 28). The total yearly benefits (safety and operational combined) for MR installation at AWSC locations was estimated as $402,423 in 2020 dollars, whereas the safety-only benefit was $86,074, similar to the benefit of TWSC intersections. Using the same 2020 cost of construction estimate ($300,000) and a useful life of 10 yr with no salvage value at the end of that period, the B/C ratio for the MR installation at AWSC locations is estimated as 13.41 when both safety and operations benefits are considered. The B/C ratio was 2.87 when only safety benefits were considered.

CHAPTER SUMMARY

This chapter describes the assumptions and sources to perform an estimation of the economic effectiveness of implementing MRs at locations with either AWSC or TWSC configurations. B/C ratios are developed for the two types of conversions. B/C ratios were found to be larger than 1.0 (2.88 and 2.87 for AWSC and TWSC conversions, respectively, when only safety benefits were considered, and 13.41 for AWSC when operational benefits were also considered), indicating more benefits than costs for these implementations. Chapter 6 provides a summary and conclusions of the project.

CHAPTER 6. SUMMARY AND CONCLUSIONS

The objective of this study was to perform rigorous safety-effectiveness evaluations of MR installations at TWSC and AWSC locations. The study database included three States and had a longitudinal design, including comparison sites. This data structure allowed ITS-CG evaluations, as well as a more general panel evaluation. The analyses were performed using FB models, as well as generalized linear mixed binomial models.

The safety data for these evaluations were compiled for locations of known MR installations around the United States where the date of installation and prior intersection condition could be known. A set of suitable comparison locations was identified to include allowing the analyses to control for extraneous variables. Additionally, geometric features were collected for analysis, as well as AADT where available. Model-based AADT imputation was performed at locations where AADT was partially available and enough for that task. After data filtering and assembly, the study included 15 MR locations from Washington, 6 from Michigan, and 6 from Maryland. Crash data from 2003 through 2019 were available from Washington, crash data from Michigan represented 2013 through 2019, and crash data from Maryland represented 2015 through 2019.

The FB analyses were conducted on separated State data subsets on ITS-CG evaluations for TWSC-to-MR conversions. Statistically significant crash reductions ranging from 31 up to 42 percent for various types of crashes were estimated from these analyses. A statistically significant reduction of 39 percent in MV_Total crashes at AWSC conversions was found from an additional analysis using the complete database, now including additional locations that could not be used in the ITS-CG evaluations.

Finally, the research team performed an economic analysis of MR conversions from either AWSC or TWSC. B/C ratios were found to be larger than 1.0 (1.33 for both AWSC and TWSC conversions when only safety benefits were considered, and 8.47 for AWSC when operational benefits were also considered). These results indicate economic feasibility of MR installations.

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The original maps in figure 1 and figure 4 are the copyrighted property of Google® Earth™ and can be accessed from https://earth.google.com/web/ (Google 2019). They were modified to show the locations of study sites as callouts and yellow pins.

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