MODELING AND EVALUATING THE SAFETY EFFECTIVENESS OF MINI-ROUNDABOUTS

by

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ABSTRACT

RAUNAK MISHRA. Modeling and Evaluating the Safety Effectiveness of Mini-Roundabouts. (Under the direction of DR. SRINIVAS S. PULUGURTHA)

Mini-roundabouts are a type of roundabout characterized by a small diameter, and fully traversable central island and splitter islands. They are an alternative intersection design option in areas with constraints requiring additional land acquisition. They may be retrofitted within the existing intersection boundaries. They are suited to environments where speeds are relatively low and environmental constraints preclude the use of larger roundabouts with raised central islands. The standard-size roundabouts are safer than traditional minor road stop-controlled or signalized intersections, better suited for traffic calming, and reduce delay as well as emissions. However, the safety benefits associated with mini-roundabouts are not well documented and must be evaluated for planners and engineers to consider more mini-roundabout installations in the United States. Therefore, the focus of this research is on evaluating the safety effectiveness of mini-roundabouts converted from prior control types like two-way stop-controlled or one-way stop-controlled (TWSC or OWSC) and all-way stop-controlled (AWSC) with at least one approach having a speed limit equal to or greater than 35 mph (~56.33 kmph). The methodology includes: 1) identification of mini-roundabout installations in the United States, 2) before and after crash data and traffic volume data collection at selected mini-roundabout locations, 3) before and after analysis for determining safety benefits of mini-roundabouts, 4) safety effectiveness and crash modification factors (CMFs) computation for mini-roundabouts based on before and after crash data, and, 5) examining the effect of traffic characteristics, geometric characteristics, and on-network and off-network characteristics on mini-roundabout safety effectiveness and after period crashes.

To accomplish these objectives, 25 mini-roundabout installations in the United States were identified. They are in Georgia (5), Iowa (1), Michigan (4), Minnesota (3), Missouri (1), North Carolina (2), Virginia (1), and Washington State (8). Data pertaining to mini-roundabout geometry, traffic crashes, and traffic volumes were collected from various sources like departments of transportation (DOTs), police departments, Highway Safety Information System (HSIS), Highway Performance Monitoring System (HPMS) database, and state public record centers. At least one year of after period data was available for each selected mini-roundabout.

The safety benefits of a mini-roundabout were assessed using naïve before-after analysis employing crashes per year and crash rate as metrics. In naïve before-after analysis, crashes per year in the before period are compared to crashes per year in the after period. The percentage change in the number of crashes per year in the after period from the before period indicates the safety effectiveness of mini-roundabouts. Likewise, the percentage change in the crash rate in the after period was compared with the crash rate in the before period. The safety effectiveness of mini-roundabouts were separately evaluated based on the number of total crashes, fatal and injury (FI) crashes, and property damage only (PDO) crashes. The analysis was carried out separately by prior control types such as two-way stop-controlled (TWSC) or one-way stop-controlled (OWSC) and all-way stop-controlled (AWSC) intersections.

The results indicate a decrease in the total number of crashes and the number of FI crashes per year as well as crash rate when a TWSC or OWSC intersection was converted to a mini-roundabout. However, the results indicate an increase in the number of PDO crashes per year while the crash rate remained nearly the same. Similarly, the results indicate an increase in the number of total crashes, FI crashes, and PDO crashes per year and crash rate when an AWSC intersection was converted to a mini-roundabout.

The naive before-after analysis based on crashes per year does not account for the effect of exposure (change in traffic volume or other patterns on a selected facility), trend effect (change in traffic composition, driver composition, etc.), and the random effect (regression-to-the-mean bias). On the other hand, before-after crash rate comparison accounts for exposure by considering traffic volume. However, it assumes a linear relationship between crash frequency and traffic volume.

Evaluating safety effectiveness using more statistical rigorous techniques such as the Empirical Bayes (EB) method would help in computing a better estimate of safety effectiveness and standard error. Crash and traffic volume data collected for an additional 723 reference intersections were used for safety performance function (mathematical model) development and calibration, and the EB method was used to evaluate safety effectiveness.

The safety effectiveness from EB method was computed considering HSM SPFs (calibrated and non-calibrated) and jurisdiction-specific SPFs (calibrated and non-calibrated). The results from the EB method indicate a decrease in the number of total crashes and FI crashes when TWSC/OWSC intersections were converted to mini-roundabouts. However, the results from the EB method indicate an increase in the number of PDO crashes when TWSC/OWSC intersections were converted to mini-roundabouts. The results from the EB method indicate an increase in the number of total crashes, FI crashes, and PDO crashes when AWSC intersections were converted to mini-roundabouts.

The safety effectiveness from EB method differed when HSM SPFs and jurisdiction-specific SPFs were used. It also differed when jurisdiction-specific SPFs were used and calibrated for subsequent years. Difference between the safety effectiveness estimates was statistically significant at a 95% confidence level for total crashes at AWSC intersections converted to mini-roundabouts. Further, it also differed when jurisdiction-specific SPFs were developed and compared using 3, 5, 7 and 9 years of crash data. Based on the findings, calibration of jurisdiction-specific SPFs is recommended to account for temporal changes in estimating expected number of crashes in the before and after periods.

The CMFs from the EB method are recommended based on calibrated HSM SPFs (TWSC and OWSC), and year-wise calibrated jurisdiction-specific SPFs [OWSC (ramp) and AWSC]. A 22.03% and 61.08% reduction in the number of total crashes and FI crashes but a 4.11% increase in the number PDO crashes is expected when a TWSC/OWSC intersection is converted to a mini-roundabout. Likewise, a 201.45%, 96.20%, and 263.68% increase in the number of total crashes, FI crashes, and PDO crashes is expected when an AWSC intersection is converted to a mini-roundabout. The recommended CMFs for converting a TWSC/OWSC intersection to a mini-roundabout are 0.78 for total crashes, 0.39 for FI crashes, and 1.04 for PDO crashes. Likewise, recommended CMFs for converting an AWSC intersection to a mini-roundabout are 3.01 for total crashes, 1.96 for FI crashes, and 3.64 for PDO crashes.

The EB method results indicate that the installation of mini-roundabouts was found to be effective in the reduction of total crashes at 60% of the selected sites (9 out of 15) when TWSC/OWSC intersections are converted to mini-roundabouts They are found to be more effective in the reduction of FI crashes at 90% of the selected sites (14 out of 15). However, they are found to be less effective in the reduction of PDO crashes - at less than 50% of the sites (7 out of 15). Likewise, the installation of mini-roundabouts was found to be effective at only 10% of the selected sites (1 out of 10) for total, FI and PDO crashes when AWSC intersections are converted to mini-roundabouts.

Overall, converting a TWSC/OWSC intersection to a mini-roundabout could result in better safety benefits than converting an AWSC intersection to a mini-roundabout. The odds ratio is lower for TWSC/OWSC intersections with a high crash history. However, FI-based odds ratio is higher for mini-roundabouts with a greater number of crashes in the after period. The odds ratio for the number of total crashes and PDO crashes is lower if entry width is higher at AWSC intersections converted to mini-roundabouts. The number of crashes in the before period, cross-street traffic volume, speed limit at major street and cross-street, and intersection skewness have a statistically significant influence on the safety effectiveness of mini-roundabouts (number of crashes in the after period) at a 90% confidence level.

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DEDICATION

To my mother and father.

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3ST	Three-Legged Stop-Controlled at Cross-Street
4ST	Four-Legged Stop-Controlled at Cross-Street
A	Serious Injury
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike Information Criterion
AICC	Akaike Information Criterion with Correction
AWSC	All-Way Stop-Controlled
B	Minor Injury
C	Possible Injury
CFI	Continuous Flow Intersection
CMF	Crash Modification Factor
DLT	Displaced Left Turn
DOT	Department of Transportation
EB	Empirical Bayes
FHWA	Federal Highway Administration
FI	Fatal and Injury
GA	Georgia
GDOT	Georgia Department of Transportation
GIS	Geographic Information Systems
HCM	Highway Capacity Manual

HPMS	Highway Performance Monitoring System
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
IA	Iowa
ICD	Inscribed Circle Diameter
IOWADOT	Iowa Department of Transportation
IQR	Interquartile Range
K	Fatal
MAD	Mean Absolute Deviation
MDOT	Michigan Department of Transportation
MI	Michigan
MN	Minnesota
MnDOT	Minnesota Department of Transportation
MO	Missouri
MoDOT	Missouri Department of Transportation
MUT	Median U-turn
NC	North Carolina
NCDOT	North Carolina Department of Transportation
O	Property Damage Only
OR	Odds Ratio
OWSC	One-Way Stop-Controlled
PDO	Property Damage Only
RCUT	Restricted Crossing U-Turn

RTM	Regression-To-Mean
SE	Safety Effectiveness
SPF	Safety Performance Function
TWSC	Two-Way Stop-Controlled
TWTL	Two-Way Two-lane Undivided Road
USDOT	United States Department of Transportation
VA	Virginia
VDOT	Virginia Department of Transportation
WA	Washington State
WSDOT	Washington State Department of Transportation

CHAPTER 1 INTRODUCTION

This chapter presents background and motivation, problem statement, research significance, research objectives and organization of this Dissertation.

1.1 Background and Motivation

Intersections are integral and critical nodes of a road transportation system. They pose challenges for safer and efficient desired movements of different road users like motorists, bicyclists, and pedestrians. The desired movements (through movement, left-turn, right-turn, and U-turn) can be uncontrolled, yield-controlled, stop-controlled, or signalized. With an increase in travel demand (due to population and new land-use developments), and site-specific crash history, the existing intersections may require an upgrade to enhance their capacity and safety of road users. The transportation planners/engineers of agencies regularly monitor the traffic flow (turning movements) and crash history to check for warrants and make design or operational improvements at intersections. From a safety perspective, quantified values of safety benefits are used by planners/engineers to justify the proposed solutions. The proposed solutions to address operational and safety problems could be at-grade related improvements or conversion to a grade-separated interchange. The traditional intersection designs may not result in an efficient and safer design in terms of capacity, delay, number of crashes, severity, environmental impacts, and construction cost (right of way impacts). New and alternative/non-traditional/unconventional designs are needed to improve traffic operations and safety. They include modern roundabouts, restricted crossing U-turn (RCUT) (also known as superstreets, J-turns, or synchronized streets), median U-turn (MUT), displaced left turn (DLT), quadrant roadway intersection and continuous flow intersection (CFI) designs. Along with the operational efficiency, safety is a major governing factor that encourages the agencies to adopt such designs.

Crashes at an intersection and near its influence area are a major concern. Intersections account for more than 50 percent of the total combined fatal and injury crashes in the United States (FHWA, 2021). Fatal crash data for the year 2015 to 2019 show that nearly 28 percent of the traffic fatalities were reported intersections. Of the total 36,671 fatal crashes per year between 2015 to 2019, 10,114 fatal crashes per year were reported at intersections (FHWA, 2021). Over the years, intersection safety related research and development led to several innovative alternative intersection designs. However, successful deployment of these alternative intersection design requires continuous persistent efforts and considerable time. Starting from the experimental design, demonstrating and convincing implementing agencies (practitioners) and communities (users), capacity and knowledge building for executions (including relaxation wherever required to build confidence), and finally an unbiased evaluation to document its effectiveness are vital for further future use. It may require a decade or so to complete this process. Here "effectiveness" in simple terms is the degree to which an alternative intersection design is successful in reducing the number of crashes (at the intersection as well as those that are intersection related).

Modern roundabouts are classified based on their size, geometry features, and functions. They include mini-roundabouts, single-lane roundabouts and multi-lane roundabouts (Rodegerdts et al., 2010; AASHTO, 2018). They are featured designs for slowing traffic, improving intersection safety, and reducing delay (Robinson et al., 2000). In general, single-lane roundabouts are considered safer than stop-controlled (at cross-street) and signalized intersections (Rodegerdts et al. 2007; Gross et al., 2013). The benefit arises from zero vehicle crossing conflict points at a single lane roundabout compared to sixteen vehicle crossing conflict points at a conventional four-legged intersection (Robinson et al., 2000).

Mini-roundabouts are a type of roundabout characterized by a small diameter (45 feet to 90 feet of inscribed circle) and fully traversable islands (central island and splitter islands) (Rodegerdts et al., 2010). The central traversable island may range from 16 feet to 45 feet (Zhang et al., Year Unknown). This innovative intersection design is typically suited for low speed (35 mph (~56.33 kmph) and lower) two-lane roads where the total entering intersection volume is less than 1,600 vehicles per hour, including low volumes of heavy vehicles and bus usage (Zhang et al., Year Unknown). They are often constructed at junctions where there are physical and environmental constraints, and when there is a need for a small footprint to lower the construction cost (Stein, 2018). Sawers (2009) summarized the experience of mini-roundabouts in the United Kingdom, and suggested retrofitting of all-way stop controlled (AWSC) intersections that do not perform well to mini-roundabouts in the United States. However, the safety benefits of installing mini-roundabouts in the United States are not well documented.

1.2 Problem Statement

Mini-roundabouts provide an alternative intersection design option in areas with constraints and requiring additional land acquisition. They may be retrofitted within the existing intersection boundaries. In the United States, mini-roundabouts have been installed in several states in the past two decades. They are suited to environments where speeds are already low and environmental constraints would preclude the use of a larger roundabout with a raised central island.

In general, the number of roundabouts constructed in the United States has seen a considerable growth particularly from the year 2000 (Pochowski et al., 2016). The research and development focus on roundabouts led to publications of Federal Highway Administration

(FHWA) information guide on roundabouts in the year 2000 and later an updated version in the year 2010. Further, past studies on roundabout safety indicated that single-lane roundabouts are safer than stop-controlled (at cross-street) and signalized intersections (Rodegerdts et al. 2007; Gross et al., 2013).

The cost of a mini-roundabout is about one-third to half of a full-sized roundabout and has fewer right-of-way impacts (Pochowski et al., 2016; HNTB, 2017; Wilkinson, 2020). The FHWA technical summary report on mini-roundabouts (FHWA, 2010) suggests mini-roundabouts installation at intersections with speed limits of 30 mph (~48.28 kmph) or less at all approaches and an 85th-percentile speed of less than 35 mph (~56.33 kmph) near the proposed yield line. However, in the United States there are a few mini-roundabouts that were installed at intersections with speed limits of 35 mph (~56.33 kmph) or higher at major streets. The primary concern from installing a mini-roundabout is the lack of documented evidence pertaining to safety benefits associated with them compared to full-sized roundabouts. Developing a knowledgebase on the safety effectiveness would help engineers and researchers to understand the safety implications or benefits, such as the most probable types of crashes, and the increase or decrease in crashes due to the installation of mini-roundabouts.

A basic survey on mini-roundabouts was conducted by contacting the staff of North Carolina Department of Transportation (NCDOT) divisions. The survey was conducted between September 2019 to November 2019 through email. The survey form is enclosed in Appendix A. The responses obtained reveal that three out of fourteen divisions have constructed mini-roundabouts in their respective divisions. Many divisions practitioner indicated that they have a plan to construct mini-roundabout or looking it as an alternative intersection option (seven out of the fourteen divisions). Further, practitioners were of positive opinion about the safety at mini-roundabouts considering motorist, pedestrian, and bicyclist. However, they indicated concerns about lack of information related to crash data, intersection locations, truck volume, and central island type (flush/raised). In summary, the survey reveals that practitioners are looking to implement mini-roundabouts but do not have specific crash related information from traffic safety perspective. Hence, there is a need to quantify the safety benefits of mini-roundabouts.

The focus of this research work is on evaluating the safety effectiveness of mini-roundabouts converted from prior control types like two-way stop-controlled or one-way stop-controlled (TWSC or OWSC) and AWSC with at least one approach having a speed limit equal to or greater than 35 mph (~56.33 kmph). In other words, the research question is whether converting a stop-controlled intersection to a mini-roundabout is effective in crash reduction.

1.3 Research Significance

In the United States, not many studies focused on the safety effectiveness of converting stop-controlled intersections with a speed limit equal to or greater than 35 mph (~56.33 kmph) to mini-roundabouts. This research work aims to address this gap and examine the role of factors that could influence safety at mini-roundabouts. Further, safety impacts in terms of crash modification factor (CMF) on converting regular intersections to mini-roundabouts are unknown. CMFs are used by researchers and practitioners to evaluate countermeasures. Thus, there is a need to develop CMFs for converting stop-controlled intersections with speed limits equal to or greater than 35 mph (~56.33 kmph) to mini-roundabouts.

The safety effectiveness of mini-roundabouts may not only depend on the prior control type but also crashes and traffic volumes during the before and after periods. The effectiveness may also depend on the speed limit at the major street and cross-street, entry width, intersection skewness, and other geometric/design features. There is also a need to examine the role of geometric, traffic, and crash history related factors on the safety effectiveness of mini-roundabouts. The findings will help practitioners make informed decisions and assess potential benefits of installing mini-roundabouts.

A quote by W. Edwards Deming, “without data, you're just another person with an opinion” is quite relevant to the posed research question. The quantified safety benefits in terms of CMFs for installing mini-roundabouts based on crash severity could be added to CMF clearinghouse database. It could also be included in the updated version of Highway Safety Manual (HSM) volume 3 (part D) published by the American Association of State Highway and Transportation Officials (AASHTO).

The scope of this research work is limited to the mini-roundabouts built in the United States, and quantifying safety benefits with respect to crash severity (fatal and injury and non-injury related).

1.4 Research Objectives

The goal of this research work is to enhance traffic safety at intersections. A prior knowledge of quantified safety by crash severity (injury and non-injury) of different alternatives at the planning stage would help to achieve vision zero (a vision to reduce fatal and serious injuries).

The objectives of the research work are:

1) to develop safety performance functions (SPFs) for a stop-controlled intersection,
2) to determine the safety effectiveness of converting a stop-controlled intersection to a mini-roundabout,
3) to analyze and compare the safety effectiveness using calibrated and non-calibrated SPFs,

4) to compute crash modification factors (CMFs) of mini-roundabout when converted from a stop-controlled intersection, and,
5) to examine the effect of traffic characteristics, geometric characteristics, and on-network and off-network characteristics on mini-roundabout safety effectiveness, and after period crashes.

1.5 Organization of the Report

The remainder of this report is comprised of nine chapters. A review of existing literature on roundabouts (in particular, mini-roundabouts) and their safety benefits is discussed in Chapter 2. The methodological framework including mini-roundabout identification, inventory, crash and traffic volume data collection, data processing details, and analysis methods is presented in Chapter 3. The analysis using descriptive statistics, naïve method and the Empirical Bayes (EB) method is described in chapters 4, 5 and 6, respectively. Further, analysis on the influence of traffic, network, and off-network characteristics on safety at mini-roundabouts is discussed in Chapter 7. A summary and comparison of CMFs from naïve and EB method, and recommended CMFs are presented in chapter 8. The findings from this research study, policy/practice recommendations, and further steps for research are discussed in Chapter 9.

CHAPTER 2 LITERATURE REVIEW

Roundabouts are a subset of road intersection control designs. They belong to the family of elliptical (circular or oval) intersections. In general, the primary parameters for considering intersection shape is the availability of land space and adequate sight distance, easy navigation by road users while changing direction (simplicity in understanding the design by different users), accessibility, economy, specific sight geometry requirements (e.g., three-legged or four-legged), aesthetic aspects, traffic volumes, and so on. The junctions constructed in the past, such as Circus in the city of Bath, United Kingdom (1768) and Columbus Circle in New York City, United States (1905), are a few historical examples of circular junctions.

In the twentieth century, the growing demand for travel, the need for high-speed mobility, industrial growth, the advent of car technology and its penetration among the public led to an increase in the miles of road network, the number of access points, and consequently the number of road intersections. In the United States, roundabouts (also referred to as traffic circles, circular intersections, or rotaries) were built to facilitate high-speed mobility at road junctions without major disruptions. However, high-speed merging and weaving of vehicles, high crash experience, and congestion (grid-lock) led to a decline in construction of roundabouts in the United States after the 1950s (FHWA, 2010). Other countries had similar experiences. Therefore, the design of roundabouts was re-engineered with the introduction of the priority (yield-on-entry) concept in the United Kingdom in the 1960s. These modern roundabouts gained more acceptance among practitioners by the 1990s in the United Kingdom, Europe, and other parts of the world.

The argument behind the implementation of modern roundabouts instead of the conventional intersection is fewer conflict points (zero crossing conflict points compared to sixteen crossing conflict points in the case of a conventional four-legged intersection), proven reduced crash severity, reduced speed at approaches, and uninterrupted traffic flow (Badgley et al., 2018; FHWA, 2018). Modern roundabouts are classified based on their size, geometry features, and functions. They include mini-roundabouts, compact roundabouts, single-lane and multi-lane roundabouts, turbo roundabouts, rotaries, signalized traffic circles, and neighborhood traffic circles. Table 2-1 shows the different types of modern roundabouts based on the inscribed circle diameter and average daily traffic (ADT).

Table 2-1. Roundabout types.

Design Element	Mini-Roundabout	Single-Lane Roundabout	Multilane Roundabout
Desirable maximum entry design speed	15 to 20 mph (25 to 30 km/h)	20 to 25 mph (30 to 40 km/h)	25 to 30 mph (40 to 50 km/h)
Maximum number of entering lanes per approach	1	1	2+
Typical inscribed circle diameter	45 to 90 ft (13 to 27 m)	90 to 180 ft (27 to 55 m)	150 to 300 ft (46 to 91 m)
Central island treatment	Fully traversable	Raised (may have traversable apron)	Raised (may have traversable apron)
Typical daily service volumes on 4-leg roundabout (veh/day)	Up to approximately 15,000	Up to approximately 25,000	Up to approximately 45,000 for two-lane roundabout

Source: Rodegerdts et al. (2010) Exhibit 1-9.

The subsequent sections in this chapter are primarily devoted to roundabouts and mini-roundabouts with a special emphasis on traffic safety. The first section deals with conventional roundabout safety assessment. This is followed by the definitions and design considerations of mini-roundabouts, findings from past research on the safety assessment of mini-roundabouts, and vulnerable road user's safety assessment at mini-roundabouts. Some key points and limitations of past research are summarized in the last section.

2.1 Conventional Roundabouts Safety Assessment

Numerous studies were conducted to assess the safety of roundabouts using the EB method (Persaud et al., 2001; Montella, 2007; Qin et al., 2013). Persaud et al. (2001) conducted a before-after evaluation of safety at roundabouts in seven different states with a mix of rural, urban, and suburban environments. At these locations, 23 intersections were replaced with roundabouts for their potential benefits. The before-after comparison showed that the total number of crashes and fatal-incapacitating injury crashes decreased by 40% and 90%, respectively. The results showed improved safety after the installation of roundabouts. A similar study performed using data for high-speed (>40 mph [~64.4 kmph]) rural intersections showed that the number of injury crashes, angle collisions, and fatal crash frequency decreased by 84%, 86%, and 100%, respectively (Isebrands, 2009).

Elvik (2003) performed the meta-regression analysis of converting intersections to roundabouts outside the United States, and suggested an estimate of 30% to 50% reduction in crashes (fatal crash reduction by 50% to 70%). Also, the study suggested greater safety effects on injury crashes at four-legged than at three-legged roundabouts. Further, the study indicated that small central island diameter of roundabout is associated with low injury crash rate.

In Maryland, 38 roundabouts with 283 crash reports were examined to propose countermeasures based on field observations (Mandavilli et al., 2009). The most common crash type included single-vehicle run-off, rear-end, and sideswipe crashes. Based on the crash reports and field observations, most of the roundabout crashes occurred at the entrance due to the high approach speed. Introducing advisory signs like “roundabout ahead”, “reduced speed ahead”, and “yield” signs, along with proper landscaping and reflective pavement markings can alert drivers, especially at night.

Montella (2011) found that the radius of deflection and angle of deviation at the entrance/ approach was associated with angle and rear-end crashes at the selected roundabouts in Italy. Likewise, improper or lack of yield signs and pedestrian crossing signs at the entry and exit points resulted in a higher number of angle and pedestrian-related crashes. Inadequate friction, sight distance, and failure to yield were also identified as significant contributing factors.

Qin et al. (2013) evaluated 24 roundabouts (12 single-lane and 12 multi-lane roundabouts) in Wisconsin. They considered before-after period crash data, three years each, and analyzed using the EB method. Before control types included no control/yield control (2 roundabouts), TWSC (12 roundabouts), AWSC (5 roundabouts) and signalized (5 roundabouts). Their results showed a 9% decrease in the total number of crashes and a 52% decrease in the number of fatal and injury (FI) crashes. Likewise, their results showed a 35.98% reduction in the number of total crashes at single-lane roundabouts but a 6.23% increase in number of total crashes at multi-lane roundabouts. A reduction in the number of FI crashes was observed at both single-lane (18.20% reduction) and multi-lane roundabouts (63.28% reduction). They concluded that TWSC intersections converted into roundabouts had higher safety benefits (24.89% reduction) compared to no control/yield controlled (24.18% increase), AWSC (11.36% increase), and signalized intersections (4.54% reduction) when compared using the number of total crashes. A reduction in FI crashes was observed for all considered before control types. The CMF Clearinghouse documented several CMFs related to intersection geometry for high-speed and low-speed roundabouts, single-lane and multi-lane roundabouts, and for different types of controls (CMF Clearinghouse, 2021). However, CMFs for mini-roundabouts were not explored extensively in the past.

2.2 Definitions of Mini-Roundabout and Design Considerations

Frank Blackmore, a traffic engineer at the Transport and Road Research Laboratory in the United Kingdom, conceptualized the mini-roundabout design in 1969. The first mini-roundabout design was installed in Peterborough near London Road and Oundle Road (Rhodes, 2008). The mini-roundabout is also referred to as humpabout and mini-circle.

The FHWA defined mini-roundabouts as "small roundabouts with a fully traversable central island. They are most commonly used in low-speed urban environments with average operating speeds of 30 mph (~48 kmph) or lower. They can be useful in such environments where conventional roundabout design is precluded by right-of-way constraints" (FHWA, 2010). The Department for Transport, United Kingdom defined mini-roundabouts as "a type or form of junction control at which vehicles circulate around a white, reflectorized, central circular road marking (central island) of between ~3.28 feet (1 meter) and ~13.12 feet (4 meters) in diameter. Vehicles entering the junction must give way to vehicles approaching from the right, circulating the central island. The central road marking is either flush or slightly raised like a dome (no more than ~4.92 inches [125 millimeters]), in order that it can be driven over by larger vehicles that are physically incapable of maneuvering around it. The dome is also raised to discourage vehicles from driving over the central island. Three white arrows are painted on the carriageway, within the gyratory area, around the central road marking, showing the direction of circulation" (Department for Transport, 2006).

A brief summary of selected mini-roundabout design considerations is presented next.

2.2.1 Traffic Volume

The FHWA technical summary report on mini-roundabouts (FHWA, 2010) recommends the use of mini-roundabouts at intersections where the total entering daily traffic is no more than approximately 15,000 vehicles. In another study, Brilon (2011) indicated that mini-roundabouts could carry traffic up to 17,000 vehicles per day without major delay.

2.2.2 Capacity

The capacity of a roundabout is a function of geometric design, demand flow, and local conditions (different traffic rules, driving behavior, and cultural attitudes) (Brilon, 2011; Yap et al., 2013). Empirical models, gap acceptance models, and simulation models were used to estimate the capacity of roundabouts. For mini-roundabouts, Lochrane et al. (2014) calculated the capacity of 50 feet (~15.24 meters) and 75 feet (~15.24 meters) mini-roundabouts using micro-simulation. The micro-simulation model was calibrated using the field data based on headway, speed, and gap. They developed a linear model from simulated data and compared 50 feet (~15.24 meters) and 75 feet (~22.86 meters) mini-roundabout capacities with single-lane conventional roundabouts. They concluded that the capacity of mini-roundabout was higher than the AWSC intersection, however, it was lower than the single-lane roundabout. Brilon (2011) examined the capacity of different roundabouts in Germany using an equation based on gap acceptance. Rodegerdts et al. (2010) illustrated the planning-level maximum daily service volumes for mini-roundabouts. It differs based on cross-street volume share and percentage of left turns (AADT ranges approximately 12,000 to 15,000 vehicle per day). The Department for Transport (2006) recommended the use of assessment of roundabout capacity and delay to assess the capacity of mini-roundabouts. Further, they emphasized that mini-roundabouts should not be introduced where total entry flows were below 500 vehicles per hour in the case of four-legged mini-roundabouts, and also at sites where minor road traffic flow is less than 15% of the major road traffic flow. It was also suggested that mini-roundabouts are particularly suited to handle high proportions of right-turning traffic (left-hand driving rule).

2.2.3 Central Island

The FHWA technical summary on mini-roundabouts (FHWA, 2010) recommended the maximum height of the central island as ~4.72 inches (120 millimeters). The Department for Transport (2006) suggested that the height of the central island could be up to ~4.92 inches (125 millimeters). It was also emphasized to limit the maximum height to ~3.94 inches (100 millimeters) to reduce unnecessary noise, vibration, and scuffing.

2.2.4 Limitations of Mini-Roundabout Design

Some of the limitations of mini-roundabout intersection design as reported in the literature include the need for an increase in maintenance, U-turn movement, noise, and vibration. The marking on flush type central island requires frequent maintenance (repainting) compared to the raised central island in order to maintain conspicuity. At sites where truck traffic is relatively high, the central island may suffer from rapid wear, and hence road markings may require repeated maintenance. Passenger cars can make the U-turn maneuver around the central island. However, large vehicles may not be able to make a U-turn. The raised central island may also result in noise and ground vibrations, especially in residential areas where mini-roundabouts are located near houses (Department for Transport, 2006; FHWA, 2010). Šurdonja et al. (2012) suggested special attention to street lighting and other traffic calming measures at approaches since mini-roundabouts without a raised central island may be poorly visible to drivers.

2.3 Safety Assessment of Mini-Roundabout Design

A few researchers have assessed the safety benefits of the mini-roundabout design. Lalani (1975) analyzed 20 mini-roundabouts in the United Kingdom. They indicated a 29.5% and 30.3% reduction in the number of vehicle and pedestrian crashes, respectively, and a 30.3% reduction in the total number of injury crashes within a ~164 feet (50 meters) proximity to the mini-roundabout area. Similarly, Green (1977) analyzed 88 small and mini-roundabouts converted from priority controlled junctions, and noted a 34% reduction in the number of injury crashes and a 46% reduction in the number of fatal and serious injury crashes. Walker and Pittam (1989) conducted a comprehensive study of nearly 1600 mini-roundabouts in the United Kingdom. They analyzed 1379 mini-roundabouts and reported an average frequency of 0.61 personal injury crashes per mini-roundabout per year for three-legged mini-roundabouts. Similarly, for four-legged mini-roundabouts, they reported an average frequency of 0.88 personal injury crashes per mini-roundabout per year. Further, they indicated a crash rate of 10 and 17 crashes per 100 million vehicles for three-legged and four-legged mini-roundabouts, respectively. Later, Ibrahim and Metcalfe (1993) applied the Bayesian overview for evaluating mini-roundabouts as a road safety measure. They concluded that replacing the priority-controlled intersections with mini-roundabouts leads to a reduction in the number of crashes by at least 13%. They also indicated that the best estimate of the benefit is a 23% to 28% reduction in crashes. Kennedy et al. (1997) analyzed crashes during 1986-1992 at 200 three-legged and 100 four-legged mini-roundabouts installed in urban areas in the United Kingdom. They indicated a crash rate of 12.5 and 22.8 crashes per 100 million vehicles for three-legged and four-legged mini-roundabouts, respectively. The crash rate based on severity (fatal and serious injury) was found to be lower at mini-roundabouts compared to priority-controlled intersections and signalized intersections. The Department for

Transport (2006) observed a similar crash rate for a three-legged mini-roundabout and a priority T-intersection but a considerably lower crash severity for a mini-roundabout, particularly at 30 mph (~48 kmph) T-intersections. Further, the crash rate and severity of crashes could be 30% lower at a mini-roundabout when compared with a signalized three-legged intersection.

Brilon (2011) summarized the practice design of different roundabouts, their safety effects, and lessons learned from installations in Germany. The safety effects of 13 unsignalized intersections converted to mini-roundabouts showed a decline in the crash rate from 0.79 crashes/million-vehicles to 0.56 crashes/million-vehicles, resulting in a 29% reduction in crash rate after the implementation of mini-roundabouts.

Austroads (2015) indicated that the number of crashes after the installation of 35 mini-roundabouts in Monash, Australia decreased from 20 in the previous five years to one in the years post-installation. Delbosc et al. (2017) analyzed 40 mini-roundabouts in Monash, Australia. The analysis of crash data from the year 2004 to the year 2014 showed a reduction in the number of crashes from 19 to 4 (79%). They also conducted surveys at two mini-roundabouts built in 2016.

A few researchers have assessed the operational performance at mini-roundabouts. Zito and Taylor (1996) examined the before-after average speed at mini-roundabouts in Mitcham, South Australia. They observed a 17.9% reduction in the average (from ~30 mph [48.2 kmph] to ~25.4 mph [40.9 kmph]). Delbosc et al. (2017) observed a marginal decrease in the average approach speed, from ~26.6 mph (43 kmph) to ~24.4 mph (39.3 kmph), at two mini-roundabouts compared to two control sites. They also observed a decrease in the proportion of vehicles exceeding the speed limit of 50 kmph (~31.1 mph) from 5.4% to 3.4%.

The FHWA informational guide on roundabouts (Rodegerdts et al., 2010) and technical summary on mini-roundabouts (FHWA, 2010) indicate that safety benefits will be similar for roundabouts and mini-roundabouts. However, studies on the evaluation of the safety effects of mini-roundabouts in the United States are currently limited. Waddell and Albertson (2005) described the United States first mini-roundabout in Dimondale, a suburb of Lansing, Michigan. It was opened to traffic on May 30, 2001. The speed limit during the after period was the same as the before period (25 mph [~40.2 kmph]). The three-year before-after study of crash data revealed that the average annual cost of crashes within 300 feet (~91.44 meters) of the intersection declined by $733 (3.9%). The 85th percentile speed on the uncontrolled west leg approach was observed to decrease from 32 mph (~51.5 kmph) to 24 mph (~38.6 kmph) after the mini-roundabout construction.

Zhang and Kronprasert (2014) compared the number of crashes before and after the installation of a mini-roundabout in Jefferson, Georgia. They noted that the AWSC intersection used to experience 7 to 8 crashes (including 2-3 injury crashes) per year during the before period. However, only seven property damage only (PDO) crashes were observed during the after period; a decrease in the severity of crashes. Cowhig (2019) conducted a simple before and after analysis of a mini-roundabout in Durham, North Carolina, and found a 27.3% reduction in the number of total crashes.

In general, previous studies show about a 30% reduction in the number of injury crashes after the installation of a mini-roundabout. There could also be a reduction in the approach speed after the installation of a mini-roundabout (Lalani, 1975; Green, 1977; Zito and Taylor, 1996; Waddell and Albertson, 2005; Department for Transport, 2006; Brilon, 2011). However, additional research needs to be conducted to investigate the effectiveness of mini-roundabout installations in the United States.

2.4 Vulnerable Road Users Safety Assessment at Mini-Roundabouts

The users of a mini-roundabout could include motorists, pedestrians, bicyclists, and emergency vehicles. Hence, the structure accommodates crosswalks around the perimeter and a splitter/refugee island to allow safe passage of all the user types. The mini-roundabouts tend to reduce pedestrian-vehicle conflict points by shortening crossing distance and exposure time. However, clear, visible, and proper signage and pavement markings must be provided for all the user types, taking into consideration older drivers as well.

A few studies focused specifically on pedestrian and bicyclist crashes at mini-roundabouts. Kennedy et al. (1997) analyzed crashes at three-legged and four-legged mini-roundabouts installed in urban areas in the United Kingdom. They found a 17% and a 12% of the total number of crashes were pedestrian crashes at three-legged and four-legged mini-roundabouts, respectively. The proportion of pedestrian crashes was lower than that at priority-controlled intersections and signalized intersections. Further, they found that bicyclists crash rate at mini-roundabouts were higher than at priority-controlled intersections and signalized intersections. The Department for Transport (2006) emphasized that moderate use of mini-roundabouts by pedestrians and bicyclists causes little concern. However, at sites where pedestrian and bicyclist activities were high such as in a university area, in two instances, mini-roundabouts were replaced with signals. At these locations, bicyclists were involved in 75% of the crashes.

Germany, the United Kingdom, and the United States guidelines recommend bicyclists mix with traffic and navigate along the circular lane with vehicles (Department for Transport, 2006; FHWA, 2010; Brilon, 2011). For pedestrians with vision disabilities, the FHWA technical summary report on mini-roundabouts (FHWA, 2010) emphasized the use of similar treatments for mini-roundabouts, like those provided for single-lane roundabouts. Further, from a pedestrian safety viewpoint, the clear visibility requirement is emphasized for motorists from an entry leg to the exit legs (FHWA, 2010).

Delbosc et al. (2017) conducted surveys in Monash, Australia and observed that people felt safer walking around the mini-roundabouts (81% of 32 participants responded yes). The before-after survey data also indicates that more drivers gave way at the mini-roundabout than at the previous give-way controlled intersection. Although the study revealed positive results in the favor of mini-roundabouts, the sample size is too small to make a concrete conclusion about their effectiveness.

2.5 Crash Modification Factors (CMFs)

CMFs are used to compute the expected number of crashes after implementing a countermeasure on a road or at an intersection. The CMF is defined in the HSM (AASHTO, 2010) as "the relative change in crash frequency due to a change in one specific condition (when all other conditions and site characteristics remain constant). CMFs are the ratio of the crash frequency of a site under two different conditions. Therefore, a CMF may serve as an estimate of the effect of a particular geometric design or traffic control feature or the effectiveness of a particular treatment or condition" (AASHTO, 2010). Gross et al. (2010) researched on study designs for CMF development with their application, strengths, and weaknesses. The CMFs of stop-controlled and signalized intersection converted to a single-lane roundabout are summarized in Table 2-2.

Table 2-2. CMFs for conversion of stop-control and signalized intersection to a single-lane roundabout.

Study title	Prior condition	# of sites	Area	Crash severity type	CMF	Standard error	Source
NCHRP report 572: applying roundabouts in the United States	TWSC	9	Rural	All	0.29	0.04	Rodegerdts et al. (2007)
				K, A & B	0.13	0.03	
		16	Urban / suburban	All	0.44	0.06	
				K, A & B	0.22	0.07	
	AWSC	10*	All	All	1.03	0.15	
				K, A & B	1.28	0.41	
Statistical analysis and development of crash prediction model for roundabouts on high-speed rural roadways	TWSC	16	Rural	All	0.26	NA	Isebrands and Hallmark (2012)
				K, A, B & C	0.11	NA	
	OWSC	2	Rural	All	0.74	NA	
				K, A, B & C	0.28	NA	
Evaluation of roundabouts on high-speed roadways	TWSC	13	All	All	0.59	0.10	NCDOT (2020)
			All	K, A, B & C	0.21	0.08	
Safety effectiveness of converting signalized intersections to roundabouts	Signalized	12	Urban / suburban	All	0.74	0.09	Gross et al. (2013)
				K, A, B & C	0.45	0.12	

Note: K is fatal, A is serious injury, B is minor injury, C is possible injury, and O is property damage only; *including one two-lane roundabout.

2.6 Summary and Limitations of Past Research

Some key points related to mini-roundabouts are summarized below.

- Mini-roundabouts differ in the size of the inscribed circle diameter and central island compared to conventional roundabouts. In addition, mini-roundabouts specifically differ in the mountable central island, i.e., large vehicles such as trucks and buses can drive on the fully traversable central island.
- Mini-roundabouts are built mainly in low-speed urban environments, particularly in the United Kingdom, Europe, and Australia. These were used as countermeasures to replace three- and four-legged stop-controlled intersections (TWSC and AWSC) as well as signalized controlled intersections.

- The literature advocates the use of raised domed central islands over the flush island to maintain better conspicuity at an intersection and to maximize driver compliance (Department for Transport, 2006; FHWA, 2010).
- They may be installed at intersections with daily traffic volume of up to 15,000 vehicles per day.
- In general, mini-roundabouts could reduce the number of injury crashes by 30% after installation (Department of Transport, 2006; Brilon, 2011). Also, they serve as an effective traffic calming measure and reduce approach speeds (Zito and Taylor, 1996; Waddell and Albertson, 2005).

In summary, previous studies indicate a 30% reduction in the number of injury crashes and a possible reduction in the approach speed after the installation of a mini-roundabout (Lalani, 1975; Green, 1977; Zito and Taylor, 1996; Waddell and Albertson, 2005; Department for Transport, 2006; Brilon, 2011). These studies focused on mini-roundabouts built in low speed environment in urban areas. Although the design philosophy of mini-roundabouts i.e., small inscribed circle diameter, fully traversable central island, yield-controlled at entry points, and exemption to larger vehicles such as truck, bus and emergency vehicles to traverse through the central island is same, and implemented in various countries including United Kingdom, Germany, France, Netherland and United States, the recommended inscribed circle diameter thresholds of mini-roundabouts varied at the mini-roundabout locations (minimum ICD 32.80 feet [~10m] to maximum 90 feet [~27.43m]). The safety effectiveness of mini-roundabouts may depend on prior control type, intersection crash history, built environment characteristics (road characteristics, geometric design elements, area type, and land use), and driving behavior characteristics.

In past, several studies looked at the safety effectiveness of single-lane and multi-lane roundabouts in the United States. Very few studies looked at mini-roundabout safety in the United States. Further, the FHWA technical summary report on mini-roundabouts (FHWA, 2010) suggests mini-roundabouts installation at intersections with speed limits of 30 mph (~48.28 kmph) or less at all approaches and an 85th-percentile speed of less than 35 mph (~56.33 kmph) near the proposed yield line. However, in the United States there are a few mini-roundabouts that were installed at intersections with speed limits of 35 mph (~56.33 kmph) or higher at major streets. Also, safety effectiveness of mini-roundabout installation based on prior control type, crash severity type, and influence of on-network and off-network characteristics is unknown. Therefore, there is a need for investigating the safety effectiveness of mini-roundabout installations in the United States, particularly, on converting stop-controlled intersections with a speed limit equal to or greater than 35 mph (~56.33 kmph) to mini-roundabouts. This research work aims to address this gap and examine the role of factors that could influence safety at mini-roundabouts.

CHAPTER 3 METHODOLOGY

This chapter illustrates the methodology adopted for this research work. It includes intersection identification, selection, data collection (inventory details, traffic volume, and crash data at each mini-roundabout for both before and after periods), and analysis using naïve and EB methods.

3.1 Methodological Framework

Figure 3-1 illustrates the methodological framework for the before-after safety effectiveness evaluation. Several different types of performance measures, such as the percentage reduction in the number of crashes, a shift in the proportions of crashes by collision type or severity level, a CMF, and a comparison of safety benefits achieved to the cost of a project or treatment could be used to evaluate safety effectiveness (AASHTO, 2010). The three basic study designs that are used for safety effectiveness evaluations are: (i) observational before-after studies, (ii) observational cross-sectional studies, and (iii) experimental before-after studies. Based on data availability, the safety effectiveness in observational study could be evaluated using naïve before-after analysis, EB analysis, comparison group (C-G) analysis, and cross-sectional analysis. Each method has its advantages and limitations. The safety effectiveness evaluation from before-after study design is preferred over cross-sectional design. However, in cases where before-after data is not feasible, cross-sectional study could be employed. Also, cross-sectional study is useful when there is no sufficient sample available for the before-after comparison. The crash and traffic volume data collected for the same time period (after period for both treatment and non-treatment sites) is used for the cross-sectional study. A summary of before-after evaluation methods as outlined in the HSM are reproduced in Table 3-1 (AASHTO, 2010).

Table 3-1. Selection guide for observational before-after evaluation methods.

Safety measure	Data availability					Appropriate evaluation study method
	Treatment sites		Nontreatment sites			
	Before period data	After period data	Before period data	After period data	SPF	
Crash frequency	✓	✓			✓	Before-after evaluation study using the EB method.
	✓	✓	✓	✓		Before-after evaluation study using either the EB method or the comparison-group method.
		✓		✓		Cross-sectional study.
Target collision type as a proportion of total crashes	✓	✓				Before-after evaluation study for a shift in proportions.

Source: AASHTO (2010)

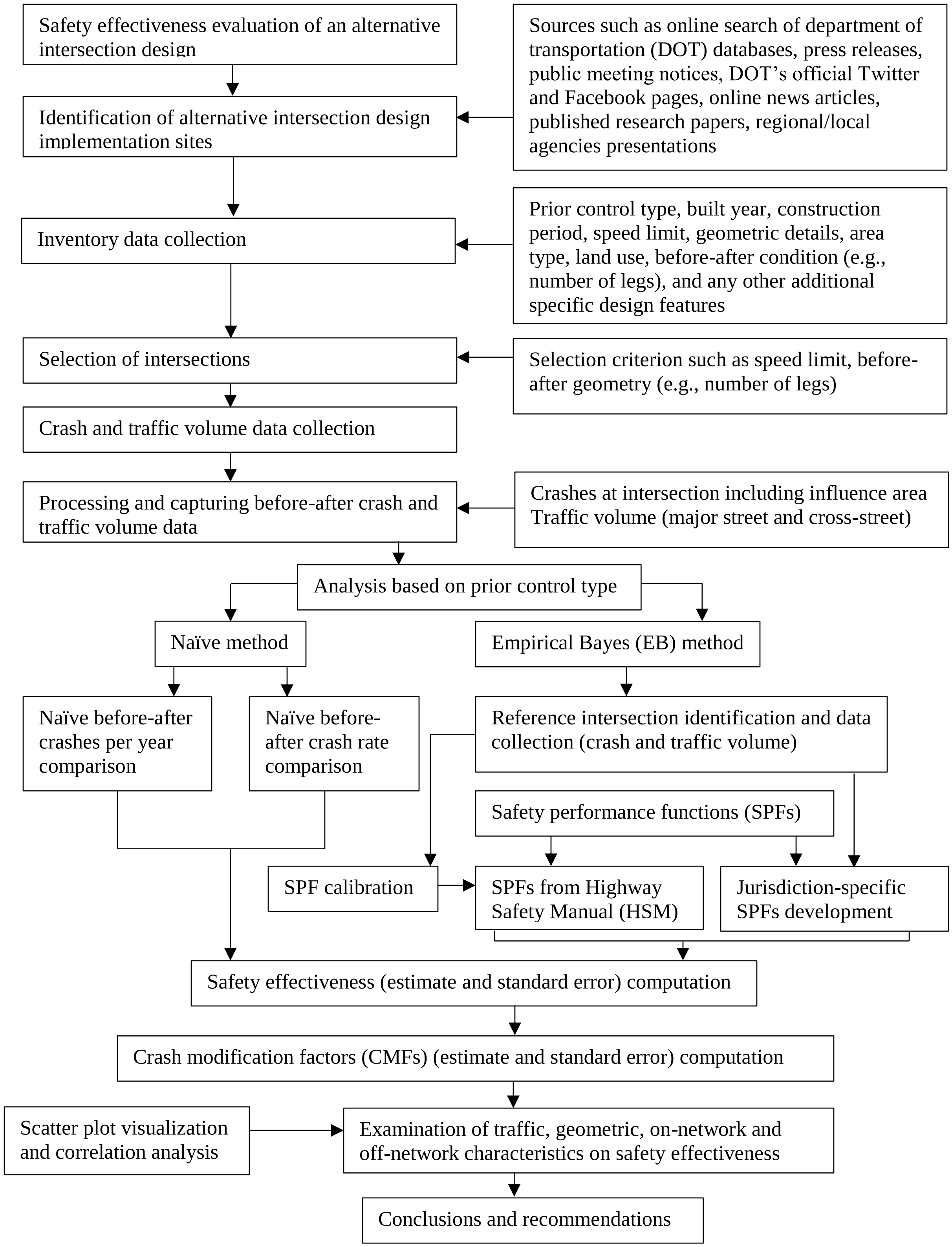


Figure 3-1. Methodology for the safety effectiveness evaluation of an alternative intersection design using before-after analysis.

3.2 Identify Mini-Roundabout Installation Locations

Mini-roundabout design implementation is relatively new in the United States. The first documented mini-roundabout was installed in the year 2001 in Dimondale, Michigan. Over the past twenty years, several mini-roundabouts were installed in different states. Mini-roundabouts installed in the United States were identified through a rigorous online search of department of transportation (DOT) databases, press releases, public meeting notices, DOT's official Twitter and Facebook pages, online news articles, published research papers, regional/local agencies presentations, and an online inventory database of roundabouts hosted and maintained by Kittelson & Associates, Inc. (Kittelson & Associates, 2019). This led to the identification of over 100 mini-roundabouts (70 fully traversable and 30 partially traversable) in the United States. A database consisting of inventory details such as geo-coordinates, intersection details (major street and cross-street name), county name, state name, number of legs, year of construction, posted speed limit (referred to as speed limit in this research), and diameter of each mini-roundabout was prepared.

3.3 Mini-Roundabout Inventory Data Collection

A database was prepared consisting of details such as prior control type (OWSC, TWSC, AWSC, and signal), built year, construction period, speed limit, geometric details, area type, land use, and other additional specific design features. Figure 3-2 shows the geometric characteristics captured for this research. Table 3-2 shows the list of variables captured for analysis. The identified mini-roundabouts database was checked for the before-after condition through satellite images and street-views on Google Earth and Google maps. The linear measurement related geometric details were captured using the ruler tool available in Google Earth while the angle related measurement details were captured using an online available on-screen protector tool laid over mini-roundabout satellite images.

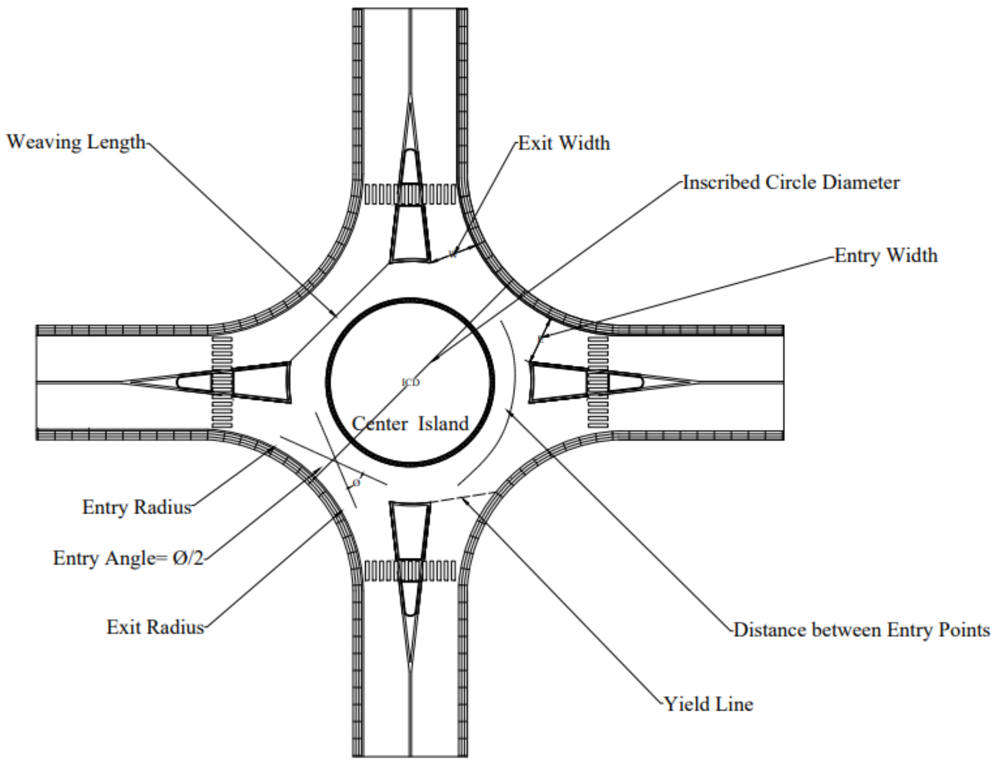


Figure 3-2. Geometric details captured.

Table 3-2. List of variables captured.

S.no.	Variable	S.no.	Variable
1	Prior control type (TWSC/OWSC, and AWSC)	15	Speed limit at the major street (mph)
2	Built year	16	Speed limit at the cross-street (mph)
3	Construction period	17	Advisory speed at the roundabout (mph)
4	Area type	18	Central island diameter (feet)
5	Cross-section type	19	Inscribed circle diameter (feet)
6	Center island type (flush/raised)	20	Entry width (feet)
7	Marking in the central island (yes/no)	21	Exit width (feet)
8	Delineators in the central island (yes/no)	22	Circulating width (feet)
9	Channelization (painting/splitter island)	23	Distance between entry to the next leg (feet)
10	Delineators in channelization (post type/raised pavement marker/none)	24	Weaving length (feet)
11	Bicycle lane/marking (Yes/No)	25	Channelization length (feet)
12	Crosswalk (Yes/No)	26	Road width (feet)
13	Yield sign board (yes/no)	27	Entry angle (degree)
14	Land use in vicinity	28	Angle to the next leg (degree)

3.4 Mini-Roundabouts Selection

The mini-roundabout installation location database consists of inventory details including speed limit at each approach. The mini-roundabouts that were considered for this research had at least one approach with a speed limit equal to 35 mph (~56.33 kmph) or higher. Based on the speed limit criteria, 37 mini-roundabout locations were initially selected in ten states (Georgia, Iowa, Michigan, Missouri, Minnesota, Maryland, North Carolina, Virginia, Tennessee, and Washington State). Crash data, traffic volume data, and built year details of the selected mini-roundabouts were captured. The before-after satellite images and street-views were checked using Google Earth and Google maps. Only, mini-roundabouts with the same geometric configuration in the before and after periods were selected. Mini-roundabouts with a change in geometry in the after period, such as adding a new approach, were not considered for this research.

The mini-roundabouts were selected based on two criteria – traversable and inscribed circle diameter (<=90 feet or ~27.43 meters). The mini-roundabouts built in the year 2019 were not considered for the analysis due to insufficient after period crash data. Crash data up to February 2020 was considered to avoid the effect of the pandemic on research results. Finally, 25 mini-roundabouts were selected for CMF development. The identified mini-roundabouts are located in Georgia (5), Iowa (1), Michigan (4), Minnesota (3), Missouri (1), North Carolina (2), Virginia (1), and Washington State (8). The spatial distribution of selected mini-roundabouts is illustrated in Figure 3-3. An example of a mini-roundabout is shown in Figure 3-4.

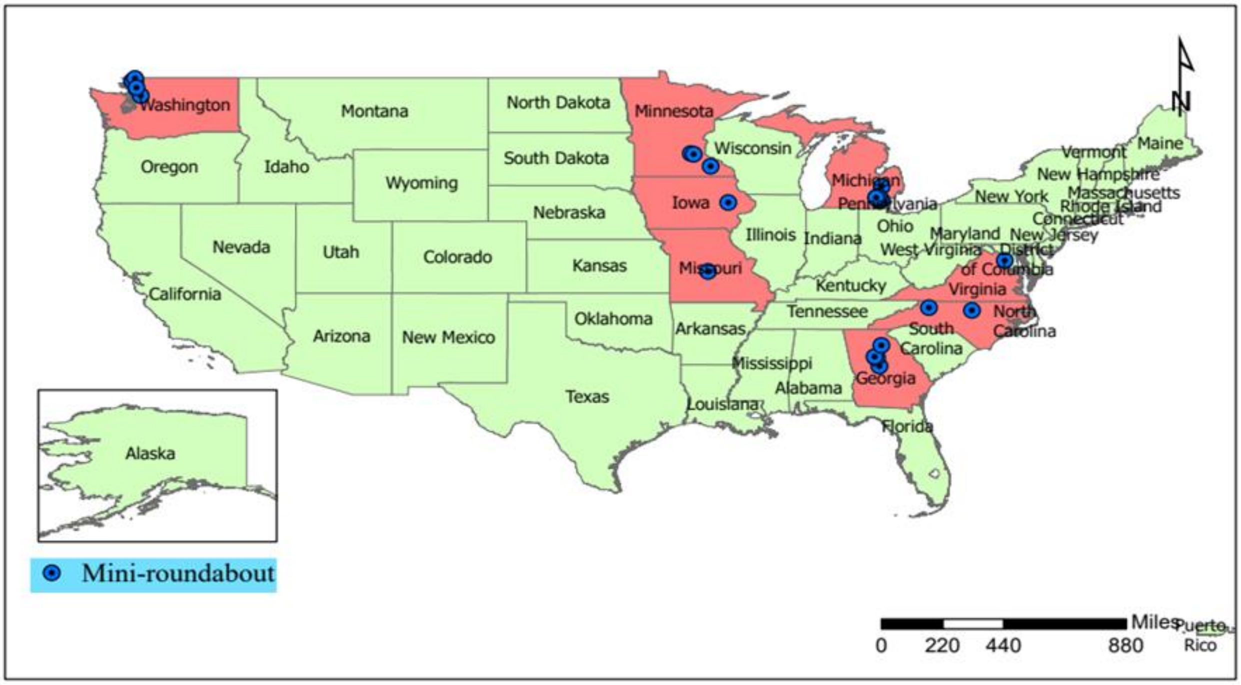


Figure 3-3. Selected mini-roundabouts.

Figure 3-4. Mini-roundabout example (Hickory Ridge Rd, Harrisburg, NC).

3.5 Reference Intersection Identification

Based on the prior control type, reference intersections were identified in each selected state. They include OWSC, TWSC, and AWSC control type intersections. The criteria considered for reference intersections included no skewed intersection, no railroad crossing, no left/right turning lanes, no additional new turning lane construction during the considered time period, and no change in control type during the considered time period. A total of 767 reference intersections in the selected states were identified based on the prior control type. Of these, 723 intersections with available crash and traffic volume data were used for the analysis. Table 3-3 shows a summary of reference intersections identified in each state based on the prior control type.

Table 3-3. Identified reference intersections – summary.

State	# of identified reference intersections by control type			Total # of identified reference intersections
	TWSC/OWSC	OWSC (ramp)	AWSC	
Georgia	50	-	50	100
Iowa	59	-	-	59
Michigan	55	-	51	106
Minnesota	51	-	50	101
Missouri	70 *	-	-	70
North Carolina	57	-	-	57
	60*	-	-	60
Virginia	42	-	-	42
Washington State	74	55	43	172
Total	518	55	194	767

*Three-legged

3.6 Traffic Crash Data

Traffic crash data for the selected mini-roundabouts and reference intersections was collected from different sources that maintain crash databases for individual states. The process included contacting respective state DOTs, state police departments, Highway Safety Information System (HSIS), and state public record centers. Table B-1 in Appendix B shows the list of state-specific agencies contacted for crash data. The crash database contains basic information related to crash incidents such as crash ID, location (street name, geo-coordinates, milepost), severity, crash type, etc. The selected mini-roundabouts in different states were built in different years. Therefore, crash data was requested from the year 2000 up to the most recent availability month of the year 2020. However, in some states it was not possible to obtain archived crash data.

Each contacted state has its own crash database management software and formats. The traffic crash data received from the states was processed using database management software such as Microsoft Access, Tableau, and ArcGIS Pro. Using crash ID as the common field, other crash related details including date, time, location (street name, geo-coordinates, and mile post), severity, and crash type were added to each crash record.

In general, the area of influence for evaluating crashes at an intersection varies from 150 feet (~45.72 meters) to 528 feet (~160.93 meters) (Wang et al., 2008). Avelar et al. (2015) suggested using a radius of 300 feet (~91.44 meters) in combination with traffic control device indicators to develop or validate safety performance functions (SPFs) for signalized intersections. The “intersect” feature in ArcGIS Pro was, therefore, used to extract crash data within 300 feet (~91.44 meters) radial distance from the center of each selected mini-roundabout and reference intersection (Figure 3-5).

The satellite images and street-views on Google Earth and Google maps were used to identify nearby intersections within the vicinity of each selected mini-roundabout. The crashes were mapped within the 300 feet (~91.44 meters) radial distance of each selected mini-roundabout. Visual inspection and verification of crash reports (if available) was performed to exclude crashes not related to the subject intersection and are more associated to the nearby intersection. For example, Figure 3-6 shows crashes in the vicinity of the mini-roundabout located at Anderson Rd/Cedardale Rd in Mount Vernon, WA and those that were considered for analysis in this research.

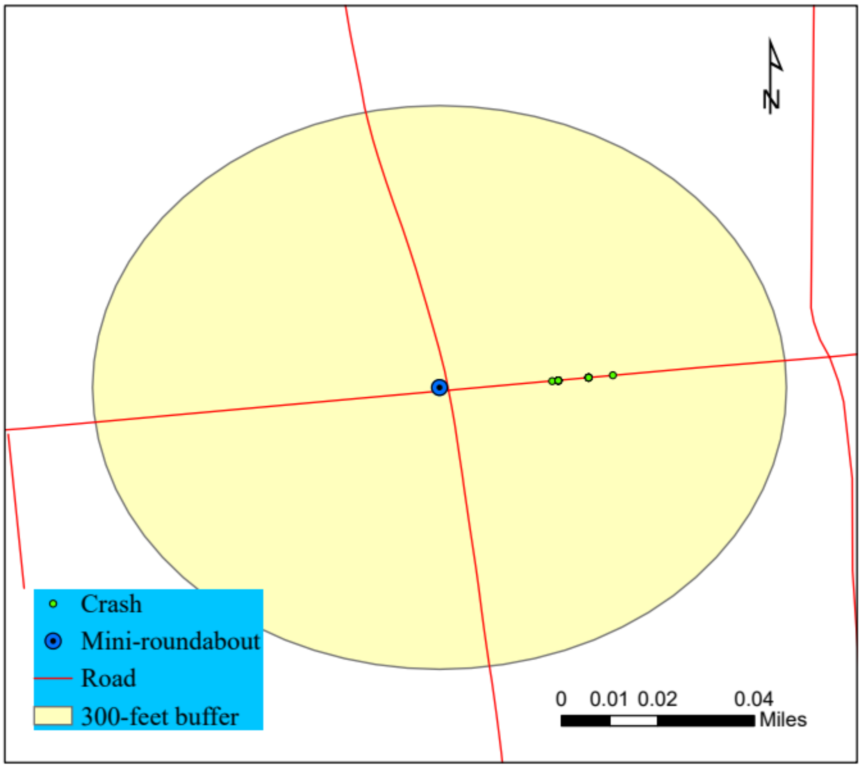
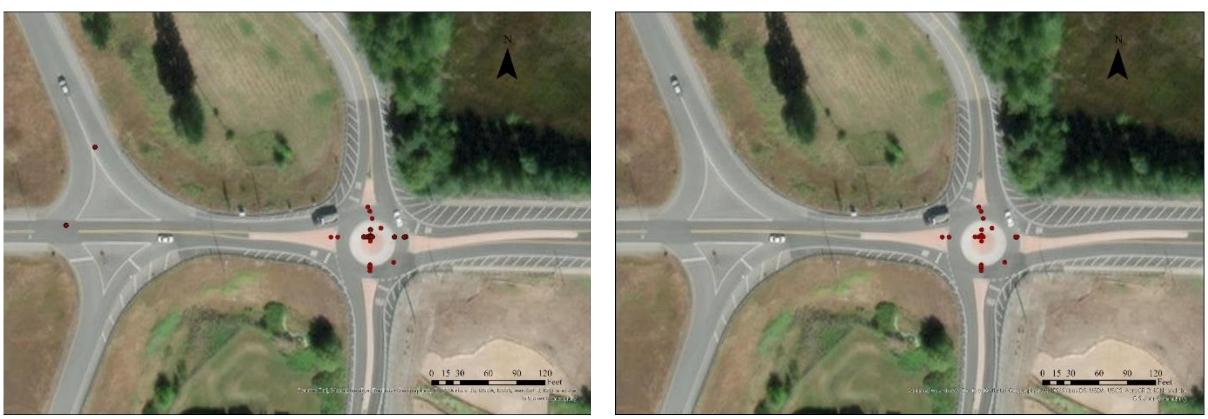


Figure 3-5. Extracting crash data using 300-feet (~91.44 meters) buffer.



(a) Crashes within the vicinity (b) Crashes considered for analysis

Figure 3-6. Identifying crashes related to the subject intersection.

3.7 Traffic Volume

Traffic volumes for the major and cross-street of the selected mini-roundabouts and reference intersections was captured from the state DOT traffic volume databases, county traffic volume databases, and the Highway Performance Monitoring System (HPMS) database. First, the traffic volumes of major street and cross-street were checked using state DOT interactive traffic volume maps. In case traffic volume data was not available/missing in the DOT database, county level databases were checked. Also, HPMS Public Release Shapefiles were gathered to capture major street and cross-street traffic volumes as illustrated in Figure 3-7.

Traffic volume for the missing year was estimated using linear interpolation. If no data was available, traffic volume was estimated from nearby parallel roads exhibiting similar road and land use characteristics. Finally, a database for each state was prepared comprising of intersection location, major street and cross-street name, and year-wise traffic volume. Table B-2 in Appendix B shows a list of sources used to capture traffic volumes.

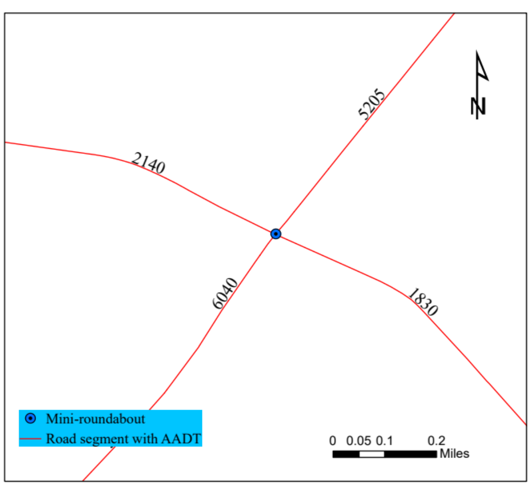


Figure 3-7. Extracting traffic volume.

3.8 Analysis

The analysis was conducted using descriptive statistics, naïve before-after analysis and the EB analysis. An overview of naïve before-after analysis is presented next.

3.8.1 Naïve Before-After Analysis: Crashes Per Year

Naïve before-after crashes per year is the simplest method for a before-after comparison study. In this method, the number of crashes per year in the before period are compared to the number of crashes per year in the after period. The percentage change in the number of crashes per year in the after period from the before period indicates the safety effectiveness of mini-roundabouts. Crashes during the construction year were not considered in the analysis to avoid the effect of the driver learning curve on mini-roundabout safety performance. Before period crash data for five years and after period crash data for one to five years was analyzed (depending on the construction year and crash data availability).

The ratio of after to before period crashes per year indicates whether the treatment is effective in crash reduction. It is also referred as odds ratio (OR). If odds ratio is less than 1, it indicates treatment is effective in crash reduction. The safety effectiveness is represented using the Equation 3.1.

$$\text{Safety Effectiveness}_i = 100 \times (1 - OR_i) \qquad (3.1)$$

where $\text{Safety Effectiveness}_i$ = safety effectiveness at intersection i.

3.8.2 Naïve Before-After Analysis: Crash Rate

Naïve method based on before-after crashes per year does not account for the effect of exposure (change in traffic volume or other patterns on a selected facility), trend effect (change in traffic composition, driver composition, etc.), and the random effect (regression-to-the-mean bias).

On the other hand, before-after crash rate comparison accounts for exposure by considering traffic volume. However, it assumes a linear relationship between crash frequency and traffic volume. Also, it does not account for the regression-to-the-mean bias.

The before-after analysis was conducted using, both, the number of crashes per year and crash rate. As stated previously, crashes during the construction year were not considered in the analysis to avoid the effect of the driver learning curve on mini-roundabout safety performance. Also, before period crash data for five years and after period crash data for one to five years was analyzed (depending on the construction year and crash data availability).

3.8.3 Empirical Bayes (EB) Before-After Analysis

The naïve before-after analysis based on crashes per year does not account for the effect of exposure (change in traffic volume or other patterns on a selected facility), trend effect (change in traffic composition, driver composition, etc.), and the random effect (regression-to-the-mean bias). On the other hand, before-after crash rate comparison accounts for exposure by considering traffic volume. However, it assumes a linear relationship between crash frequency and traffic volume. Evaluating safety effectiveness using more statistical rigorous techniques such as the EB method would help in computing a better precise estimate of safety effectiveness and standard error.

CHAPTER 4 DESCRIPTIVE ANALYSIS

This chapter covers the descriptive analysis of mini-roundabouts inventory data, traffic volume data, and crashes.

4.1 Descriptive Analysis of Mini-Roundabout Data

Inventory data includes road network and land use characteristics for all selected mini-roundabouts. Table 4-1 summarizes the geometric characteristics of the selected mini-roundabouts, and Table 4-2 summarizes road and land use characteristics.

Table 4-3 summarizes the average number of crashes at all selected mini-roundabout locations based on the prior control type. The average number of total crashes per year per intersection in the after period is 3.41 for TWSC/OWSC intersections converted to mini-roundabouts, whereas the average number of total crashes per year per intersection for AWSC intersections converted to mini-roundabouts is 11.52. A similar trend can also be observed in the case of FI crashes and PDO crashes. The average number of FI crashes per year per intersection in the after period is 0.43 for TWSC/OWSC intersections converted to mini-roundabouts, whereas the average number of FI crashes per year per intersection in the after period for AWSC intersections converted to mini-roundabouts is 1.71. The average number of PDO crashes per year per intersection in the after period is 2.98 for TWSC/OWSC intersections converted to mini-roundabouts, whereas the average number of PDO crashes per year per intersection in the after period for AWSC intersections converted to mini-roundabouts is 9.82. Overall, the AWSC intersections converted to mini-roundabouts have more crashes per year than TWSC/OWSC intersections converted to mini-roundabouts.

Table 4-4 summarizes the major street and cross-street traffic volume descriptive statistics of all the selected mini-roundabouts. The average major street and cross-street traffic volume in the after period for TWSC/OWSC intersections converted to mini-roundabouts is 8,589 and 4,004, respectively. The average major street and cross-street traffic volume for AWSC intersections converted to mini-roundabouts is 8,510, and 5,617, respectively. The minimum, median, mean and maximum traffic volume of cross-street for AWSC intersection converted to mini-roundabout is higher than the corresponding value for TWSC/OWSC intersections converted to mini-roundabout.

Table 4-1. Geometric characteristics summary.

Characteristic	Minimum	Median	Mean	Maximum	Interquartile range
Inscribed circle diameter (feet)	44	86	82	90	78-89
Central island diameter (feet)	15	45	42	59	37-50
Entry width (max.) (feet)	10	16	16	21	14-18
Entry width (min.) (feet)	8	13	14	18	12-15
Entry width (avg.) (feet)	9	15	15	19	13-16
Exit width (max.) (feet)	11	18	18	30	15-21
Exit width (min.) (feet)	10	14	14	18	13-15
Exit width (avg.) (feet)	10	16	16	23	15-18
Circulating width (feet)	15	19	19	25	17-21
Distance between entry to the next leg (max.) (feet)	44	64	70	129	58-75
Distance between entry to the next leg (min.) (feet)	31	51	49	65	45-55
Distance between entry to the next leg (avg.) (feet)	39	57	59	86	53-62
Weaving length (max.) (feet)	45	55	60	122	51-62
Weaving length (min.) (feet)	21	46	44	64	41-52
Weaving length (avg.) (feet)	35	51	52	79	47-55
Entry angle (max.) (degree)	19	29	31	51	25-33
Entry angle (min.) (degree)	10	21	20	29	15-25
Entry angle (avg.) (degree)	16	26	25	32	23-28
Angle to the next leg (max.) (degree)	88	95	108	205	92-120
Angle to the next leg (min.) (degree)	40	85	78	106	62-87
Angle to the next leg (avg.) (degree)	75	90	91	120	88-91

Note: Interquartile range is the range between the 25^{th} and 75^{th} values for the given measurement; 1 meter = 3.28 feet; max., min., and avg. are the maximum, minimum and average values considering all approaches.

Table 4-2. Selected mini-roundabouts by road and land use characteristics.

Characteristic	Category	# of mini-roundabouts	Proportion
Area type	Rural	9	0.36
	Urban/suburban	16	0.64
Cross section type	2-lane divided	1	0.04
	2-lane undivided	22	0.88
	4-lane undivided	2	0.08
Prior control type	TWSC/OWSC	15	0.60
	AWSC	10	0.40
# of legs	3	2	0.08
	4	23	0.92
Center island type	Flush	3	0.12
	Raised	22	0.88
Marking in central island	Yes	21	0.84
	No	4	0.16
Delineators in central island	Yes	12	0.48
	No	13	0.52
Delineators in central island type	Post-type	4	0.33
	Raised pavement marker	7	0.58
	Both	1	0.08
Channelization	Painting	6	0.24
	Splitter island	19	0.76
Delineators in channelization	Post type	10	0.40
	Raised pavement marker	5	0.20
	Both	4	0.16
	None	6	0.24
Yield sign board	Yes	25	1.00
	No	0	0.00
Speed limit major street (mph)	35	9	0.36
	40	2	0.08
	45	7	0.28
	50	2	0.08
	55	5	0.20
Speed limit cross-street (mph)	25	3	0.12
	30	2	0.08
	35	10	0.40
	45	6	0.24
	50	1	0.04
	55	3	0.12
Land use	Residential	6	0.24
	Commercial	1	0.04
	Mixed (residential + commercial)	15	0.60
	Mixed (residential + industrial)	3	0.12

Table 4-3. Crashes per year data summary– intersections converted to mini-roundabout.

Intersection	Period	Minimum	Median	Mean	Maximum	Std. dev.
Total crashes						
TWSC/OWSC	Before	0.00	2.60	3.49	11.20	3.18
(n = 15)	After	1.00	3.00	3.41	9.00	2.52
AWSC	Before	0.60	3.00	3.18	8.40	2.21
(n = 10)	After	1.33	11.60	11.52	28.33	7.74
All (n = 25)	Before	0.00	2.60	3.37	11.20	2.79
	After	1.00	4.00	6.65	28.33	6.53
FI crashes						
TWSC/OWSC	Before	0.00	1.00	1.07	4.60	1.10
(n = 15)	After	0.00	0.40	0.43	1.67	0.53
AWSC	Before	0.00	0.80	0.82	1.60	0.53
(n = 10)	After	0.25	1.35	1.71	4.25	1.23
All (n = 25)	Before	0.00	1.00	0.97	4.60	0.91
	After	0.00	0.67	0.94	4.25	1.07
PDO crashes						
TWSC/OWSC	Before	0.00	1.80	2.43	7.40	2.38
(n = 15)	After	1.00	2.60	2.98	7.33	2.11
AWSC	Before	0.60	2.10	2.36	6.80	1.75
(n = 10)	After	0.67	10.20	9.82	25.33	6.91
All (n = 25)	Before	0.00	1.80	2.40	7.40	2.11
	After	0.67	3.50	5.71	25.33	5.67

Table 4-4. Major and cross-street traffic volume descriptive of all the selected mini-roundabouts.

Street	Period	Minimum	Median	Mean	Maximum	Std. dev.
TWSC/OWSC intersections converted to mini-roundabouts						
Major street	Before	1,970	7,345	7,762	14,726	3,563.97
	After	2,100	7,883	8,589	14,854	3,452.27
Cross-street	Before	386	3,072	3,668	6,846	1,918.22
	After	370	3,380	4,004	6,806	1,936.46
AWSC intersections converted to mini-roundabouts						
Major street	Before	5,454	7,437	7,712	11,640	1,832.58
	After	5,344	7,162	8,510	14,133	2,887.48
Cross-street	Before	1,834	4,676	4,959	8,590	1,947.76
	After	1,588	5,525	5,617	9,823	2,203.56

CHAPTER 5 RESULTS FROM NAÏVE BEFORE-AFTER ANALYSIS

This chapter illustrates the safety effectiveness of mini-roundabouts converted from stop-controlled intersection using the naïve method employing metrics crashes per year and crash rate.

5.1 Effectiveness Based on the Naïve Method: Crashes Per Year

Table 5-1 shows the naïve before-after analysis based on crashes per year results for TWSC/OWSC intersections converted to mini-roundabouts. Based on the total number of crashes, odds ratio was less than 1 at seven TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in the number of total crashes in the after period. However, odds ratio was greater than 1 at seven TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crashes. One three-legged intersection does not have any crashes in the before period.

For the number of FI crashes, odds ratio was less than 1 at ten TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in the number of total crashes in the after period. However, odds ratio was greater than 1 at four TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crashes. One three-legged intersection does not have any crashes in the before period.

For the number of PDO crashes, odds ratio was less than 1 at three TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in the number of total crashes in the after period. However, odds ratio was greater than 1 at ten TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crashes. One three-legged intersection does not have any crashes in the before period.

Table 5-1. Naïve before-after analysis based on crashes per year - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Before control type	Built year	Crash severity	Before period: # of years	Before period: Crashes per year	Before period: Total traffic volume	After period: # of years	After period: Crashes per year	After period: Total traffic volume	After crashes / Before crashes	% change in traffic volume
1	GA	TWSC	2016	Total	5	11.2	6,276	3	9	8,015	0.8	27.71
				FI		4.6			1.67		0.36	
				PDO		6.6			7.33		1.11	
6	IA	TWSC	2016	Total	5	5	9,678	3	4.33	12,691	0.87	31.14
				FI		1.2			0.67		0.56	
				PDO		3.8			3.67		0.96	
12	MN	TWSC	2018	Total	5	2.4	12,536	1	4	12,950	1.67	3.3
				FI		1			0		0	
				PDO		1.4			4		2.86	
13	MN	TWSC	2016	Total	5	0.4	9,755	3	2.33	11,325	5.83	16.09
				FI		0.2			0		0	
				PDO		0.2			2.33		11.67	
14*	MO	OWSC	2014	Total	5	8.4	9,768	5	1.6	10,942	0.19	12.02
				FI		1			0		0	
				PDO		7.4			1.6		0.22	
15	NC	TWSC	2016	Total	5	7.2	17,370	3	4.67	15,850	0.65	-8.75
				FI		1.8			0		0	
				PDO		5.4			4.67		0.86	
16*	NC	OWSC	2017	Total	5	0	2,356	2	1	2,470	-	4.84
				FI		0			0		-	
				PDO		0			1		-	
17	VA	TWSC	2018	Total	5	2.6	16,686	1	1	16,119	0.38	-3.4
				FI		1.6			0		0	
				PDO		1			1		1	
18	WA	TWSC	2013	Total	5	2.6	7,004	5	8.6	9,771	3.31	39.51
				FI		0.4			1.4		3.5	
				PDO		2.2			7.2		3.27	
20	WA	TWSC	2014	Total	5	2.8	10,666	5	3	15,675	1.07	46.97
				FI		1			0.4		0.4	
				PDO		1.8			2.6		1.44	
21	WA	TWSC	2016	Total	5	1.8	9,282	3	1.67	9,714	0.93	4.65
				FI		1.2			0.67		0.56	
				PDO		0.6			1		1.67	
22	WA	TWSC	2015	Total	5	0.4	10,572	4	1.75	10,880	4.38	2.91
				FI		0.4			0.5		1.25	
				PDO		0			1.25		-	
23$^{\Psi}$	WA	OWSC	2014	Total	5	3.6	21,573	5	3.8	21,660	1.06	0.4
				FI		0.6			0.8		1.33	
				PDO		3			3		1	
24$^{\Psi}$	WA	OWSC	2014	Total	5	2.4	15,009	5	3.4	16,380	1.42	9.13
				FI		0.4			0.4		1	
				PDO		2			3		1.5	
25$^{\Psi}$	WA	OWSC	2018	Total	5	1.6	12,923	1	1	14,438	0.63	11.72
				FI		0.6			0		0	
				PDO		1			1		1	

Note: *Three-legged, $^{\Psi}$OWSC (ramp), total traffic volume (major street + cross-street), FI crashes are fatal and injury type A, B and C crashes, PDO crashes are property damage only crashes.

Table 5-2 shows the naïve before-after analysis based on crashes per year results for AWSC intersections converted to mini-roundabouts. Based on the total number of crashes, odds ratio was greater than 1 at all ten AWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crashes.

For the number of FI crashes, odds ratio was less than 1 at one AWSC intersections converted to mini-roundabouts, indicating a decrease in the number of total crashes in the after period. However, odds ratio was greater than 1 at eight AWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crashes. One intersection does not have any crashes in the before period.

For the number of PDO crashes, odds ratio was greater than 1 at all ten AWSC intersections converted to mini-roundabouts, indicating an increase in the after period PDO crashes.

Table 5-3 summarizes the number of intersections where mini-roundabouts implementation was effective or not effective in crash reduction based on crash severity. Overall, a reduction in the number of FI crashes was observed at relatively a greater number of intersections (ten), compared to the total number of crashes (seven intersections) and PDO crashes (three intersections) when TWSC/OWSC intersections converted to mini-roundabouts. Likewise, an increase in the number of total crashes, FI crashes and PDO crashes was observed when AWSC intersections converted to mini-roundabouts.

Table 5-2. Naïve before-after analysis based on crashes per year - AWSC intersections converted to mini-roundabouts.

Site ID	State	Before control type	Built year	Crash severity	Before period # of years	Before period Crashes per year	Before period Total traffic volume	After period # of years	After period Crashes per year	After period Total traffic volume	After crashes / Before crashes	% change in traffic volume
2	GA	AWSC	2017	Total	5	1.6	7,288	2	5	7,291	3.13	0.04
				FI		0.4			1.5		3.75	
				PDO		1.2			3.5		2.92	
3	GA	AWSC	2015	Total	5	3.6	11,512	4	17.25	14,811	4.79	28.65
				FI		1.2			4.25		3.54	
				PDO		2.4			13		5.42	
4	GA	AWSC	2013	Total	5	3.6	10,696	5	11.2	16,482	3.11	54.09
				FI		1.2			2.2		1.83	
				PDO		2.4			9		3.75	
5	GA	AWSC	2016	Total	5	8.4	20,230	3	28.33	23,957	3.37	18.42
				FI		1.6			3		1.88	
				PDO		6.8			25.33		3.73	
7	MI	AWSC	2016	Total	5	0.6	13,592	3	1.33	15,468	2.22	13.8
				FI		0			0.67		-	
				PDO		0.6			0.67		1.11	
8	MI	AWSC	2015	Total	5	1.6	12,719	4	3.25	13,910	2.03	9.36
				FI		0.4			0.25		0.63	
				PDO		1.2			3		2.5	
9	MI	AWSC	2015	Total	5	1.8	11,537	4	12	10,693	6.67	-7.31
				FI		0.4			0.75		1.88	
				PDO		1.4			11.25		8.04	
10	MI	AWSC	2018	Total	5	2.4	13,184	1	12	13,631	5	3.39
				FI		0.6			1		1.67	
				PDO		1.8			11		6.11	
11	MN	AWSC	2014	Total	5	3.6	14,646	5	10.6	14,214	2.94	-2.95
				FI		1			1.2		1.2	
				PDO		2.6			9.4		3.62	
19	WA	AWSC	2015	Total	5	4.6	11,306	4	14.25	10,805	3.1	-4.43
				FI		1.4			2.25		1.61	
				PDO		3.2			12		3.75	

Note: Total traffic volume (major street + cross-street), FI crashes are fatal and injury type A, B and C crashes, PDO crashes are property damage only crashes.

Table 5-3. Naïve before-after analysis based on crashes per year - # of intersections where the treatment is effective and not effective.

Prior control type	Crash severity type	# of intersections where treatment is effective	# of intersections where treatment is not effective
TWSC/OWSC	Total	7	7
	FI	10	4
	PDO	3	10
AWSC	Total	0	10
	FI	1	8
	PDO	0	10

Safety effectiveness and standard error estimate was computed for the 25 mini-roundabouts converted from stop-controlled intersections. The equations for the naïve before-after analysis based on crashes per year are referred from Hauer (1997) and Tsapakis et al. (2019), and shown in Appendix C.

Table 5-4 summarizes overall safety effectiveness of mini-roundabouts from naïve before-after analysis based on crashes per year. A 0.98% decrease in the number of total crashes, a 47.50% decrease in the number of FI crashes, and a 15.41% increase in the number of PDO crashes was observed when TWSC/OWSC intersections were converted to mini-roundabouts. The standard error was 9.77% for total crashes, 11.94% for FI crashes, and 12.84% for PDO crashes.

A 251.49% increase in the number of total crashes, a 96.09% increase in the number of FI crashes, and a 305.97% increase in the number of PDO crashes was observed when AWSC intersections were converted to mini-roundabouts. The standard error was 33.74% for total crashes, 39.47% for FI crashes, and 44.41% for PDO crashes.

Table 5-4. Naïve before-after analysis based on crashes per year – summary.

Crash severity type	Odds ratio based on crashes per year (standard error)	Safety effectiveness based on crashes per year (standard error) (%)
15 TWSC/OWSC converted to mini-roundabouts		
Total	0.99 (0.10)	0.98 (9.77)
FI	0.53 (0.12)	47.50 (11.94)
PDO	1.15 (0.13)	-15.41 (12.84)
10 AWSC intersections converted to mini-roundabouts		
Total	3.51 (0.34)	-251.49 (33.74)
FI	1.96 (0.39)	-96.09 (39.47)
PDO	4.06 (0.44)	-305.97 (44.41)

5.2 Effectiveness Based on the Naïve Method: Crash Rate

Table 5-5 shows the naïve before-after method based on crash rate results for TWSC/OWSC intersections converted to mini-roundabouts. Based on the total crash rate, the odds ratio was less than 1 at eight TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in the total crash rate in the after period. However, the odds ratio was greater than 1 at six TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crash rate. One three-legged intersection does not have any crashes in the before period.

Based on the FI crash rate, the odds ratio was less than 1 at eleven TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in the FI crash rate in the after period. However, the odds ratio was greater than 1 at three TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period FI crash rate. One three-legged intersection does not have any FI crashes in the before period.

Based on the PDO crash rate, the odds ratio was less than 1 at six TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in the number of PDO crash rate in the after period. However, the odds ratio was greater than 1 at seven TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period PDO crash rate. One three-legged intersection does not have any PDO crashes in the before period.

Table 5-5. Naïve before-after analysis based on crash rate - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Before control type	Built year	Crash severity	Before period			After period			After crash rate / Before crash rate	% change in traffic volume
					# of years	Crash rate for 10,000 AADT	Total traffic volume	# of years	Crash rate for 10,000 AADT	Total traffic volume		
1	GA	TWSC	2016	Total	5	17.85	6,276	3	11.23	8,015	0.63	27.71
				FI		7.33			2.08		0.28	
				PDO		10.52			9.15		0.87	
6	IA	TWSC	2016	Total	5	5.17	9,678	3	3.41	12,691	0.66	31.14
				FI		1.24			0.53		0.42	
				PDO		3.93			2.89		0.74	
12	MN	TWSC	2018	Total	5	1.91	12,536	1	3.09	12,950	1.61	3.3
				FI		0.8			0		0	
				PDO		1.12			3.09		2.77	
13	MN	TWSC	2016	Total	5	0.41	9,755	3	2.06	11,325	5.02	16.09
				FI		0.21			0		0	
				PDO		0.21			2.06		10.05	
14*	MO	OWSC	2014	Total	5	8.6	9,768	5	1.46	10,942	0.17	12.02
				FI		1.02			0		0	
				PDO		7.58			1.46		0.19	
15	NC	TWSC	2016	Total	5	4.15	17,370	3	2.94	15,850	0.71	-8.75
				FI		1.04			0		0	
				PDO		3.11			2.94		0.95	
16*	NC	OWSC	2017	Total	5	0	2,356	2	4.05	2,470	-	4.84
				FI		0			0		-	
				PDO		0			4.05		-	
17	VA	TWSC	2018	Total	5	1.56	16,686	1	0.62	16,119	0.4	-3.4
				FI		0.96			0		0	
				PDO		0.6			0.62		1.04	
18	WA	TWSC	2013	Total	5	3.71	7,004	5	8.8	9,771	2.37	39.51
				FI		0.57			1.43		2.51	
				PDO		3.14			7.37		2.35	
20	WA	TWSC	2014	Total	5	2.63	10,666	5	1.91	15,675	0.73	46.97
				FI		0.94			0.26		0.27	
				PDO		1.69			1.66		0.98	
21	WA	TWSC	2016	Total	5	1.94	9,282	3	1.72	9,714	0.88	4.65
				FI		1.29			0.69		0.53	
				PDO		0.65			1.03		1.59	
22	WA	TWSC	2015	Total	5	0.38	10,572	4	1.61	10,880	4.25	2.91
				FI		0.38			0.46		1.21	
				PDO		0			1.15		-	
23^{Ψ}	WA	OWSC	2014	Total	5	1.67	21,573	5	1.75	21,660	1.05	0.4
				FI		0.28			0.37		1.33	
				PDO		1.39			1.39		1	
24^{Ψ}	WA	OWSC	2014	Total	5	1.6	15,009	5	2.08	16,380	1.3	9.13
				FI		0.27			0.24		0.92	
				PDO		1.33			1.83		1.37	
25^{Ψ}	WA	OWSC	2018	Total	5	1.24	12,923	1	0.69	14,438	0.56	11.72
				FI		0.46			0		0	
				PDO		0.77			0.69		0.9	

Note: *Three-legged, $^{\Psi}$OWSC (ramp), total traffic volume is the sum of traffic volume at major street and cross-street.

Table 5-6 shows the naïve before-after analysis based on crash rate results for AWSC intersections converted to mini-roundabouts. Based on the total crash rate, the odds ratio was greater than 1 at all ten AWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crash rate.

Based on the number of FI crashes, the odds ratio was less than 1 at one AWSC intersection converted to mini-roundabout, indicating a decrease in the FI crash rate in the after period. However, the odds ratio was greater than 1 at eight AWSC intersections converted to mini-roundabouts, indicating an increase in the after period FI rate. One intersection does not have any FI crashes in the before period.

Based on the number of PDO crashes, the odds ratio was less than 1 at one AWSC intersection converted to mini-roundabout, indicating a decrease in the PDO crash rate in the after period. However, the odds ratio was greater than 1 at nine AWSC intersections converted to mini-roundabouts, indicating an increase in the after period PDO crash rate.

Table 5-7 summarizes the number of intersections where mini-roundabouts implementation was effective or not effective in crash rate reduction based on crash severity. Overall, a reduction in the FI crash rate was observed at a relatively greater number of intersections (eleven), compared to the total crash rate (eight intersections) and PDO crash rate (six intersections), when TWSC/OWSC intersections were converted to mini-roundabouts. Likewise, an increase in the total crash rate, FI crash rate and PDO crash rate at majority of the intersections was observed when AWSC intersections were converted to mini-roundabouts.

Table 5-6. Naïve before-after analysis based on crash rate - AWSC intersections converted to mini-roundabouts.

Site ID	State	Before control type	Built year	Crash severity	Before period			After period			After crash rate / Before crash rate	% change in traffic volume
					# of years	Crash rate for 10,000 AADT	Total traffic volume	# of years	Crash rate for 10,000 AADT	Total traffic volume		
2	GA	AWSC	2017	Total	5	2.2	7,288	2	6.86	7,291	3.12	0.04
				FI		0.55			2.06		3.75	
				PDO		1.65			4.8		2.92	
3	GA	AWSC	2015	Total	5	3.13	11,512	4	11.65	14,811	3.72	28.65
				FI		1.04			2.87		2.75	
				PDO		2.08			8.78		4.21	
4	GA	AWSC	2013	Total	5	3.37	10,696	5	6.8	16,482	2.02	54.09
				FI		1.12			1.33		1.19	
				PDO		2.24			5.46		2.43	
5	GA	AWSC	2016	Total	5	4.15	20,230	3	11.83	23,957	2.85	18.42
				FI		0.79			1.25		1.58	
				PDO		3.36			10.57		3.15	
7	MI	AWSC	2016	Total	5	0.44	13,592	3	0.86	15,468	1.95	13.8
				FI		0			0.43		-	
				PDO		0.44			0.43		0.98	
8	MI	AWSC	2015	Total	5	1.26	12,719	4	2.34	13,910	1.86	9.36
				FI		0.31			0.18		0.57	
				PDO		0.94			2.16		2.29	
9	MI	AWSC	2015	Total	5	1.56	11,537	4	11.22	10,693	7.19	-7.31
				FI		0.35			0.7		2.02	
				PDO		1.21			10.52		8.67	
10	MI	AWSC	2018	Total	5	1.82	13,184	1	8.8	13,631	4.84	3.39
				FI		0.46			0.73		1.61	
				PDO		1.37			8.07		5.91	
11	MN	AWSC	2014	Total	5	2.46	14,646	5	7.46	14,214	3.03	-2.95
				FI		0.68			0.84		1.24	
				PDO		1.78			6.61		3.73	
19	WA	AWSC	2015	Total	5	4.07	11,306	4	13.19	10,805	3.24	-4.43
				FI		1.24			2.08		1.68	
				PDO		2.83			11.11		3.92	

Note: Total traffic volume is the sum of traffic volume at major street and cross-street, FI crashes are fatal and injury type A, B and C crashes, PDO crashes are property damage only crashes.

Table 5-7. Naïve before-after analysis based on crash rate - # of intersections where the treatment is effective and not effective.

Prior control type	Crash severity type	# of intersections where treatment is effective	# of intersections where treatment is not effective
TWSC/OWSC	Total	8	6
	FI	11	3
	PDO	6	7
AWSC	Total	0	10
	FI	1	8
	PDO	1	9

Safety effectiveness and standard error estimate was computed for the 25 mini-roundabouts converted from stop-controlled intersection. The equations for the naïve before-after analysis based on crash rate (with traffic volume correction) are referred from Hauer (1997) and Tsapakis et al. (2019), and shown in Appendix D.

Table 5-8 summarizes the overall safety effectiveness of mini-roundabouts from naïve before-after method based on crash rate. A 15.35% decrease in the total crash rate, a 55.64% decrease in the FI crash rate, and a 0.97% decrease in the PDO crash rate was observed when TWSC/OWSC intersections were converted to mini-roundabouts. The standard error was 9.36% for total crash rate, 11.37% for FI crash rate, and 12.15% for PDO crash rate.

A 203.99% increase in the total crash rate, a 67.19% increase in the FI crash rate, and a 252.74% increase in the PDO crash rate was observed when AWSC intersections were converted to mini-roundabouts. The standard error was 33.55% for total crash rate, 35.26% for FI crash rate, and 43.19% for PDO crash rate.

Table 5-8. Naïve before-after analysis based on crash rate – summary.

Crash severity type	Odds ratio based on crash rate (standard error)	Safety effectiveness based on crash rate (standard error) (%)
15 TWSC/OWSC converted to mini-roundabouts		
Total	0.85 (0.09)	15.35 (9.36)
FI	0.44 (0.10)	55.64 (10.37)
PDO	0.99 (0.12)	0.97 (12.15)
10 AWSC intersections converted to mini-roundabouts		
Total	3.04 (0.34)	-203.99 (33.55)
FI	1.67 (0.35)	-67.19 (35.26)
PDO	3.53 (0.43)	-252.74 (43.19)

CHAPTER 6 RESULTS FROM EMPIRICAL BAYES (EB) BEFORE-AFTER ANALYSIS

This chapter illustrates the safety effectiveness computation for mini-roundabouts converted from stop-controlled intersection using the EB method. Crash and traffic volume data collected for 723 reference intersections are used for SPF (mathematical model) development, and the computation of safety effectiveness using the EB method.

6.1 Empirical Bayes (EB) Before and After Analytical Method

The EB method is a widely used method for evaluating the countermeasures or any improvements at a given location. It was first applied for safety evaluation by Abbess et al. in 1981. Over the years, the EB method was successfully used by several researchers in various traffic safety studies (Persaud et al., 2001; Montella, 2007; Qin et al., 2013). The method helps in estimating the number of crashes that would have occurred at an individual treated site in the after period had a treatment not been implemented. It requires the observed number of crashes and traffic volume in the before and after periods for analysis. The HSM published by the American Association of State Highway and Transportation Officials (AASHTO, 2010) provides a comprehensive background and details of the EB method to be used for safety evaluation. The EB method combines the number of crashes of similar entities (for example, similar control type or reference intersections) with the observed number of crashes of individual subject mini-roundabouts. The expected number of crashes is estimated using both these factors. This helps with regression-to-mean bias correction (Hauer, 1997; AASHTO, 2010). “Regression-to-mean (RTM) is the tendency for the occurrence of crashes at a particular intersection to fluctuate up or down, over the long term and to converge to a long term average. This tendency led to the regression-to-mean bias in crash estimation, making treatments at sites with extremely high frequency appear to be more effective than they truly are" (AASHTO, 2010). Figure 6-1 shows the regression-to-mean and regression-to-mean bias concept. The EB method as illustrated in the HSM (AASHTO, 2010) for safety evaluation is briefly summarized next.

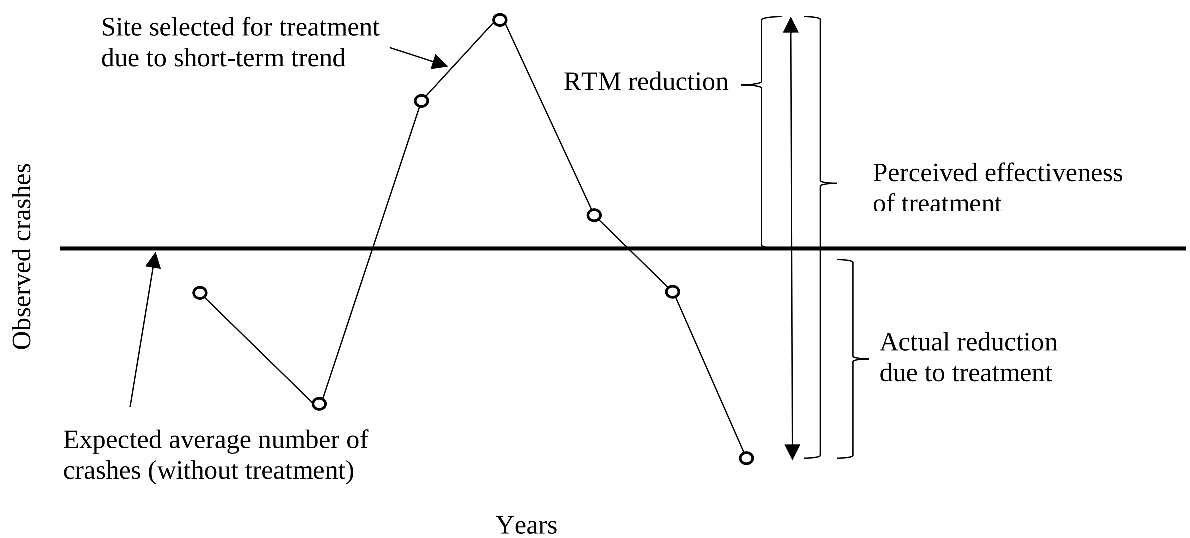


Figure 6-1. Regression-to-mean (RTM) and RTM bias (figure 3-5 AASHTO, 2010).

6.2 Safety Performance Functions (SPFs)

Crashes are rare events, and in general, the variance of the crash data usually exceeds the mean (Hauer, 1997; AASHTO, 2010). This condition is known as overdispersion. SPFs are the crash prediction models. The SPF is defined in the HSM as regression equations that estimate the average crash frequency for a specific site type as a function of annual average daily traffic (AADT) and, in the case of roadway segments, the segment length (AASHTO, 2010). The HSM provides SPFs for certain intersection control types (TWSC, OWSC, and signal) and area type (rural and urban/suburban). These SPFs in HSM were developed using crash and traffic volume data prior to 2010. The HSM SPFs can be calibrated to account for spatial (jurisdiction) and temporal (year-wise) variations. The SPF development guide suggests developing jurisdiction-specific SPFs (Srinivasan and Bauer, 2013). It requires crash and traffic volume data from a large sample of untreated intersections, similar to the before condition control type and intersection geometry that were not converted to mini-roundabouts. Equation 6.1 shows the general form of a SPF used for predicting the number of crashes at an intersection in the HSM. The base condition for intersection SPF as indicated in the HSM are zero intersection skew angle, zero intersection left-turn and right-turn lanes, and no lighting. Table 6-1 shows the SPF regression coefficient and overdispersion parameter from the HSM based on intersection, area, and crash severity type.

$$N_{SPF} = exp[a + b \times \ln(AADT_{MS}) + c \times \ln(\mathrm{AADT}_{CS})] \quad (6.1)$$

where N_{SPF} = SPF estimate of intersection-related average number of crashes for the base condition,

$AADT_{MS}$ = AADT (vehicles per day) for the major street approaches,

$AADT_{CS}$ = AADT (vehicles per day) for the cross-street approaches, and,

a, b, c = regression coefficients.

Table 6-1. SPF regression coefficient and overdispersion parameter from HSM – AASHTO (2010).

Area type	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)
Total crashes					
Rural	4ST	-8.56	0.60	0.61	0.24
Urban/suburban	4ST	-8.90	0.82	0.25	0.40
Rural	3ST	-9.86	0.79	0.49	0.54
Urban/suburban	3ST	-13.36	1.11	0.41	0.80
Fatal and injury (FI) crashes					
Urban/suburban	4ST	-11.13	0.93	0.28	0.48
Urban/suburban	3ST	-14.01	1.16	0.30	0.69
PDO crashes					
Urban/suburban	4ST	-8.74	0.77	0.23	0.40
Urban/suburban	3ST	-15.38	1.20	0.51	0.77

Note: 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street, urban/suburban SPFs for multiple-vehicles crashes.

A minimum of three years crash data is recommended for SPF development in the SPF decision guide (Srinivasan et al., 2013). The HSM suggests use of SPFs to predict long-term expected average number of crashes to address regression-to-mean bias. However, the safety effectiveness may vary based on the calibrated HSM SPFs and developed jurisdiction-specific SPFs using crash data for different numbers of years (say, 3 year, 5 year, 7 year and 9 year crash data). It may also vary with the developed jurisdiction-specific SPFs calibrated year-wise to account for temporal variation (due to advancement in automobile technologies focused on traffic safety, policies such as vision zero plan and socio-demographic changes).

The SPFs available in the HSM as well as jurisdiction-specific SPFs were developed to compute safety effectiveness from EB method. The safety effectiveness was computed and compared using a) calibrated HSM SPFs, b) non-calibrated HSM SPFs, c) developed jurisdiction-specific SPFs from 3 year crash data with year-wise calibration, d) developed jurisdiction-specific SPFs from 3 year crash data without year-wise calibration, e) developed jurisdiction-specific SPFs from 5 year crash data with year-wise calibration, f) developed jurisdiction-specific SPFs from 5 year crash data without year-wise calibration, g) developed jurisdiction-specific SPFs from 7 year crash data with year-wise calibration, h) developed jurisdiction-specific SPFs from 7 year crash data without year-wise calibration, and i) developed jurisdiction-specific SPFs from 9 year crash data.

Crash and traffic volume data for reference intersections were gathered and used for jurisdiction-specific SPFs development and computing the calibration factors. The reference intersections based on the control type (TWSC, OWSC, OWSC (ramp) and AWSC) and geometry (four-legged and three-legged) were randomly identified (spatially distributed) without any prior information of traffic volume and crash history. Any change in control type during the considered time period was verified through Google Earth and Google maps satellite images and street-views.

Crash data (KABCO classification – fatal, injury types A, B, and C, and PDO) and traffic volume data (major street and cross-street) were captured for each identified intersection. The intersection database was divided into 75% for model development and 25% for model validation. A summation of crashes for the three, five, seven and nine year period was considered as the dependent variable in Equations 6.2, 6.3, 6.4 and 6.5, respectively, and average traffic volumes for the major street and cross-street (three-year and nine-year period) were taken as the independent variables. The jurisdiction-specific SPFs were developed separately for total crashes, FI crashes, and PDO crashes based on control types [TWSC (four-legged), OWSC (three-legged), OWSC (ramp) (four-legged) and AWSC (four-legged)].

IBM SPSS software was used to develop negative binomial log link function-based SPF models. Overdispersion parameter "k" and regression coefficients were estimated. The goodness-of-fit measures were used to check the statistical validity of the models. The goodness-of-fit of developed SPF was assessed using Akaike Information Criterion (AIC), corrected Akaike Information Criterion (AICC), and Mean Absolute Deviation (MAD). The lower value of AIC, AICC and MAD indicate a better fit of the model. Tables 6-2 to 6-9 shows the SPF regression coefficients for different control types used in this research.

Equation 6.1 shows the general form of a SPF used for predicting the number of crashes at an intersection in the HSM. Equation 6.2 to 6.5 are the general form of jurisdiction-specific SPFs developed for predicting the number of crashes at an intersection from 3, 5, 7, and 9 years of crash data, respectively.

$$N_{SPF} = [\exp\{[a + b \times \ln(AADT_{MS}) + c \times \ln(\mathrm{AADT}_{CS})\}]/3 \quad (6.2)$$

$$N_{SPF} = [\exp\{[a + b \times \ln(AADT_{MS}) + c \times \ln(\mathrm{AADT}_{CS})\}]/5 \quad (6.3)$$

$$N_{SPF} = [\exp\{[a + b \times \ln(AADT_{MS}) + c \times \ln(\mathrm{AADT}_{CS})\}]/7 \quad (6.4)$$

$$N_{SPF} = [\exp\{[a + b \times \ln(AADT_{MS}) + c \times \ln(\mathrm{AADT}_{CS})\}]/9 \quad (6.5)$$

where N_{SPF} = SPF estimate of intersection-related average number of crashes for the base condition, $AADT_{MS}$ = AADT (vehicles per day) for the major street approaches, $AADT_{CS}$ = AADT (vehicles per day) for the cross-street approaches, and, a, b, c = regression coefficients.

Table 6-2. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for TWSC/OWSC from 3 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	Year	AIC	AICC	MAD
Total crashes									
Georgia	4ST	-3.84	0.39	0.36	0.38	2011-2013	169.85	171.18	1.25
Iowa	4ST	-7.52	0.88	0.21	0.49	2011-2013	195.93	196.98	1.14
Minnesota	4ST	-3.77	0.40	0.25	0.46	2011-2013	189.65	190.86	1.25
Missouri	3ST	-7.64	0.79	0.30	0.38	2011-2013	110.11	111.71	1.27
North Carolina	4ST	-3.36	0.08	0.59	0.15	2013-2015	206.54	207.59	1.10
	3ST	-5.91	0.23	0.67	0.58	2011-2013	163.97	165.02	1.22
Virginia	4ST	-7.52	0.23	0.98	0.56	2013-2015	164.13	165.73	1.30
Washington State	4ST	-4.84	0.65	0.05	0.37	2010-2012	228.65	229.44	1.24
	4ST (ramp)	-4.58	0.30	0.42	0.34	2013-2015	193.93	195.05	1.29
Fatal and injury (FI) crashes									
Georgia	4ST	-5.89	0.68	0.13	0.23	2011-2013	103.25	104.59	1.13
Iowa	4ST	-10.95	0.98	0.44	0.77	2011-2013	136.70	137.75	1.09
Minnesota	4ST	-3.64	0.31	0.24	0.38	2011-2013	146.09	147.31	1.22
Missouri	3ST	-8.97	0.76	0.36	0.04	2011-2013	63.28	64.88	1.03
North Carolina	4ST	-3.94	0.03	0.62	0.02	2013-2015	153.74	154.79	1.34
	3ST	-8.06	0.39	0.67	0.13	2011-2013	118.31	119.36	1.46
Virginia	4ST	-8.99	0.34	0.95	0.88	2013-2015	126.78	128.38	1.18
Washington State	4ST	-6.45	0.75	0.04	0.14	2010-2012	160.91	161.69	1.41
	4ST (ramp)	-6.44	0.70	0.06	0.47	2013-2015	115.11	116.23	1.11
PDO crashes									
Georgia	4ST	-3.61	0.24	0.46	0.38	2011-2013	150.57	151.90	1.25
Iowa	4ST	-6.63	0.80	0.11	0.48	2011-2013	161.65	162.70	1.16
Minnesota	4ST	-4.56	0.43	0.22	0.49	2011-2013	147.74	148.95	1.26
Missouri	3ST	-7.71	0.83	0.22	0.51	2011-2013	95.64	97.24	1.24
North Carolina	4ST	-4.14	0.12	0.57	0.19	2013-2015	173.09	174.14	1.14
	3ST	-9.48	0.72	0.52	0.10	2011-2013	121.82	122.87	1.22
Virginia	4ST	-7.66	0.03	1.16	0.16	2013-2015	126.58	128.18	1.33
Washington State	4ST	-4.50	0.56	0.04	0.20	2010-2012	181.78	182.57	1.22
	4ST (ramp)	-4.88	0.21	0.53	0.24	2013-2015	172.19	173.30	1.33

Note: 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-3. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for TWSC/OWSC from 5 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	4ST	-3.47	0.41	0.36	0.20	255.17	256.13	1.24
Iowa	4ST	-7.89	0.86	0.34	0.19	227.64	228.64	1.08
Minnesota	4ST	-3.72	0.43	0.27	0.35	217.91	219.13	1.16
Missouri	3ST	-6.76	0.45	0.62	0.54	123.41	125.01	1.33
North Carolina	4ST	-3.47	0.24	0.50	0.09	282.98	283.78	1.08
	3ST	-6.13	0.41	0.57	0.43	200.35	201.40	1.25
Virginia	4ST	-6.58	0.41	0.71	0.42	189.59	191.19	1.17
Washington State	4ST	-3.47	0.46	0.17	0.48	346.10	346.75	1.17
	4ST (ramp)	-4.44	0.21	0.57	0.24	258.23	259.14	1.01
Fatal and injury (FI) crashes								
Georgia	4ST	-4.46	0.45	0.32	0.12	183.65	184.60	1.28
Iowa	4ST	-9.77	0.75	0.58	0.21	163.51	164.51	1.24
Minnesota	4ST	-3.50	0.29	0.33	0.56	183.61	184.82	1.23
Missouri	3ST	-7.31	0.33	0.61	0.09	59.35	60.95	0.93
North Carolina	4ST	-4.35	0.19	0.57	0.01	215.99	216.79	1.13
	3ST	-6.79	0.26	0.71	0.46	142.89	143.94	1.16
Virginia	4ST	-7.34	0.28	0.85	0.77	150.33	151.93	1.29
Washington State	4ST	-4.13	0.39	0.24	0.80	268.97	269.61	1.20
	4ST (ramp)	-5.04	0.60	0.07	0.39	173.98	174.89	1.14
PDO crashes								
Georgia	4ST	-3.85	0.38	0.38	0.26	222.98	223.93	1.20
Iowa	4ST	-7.60	0.86	0.25	0.16	197.04	198.04	1.14
Minnesota	4ST	-4.98	0.54	0.21	0.19	165.84	167.05	1.31
Missouri	3ST	-7.25	0.52	0.58	0.47	113.10	114.70	1.32
North Carolina	4ST	-4.06	0.28	0.44	0.15	243.55	244.35	1.11
	3ST	-7.97	0.68	0.45	0.34	162.16	163.22	1.23
Virginia	4ST	-7.03	0.44	0.66	0.31	157.55	159.15	1.22
Washington State	4ST	-4.14	0.50	0.12	0.58	276.49	277.13	1.18
	4ST (ramp)	-5.09	0.09	0.73	0.18	228.90	229.81	1.14

Note: Crash data used 2011-2015, 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-4. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for TWSC/OWSC from 7 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	4ST	-3.32	0.49	0.36	0.18	277.45	278.41	1.24
Iowa	4ST	-7.85	0.82	0.43	0.21	258.30	259.30	1.10
Minnesota	4ST	-4.04	0.45	0.32	0.25	227.97	229.19	1.20
Missouri	3ST	-6.91	0.67	0.44	0.30	140.44	142.04	1.41
North Carolina	4ST	-2.89	0.19	0.53	0.10	257.53	258.58	1.20
	3ST	-6.21	0.62	0.40	0.31	224.89	225.94	1.22
Virginia	4ST	-6.62	0.36	0.82	0.41	204.98	206.58	1.20
Washington State	4ST	-4.67	0.68	0.14	0.45	382.54	383.20	1.18
	4ST (ramp)	-5.22	0.35	0.56	0.35	274.29	275.31	1.15
Fatal and injury (FI) crashes								
Georgia	4ST	-4.57	0.53	0.37	0.23	212.04	212.99	1.21
Iowa	4ST	-9.83	0.75	0.65	0.20	195.03	196.03	1.39
Minnesota	4ST	-4.05	0.35	0.36	0.37	193.76	194.97	1.19
Missouri	3ST	-8.05	0.62	0.43	0.05	72.02	73.62	1.15
North Carolina	4ST	-4.01	0.25	0.51	0.03	199.94	200.99	1.25
	3ST	-7.00	0.44	0.59	0.52	167.10	168.15	1.19
Virginia	4ST	-7.22	0.21	0.97	0.72	166.16	167.76	1.32
Washington State	4ST	-7.48	0.70	0.39	0.85	292.69	293.35	1.19
	4ST (ramp)	-5.65	0.17	0.65	0.44	188.15	189.17	1.09
PDO crashes								
Georgia	4ST	-3.61	0.47	0.35	0.26	247.08	248.03	1.29
Iowa	4ST	-7.66	0.83	0.33	0.26	226.82	227.82	1.15
Minnesota	4ST	-5.06	0.52	0.28	0.10	174.27	175.48	1.39
Missouri	3ST	-7.29	0.71	0.42	0.21	129.25	130.85	1.47
North Carolina	4ST	-3.23	0.14	0.54	0.18	224.77	225.82	1.13
	3ST	-7.53	0.80	0.30	0.29	188.28	189.33	1.23
Virginia	4ST	-7.23	0.40	0.77	0.34	172.86	174.46	1.27
Washington State	4ST	-4.06	0.65	0.02	0.33	315.54	316.21	1.20
	4ST (ramp)	-5.45	0.50	0.39	0.29	245.60	246.63	1.21

Note: Crash data used 2011-2017, 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-5. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for TWSC/OWSC from 9 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	4ST	-3.87	0.50	0.41	0.19	299.94	300.89	1.13
Iowa	4ST	-6.07	0.73	0.33	0.20	285.90	286.90	1.18
Minnesota	4ST	-5.11	0.49	0.46	0.24	240.54	241.75	1.20
Missouri	3ST	-7.58	0.73	0.50	0.30	149.75	151.35	1.42
North Carolina	4ST	-2.30	0.17	0.51	0.13	284.52	285.57	1.24
	3ST	-6.04	0.61	0.43	0.29	245.08	246.14	1.16
Virginia	4ST	-6.07	0.37	0.76	0.48	222.22	223.82	1.23
Washington State	4ST	-1.90	0.47	0.04	0.57	332.18	333.07	1.22
	4ST (ramp)	-2.33	0.54	0.02	0.26	262.57	263.68	1.17
Fatal and injury (FI) crashes								
Georgia	4ST	-5.22	0.56	0.41	0.24	234.24	235.20	1.13
Iowa	4ST	-7.91	0.72	0.45	0.29	225.37	226.37	1.47
Minnesota	4ST	-5.18	0.42	0.45	0.38	206.68	207.89	1.21
Missouri	3ST	-8.01	0.64	0.45	0.10	83.34	84.94	1.37
North Carolina	4ST	-2.30	0.11	0.47	0.10	232.73	233.78	1.30
	3ST	-6.12	0.41	0.54	0.52	184.45	185.50	1.17
Virginia	4ST	-6.25	0.15	0.95	0.75	180.28	181.88	1.34
Washington State	4ST	-3.80	0.54	0.10	0.82	251.38	252.27	1.25
	4ST (ramp)	-5.51	0.48	0.29	0.10	146.06	147.27	1.20
PDO crashes								
Georgia	4ST	-4.12	0.46	0.42	0.23	265.21	266.16	1.18
Iowa	4ST	-6.34	0.74	0.28	0.24	250.49	251.49	1.12
Minnesota	4ST	-5.65	0.51	0.40	0.19	191.41	192.62	1.35
Missouri	3ST	-8.58	0.89	0.43	0.10	133.31	134.91	1.65
North Carolina	4ST	-3.62	0.22	0.54	0.15	237.59	238.64	1.16
	3ST	-8.14	0.89	0.33	0.22	201.96	203.01	1.09
Virginia	4ST	-6.32	0.33	0.77	0.44	190.97	192.57	1.32
Washington State	4ST	-1.84	0.43	0.01	0.50	284.18	285.06	1.21
	4ST (ramp)	-2.65	0.39	0.18	0.24	242.21	243.32	1.23

Note: Crash data used 2011-2019, 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-6. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for AWSC from 3 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	AWSC	-4.67	0.28	0.56	0.31	176.92	178.21	1.19
Michigan	AWSC	-6.00	0.73	0.19	0.25	189.32	190.53	1.25
Minnesota	AWSC	-6.94	0.66	0.33	0.36	203.60	204.71	1.22
Washington State	AWSC	-3.15	0.47	0.07	0.36	153.44	154.98	1.26
Fatal and injury (FI) crashes								
Georgia	AWSC	-5.34	0.03	0.75	0.27	111.45	112.74	1.20
Michigan	AWSC	-7.40	0.18	0.71	0.43	89.25	90.46	1.05
Minnesota	AWSC	-5.15	0.61	0.03	0.21	136.67	137.78	1.32
Washington State	AWSC	-1.61	0.11	0.09	0.76	94.80	96.34	1.12
PDO crashes								
Georgia	AWSC	-5.27	0.40	0.46	0.24	156.04	157.34	1.23
Michigan	AWSC	-6.18	0.82	0.10	0.22	179.13	180.34	1.33
Minnesota	AWSC	-8.89	0.63	0.54	0.62	178.69	179.80	1.16
Washington State	AWSC	-4.56	0.61	0.06	0.24	134.73	136.27	1.33

Note: Crash data used 2013-2015, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-7. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for AWSC from 5 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	AWSC	-4.15	0.30	0.52	0.25	205.91	207.16	1.14
Michigan	AWSC	-7.21	1.09	0.03	0.13	279.23	280.12	1.14
Minnesota	AWSC	-7.29	0.52	0.57	0.31	303.33	304.13	1.23
Washington State	AWSC	-2.55	0.49	0.03	0.39	167.91	169.51	1.25
Fatal and injury (FI) crashes								
Georgia	AWSC	-5.02	0.10	0.68	0.31	135.72	136.97	1.19
Michigan	AWSC	-9.95	1.08	0.19	0.35	171.97	172.86	1.06
Minnesota	AWSC	-5.94	0.56	0.23	0.26	214.53	215.33	1.26
Washington State	AWSC	-1.45	0.20	0.06	0.78	120.88	122.48	1.26
PDO crashes								
Georgia	AWSC	-4.50	0.39	0.44	0.21	185.69	186.94	1.23
Michigan	AWSC	-7.07	1.07	0.00	0.10	259.46	260.35	1.21
Minnesota	AWSC	-8.92	0.44	0.79	0.37	263.12	263.92	1.19
Washington State	AWSC	-4.28	0.66	0.00	0.22	140.99	142.59	1.33

Note: Crash data used 2011-2015, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-8. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for AWSC from 7 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	AWSC	-4.14	0.34	0.53	0.21	222.59	223.84	1.06
Michigan	AWSC	-7.06	1.06	0.09	0.10	299.41	300.30	1.12
Minnesota	AWSC	-6.92	0.59	0.49	0.25	331.09	331.89	1.13
Washington State	AWSC	-3.85	0.61	0.11	0.40	178.31	179.98	1.24
Fatal and injury (FI) crashes								
Georgia	AWSC	-4.69	0.00	0.79	0.26	151.78	153.03	1.14
Michigan	AWSC	-9.62	1.23	0.02	0.21	184.67	185.55	1.01
Minnesota	AWSC	-7.09	0.73	0.23	0.31	244.04	244.84	1.28
Washington State	AWSC	-2.21	0.10	0.31	0.69	130.36	132.03	1.27
PDO crashes								
Georgia	AWSC	-4.59	0.47	0.40	0.19	202.92	204.17	1.11
Michigan	AWSC	-7.00	1.01	0.11	0.07	279.01	279.89	1.14
Minnesota	AWSC	-7.92	0.50	0.65	0.31	294.23	295.03	1.15
Washington State	AWSC	-5.83	0.84	0.05	0.29	152.65	154.32	1.23

Note: Crash data used 2011-2017, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

Table 6-9. Jurisdiction-specific SPFs (regression coefficients, overdispersion parameter and goodness-of-fit measures) for AWSC from 9 year crash data.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	AIC	AICC	MAD
Total crashes								
Georgia	AWSC	-4.68	0.44	0.53	0.18	235.39	236.64	1.06
Michigan	AWSC	-6.15	0.89	0.19	0.09	316.79	317.69	1.11
Minnesota	AWSC	-7.41	0.59	0.58	0.24	358.36	359.16	1.16
Washington State	AWSC	-3.33	0.66	0.02	0.23	227.57	228.86	1.15
Fatal and injury (FI) crashes								
Georgia	AWSC	-5.26	0.10	0.79	0.26	160.36	161.61	1.14
Michigan	AWSC	-8.75	0.97	0.21	0.21	202.87	203.77	1.15
Minnesota	AWSC	-6.68	0.67	0.27	0.27	264.77	265.57	1.25
Washington State	AWSC	-1.40	0.23	0.10	0.37	159.72	161.20	1.26
PDO crashes								
Georgia	AWSC	-5.11	0.56	0.42	0.16	216.59	217.84	1.07
Michigan	AWSC	-6.15	0.87	0.18	0.07	297.42	298.33	1.12
Minnesota	AWSC	-9.07	0.54	0.78	0.27	320.26	321.06	1.21
Washington State	AWSC	-4.45	0.69	0.06	0.16	195.15	196.44	1.16

Note: Crash data used 2011-2019, AIC is Akaike information criterion, AICC is Akaike information criterion with correction, and MAD is mean absolute deviation.

6.3 HSM SPF Calibration

The HSM (AASHTO, 2010) suggests applying the calibration factor to the SPF to predict the number of crashes as per local site conditions. The predicted number of crashes may vary due to several factors such as local driver demographics, geographic and climatic conditions, crash reporting threshold, and crash reporting practices. First, reference intersections based on prior control type and geometry were identified in each state. Then, crash data (KABCO classification) and traffic volume data (major street and cross-street) were captured for the identified reference intersections. In case traffic volume data was not available for either intersection approach, identified reference intersections were eliminated from further analysis. Finally, calibration factors for the SPFs available in the HSM for a TWSC/OWSC intersection by the area type (urban/suburban and rural) were computed for each year using Equation 6.6.

The calibration factors were computed for total crashes, FI crashes, and PDO crashes. Tables E-1 to E-4 in Appendix E provides the descriptive statistics of reference intersections. Table 6-10 shows the year-wise calibration factors for the considered states based on the prior control, and area type.

$$C_i = \frac{\sum_{All\ sites} Observed\ crashes}{\sum_{All\ sites} Predicted\ crashes} \qquad (6.6)$$

Table 6-10. Calibration factors for the safety performance functions (SPFs) available in the HSM (AASHTO, 2010).

Year	Crash severity	Calibration factor									
		Georgia	Iowa	Michigan	Minnesota	Missouri	North Carolina		Virginia	Washington State	
		4ST	4ST	4ST	4ST	3ST	4ST	3ST	4ST	4ST	4ST
		Rural (TWTL)	Urban / suburban	Urban / suburban	Urban / suburban	Rural (TWTL)	Urban / suburban	Rural (TWTL)	Urban / suburban	Urban / suburban	Rural (TWTL)
		n = 47	n = 59	n = 49	n = 50	n = 38	n = 57	n = 57	n = 40	n = 42	n = 32
2009	Total	-	-	-	-	0.69	-	-	-	-	-
	FI	-	-	-	-	0.28	-	-	-	-	-
	PDO	-	-	-	-	0.98	-	-	-	-	-
2010	Total	1.3	-	-	-	1.03	-	-	-	1.29	0.37
	FI	1.11	-	-	-	0.46	-	-	-	1.39	0.43
	PDO	1.45	-	-	-	1.24	-	-	-	1.23	0.33
2011	Total	1.32	1.67	2.92	1.57	0.53	2.15	0.59	-	1.05	0.31
	FI	0.99	2.09	2.75	2.43	0.09	3.09	0.64	-	1.09	0.34
	PDO	1.58	1.44	3.09	1.12	0.91	1.67	0.53	-	1.01	0.29
2012	Total	1.48	1.84	2.95	1.14	0.70	2.30	0.66	-	1.03	0.29
	FI	0.94	2.05	3.11	1.75	0.09	3.18	0.63	-	1.17	0.37
	PDO	1.89	1.69	2.94	0.81	1.14	1.72	0.68	-	0.95	0.22
2013	Total	1.26	1.15	3.28	1.49	0.44	1.66	0.55	1.36	1.31	0.45
	FI	1.18	1.16	2.52	1.89	0.19	2.19	0.41	1.58	1.96	0.47
	PDO	1.32	1.14	3.50	1.18	0.61	1.38	0.61	1.21	0.95	0.44
2014	Total	1.40	1.65	3.22	1.39	0.74	2.48	0.92	1.73	1.39	0.36
	FI	1.15	1.68	2.46	1.78	0.47	3.24	0.66	1.88	1.93	0.37
	PDO	1.58	1.59	3.53	1.00	0.86	2.03	1.02	1.62	1.09	0.35
2015	Total	1.62	1.68	3.55	1.50	1.15	2.54	0.56	1.43	1.13	0.41
	FI	2.00	1.53	2.86	2.52	0.8	3.02	0.61	1.73	1.28	0.60
	PDO	1.33	1.78	3.78	0.95	1.33	2.19	0.53	1.23	1.04	0.28
2016	Total	1.27	1.81	3.67	0.94	0.81	2.03	0.81	1.54	1.03	0.51
	FI	1.50	2.22	3.83	1.13	0.51	2.73	0.74	1.84	1.00	0.57
	PDO	1.10	1.57	3.56	0.73	1.03	1.66	0.80	1.35	1.04	0.46
2017	Total	1.49	1.77	3.11	0.82	0.78	2.43	0.69	1.32	1.42	0.48
	FI	1.32	2.28	2.77	1.44	0.16	3.49	0.55	1.61	1.82	0.31
	PDO	1.63	1.49	3.35	0.50	1.22	1.80	0.79	1.13	1.09	0.62
2018	Total	1.41	1.73	3.4	1.22	0.54	2.47	0.83	1.67	1.35	0.53
	FI	1.44	1.77	3.26	1.35	0.57	3.73	0.54	2.03	2.08	0.37
	PDO	1.39	1.66	3.44	1.14	0.46	1.72	0.94	1.44	0.93	0.65
2019	Total	2.00	1.68	3.91	1.12	0.71	2.50	0.72	1.64	1.24	0.59
	FI	1.97	1.75	3.50	1.76	0.16	3.70	0.53	1.64	1.62	0.44
	PDO	2.03	1.68	4.14	0.71	1.09	1.78	0.84	1.55	1.03	0.70

Note: TWTL – Two-way two-lane undivided road, 4ST – Four-legged stop-controlled at cross-street, 3ST – Three-legged stop-controlled at cross-street.

6.4 Effectiveness Computation for Two-Way Stop-Controlled (TWSC) / One-Way Stop-Controlled Intersections Converted to Mini-Roundabouts

The SPFs available in the HSM for a TWSC/OWSC intersection were calibrated for the considered time period for Georgia, Iowa, Michigan, Minnesota, Missouri, North Carolina, Virginia, and Washington State.

The HSM methodology suggested using higher AADT in either of the two major street approaches, and higher AADT in either of the two cross-street approaches for predicting the average number of crashes using the SPF for a TWSC/OWSC intersection (AASHTO, 2010). The SPFs for a TWSC/OWSC intersection in the HSM are based on the following base conditions: a) zero intersection skew angle, b) zero exclusive left-turn lanes at the intersection, c) zero exclusive right-turn lanes at the intersection, and d) no lighting. No changes to the intersection skew angle during the before and after periods was observed from the satellite images and street-views of Google Earth and Google maps at the selected mini-roundabouts. Left-turn lanes are not applicable at the mini-roundabouts, while an exclusive right-turn lane on the major street was added at only one mini-roundabout in the after period. For lighting, the breakdown of crashes by lighting condition was not available. To keep it consistent and from a conservative perspective, the base condition calibrated SPFs from the HSM were used without any adjustments or applying any modification factors.

The observed number of crashes and traffic volume availability in the before and after periods are the prerequisite for before-after analysis using the EB method. First, crashes in the before period are predicted as a function of traffic volume (major street and cross-street) using a SPF.

The SPFs available in the HSM for estimating the predicted number of multiple-vehicle crashes, single-vehicle crashes, or all crashes based on the area type and crash severity were considered for safety analysis of a TWSC/OWSC intersection. The predicted total number of crashes were not very different (nearly the same) when SPFs for both multiple-vehicle crashes and single-vehicle crashes at a TWSC/OWSC intersection in an urban/suburban area were considered, compared to only when SPFs for multiple-vehicle crashes was considered (Table E-5 in Appendix E). Further, the SPF for estimating the predicted number of FI single-vehicle crashes was not available for a TWSC/OWSC intersection in the HSM. Likewise, separate SPFs for estimating the predicted number of multiple-vehicle or single-vehicle crashes at a TWSC/OWSC intersection in a rural area are also not available. To keep the odds ratio computation consistent for total crashes, FI crashes, and PDO crashes, only the available SPFs for multiple-vehicle crashes at a TWSC/OWSC intersection in an urban/suburban area and all crashes at a TWSC/OWSC intersection in a rural area were considered in this research. The SPFs for a TWSC/OWSC intersection in urban/suburban and rural areas were calibrated for the considered time period in each state. A cursory observation indicated that the use of calibration factors has accounted for any difference that might have been as a result of not computing and considering single-vehicle crashes for the analysis.

A five year before period was considered for the analysis of all the selected mini-roundabouts. For example, if a mini-roundabout was built in 2016, before period considered for analysis was 2011-2015. Before period crashes were predicted using SPF and calibration factor for each year. Summation of all the five years before period crashes was used to compute weight 'w_i'.

Each individual intersection was given a weight based on the observed number of crashes in the before period using Equation 6.7. The weight 'w_i' was computed for each individual intersection using the overdispersion parameter 'k' and before period predicted number of crashes (Equation 6.8). Finally, the expected number of crashes in the before period for each intersection was computed using Equation 6.7.

$$N_{Expected,B} = w_{i,B} \times N_{Predicted,B} + (1-w_i) \times N_{Observed,B} \quad (6.7)$$

where $$w_{i,B} = \frac{1}{1+k\ \sum_{Before\ years} N_{Predicted}} \quad (6.8)$$

$N_{Expected,B}$ = expected number of crashes at intersection i for the entire before period,

$N_{Predicted,B}$ = predicted number of crashes at intersection i,

$N_{Observed,B}$ = observed number of crashes at intersection i for the entire before period, and,

k = Overdispersion parameter for the applicable SPF.

Similarly, the average number of crashes for each after period year was predicted using SPF and calibration factor. For example, if a mini-roundabout was built in 2016, after period crashes were predicted for 2017, 2018, and 2019. The traffic volume of the major street and cross-street approaches during the after period was used to predict the number of crashes. To account for the change in traffic volume in the after period, the adjustment ratio 'r_i' was computed for each intersection using Equation 6.9. Then, the expected average number of crashes for the before period was multiplied with the year-wise adjustment ratio to estimate the expected number of crashes in the after period using Equation 6.10. The year-wise odds ratio was computed as a ratio of the observed and expected number of crashes in the after period for each intersection using Equation 6.11. The overall odds ratio was computed as the ratio of summation of the observed number of crashes and the expected number of crashes in the entire considered after period. The bias correction in odds ratio due to weight (w_i) was performed using the HSM methodology

(Equations 6.12-6.14). Finally, the safety effectiveness of considered mini-roundabouts was computed using Equation 6.15. The standard error (SE) of safety effectiveness was computed using Equations 6.16-6.18.

$$r_i = \frac{\sum_{After\ years} N_{Predicted,A}}{\sum_{Before\ years} N_{Predicted,B}} \tag{6.9}$$

where r_i = adjustment ratio for intersection *i*,

$N_{Predicted,A}$ = predicted average number of crashes for the after period based on applicable SPF, and,

$N_{Predicted,B}$ = predicted average number of crashes for the before period based on applicable SPF.

$$N_{Expected,A} = N_{Expected,B} \times r_i \tag{6.10}$$

where $N_{Expected,A}$ = expected average number of crashes for mini-roundabout *i* over the entire after period.

$$OR_i = \frac{N_{Observed,A}}{N_{Expected,A}} \tag{6.11}$$

where OR_i = odds ratio for intersection *i*, and,

$N_{Observed,A}$ = observed number of crashes for intersection *i* for the entire after period.

$$\text{Safety Effectiveness}_i = 100 \times (1 - OR_i) \tag{6.12}$$

where Safety Effectiveness$_i$ = safety effectiveness at intersection *i*.

$$OR' = \frac{\sum_{All\ sites} N_{Observed,A}}{\sum_{All\ sites} N_{Expected,A}} \tag{6.13}$$

where OR′ = odds ratio of all intersections combined.

$$OR = \frac{OR'}{1+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}} \tag{6.14}$$

where OR = unbiased odd ratio estimated of mini-roundabout effectiveness,

$Var\left(\sum_{All\ sites} N_{Expected,A}\right) = \sum_{All\ sites}\left[(r_i)^2 \times N_{Expected,B} \times \left(1 - w_{i,B}\right)\right]$, and,

$w_{i,B}$ and r_i are from equations (6.8) and (6.9).

Safety Effectiveness = 100 × (1- OR) (6.15)

where Safety Effectiveness = overall unbiased safety effectiveness.

$$Var(OR) = \frac{(OR')^2\left[\frac{1}{N_{Observed,\ A}}+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]}{\left[1+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]} \tag{6.16}$$

where Var(OR) = variance of the unbiased estimated safety effectiveness.

$$SE(OR) = \sqrt{Var(OR)} \tag{6.17}$$

where SE(OR) = Standard error.

SE (Safety Effectiveness) = 100 × SE(OR) (6.18)

where SE (Safety Effectiveness) = standard error of safety effectiveness.

Table 6-11 summarizes the observed number of crashes, predicted number of crashes using SPFs, and the expected number of crashes for the before and after periods for each TWSC/OWSC intersection converted to a mini-roundabout. A detailed year-wise odds ratio computation is shown in Tables E-6(A) and E-6(B) in Appendix E. A similar approach was adopted for FI crashes and PDO crashes and the results are summarized in Tables 6-12 and 6-13, respectively.

Fifteen TWSC/OWSC intersections converted to mini-roundabouts were considered for the analysis. The odds ratio was observed to be equal to or greater than 1 at six TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.95 at the remaining nine TWSC/OWSC intersections converted to mini-roundabouts.

In the case of FI crashes, the odds ratio was observed to be equal to or greater than 1 at one TWSC/OWSC intersection converted to mini-roundabouts. It was observed to be less than 0.98 at the remaining fourteen TWSC/OWSC intersections converted to mini-roundabouts. A detailed year-wise odds ratio computation for FI crashes is shown in Tables E-7(A) and E-7(B) in Appendix E.

In the case of PDO crashes, the odds ratio was observed to be equal to or greater than 1 at eight TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.98 at the remaining seven TWSC/OWSC intersections converted to mini-roundabouts. A detailed year-wise odds ratio computation for PDO crashes is shown in Tables E-8(A) and E-8(B) in Appendix E.

At one mini-roundabouts (site ID #s 18), the odds ratio was equal to or greater than 1 for total crashes, FI crashes, and PDO crashes. Figure 6-2 shows the year-wise variation of odds ratio for total crashes. Year 1 is the first year after the construction of mini-roundabout. For example, if built year is 2015, year 1 is 2016. No specific trend in year-wise odds ratio variation was observed from the analysis.

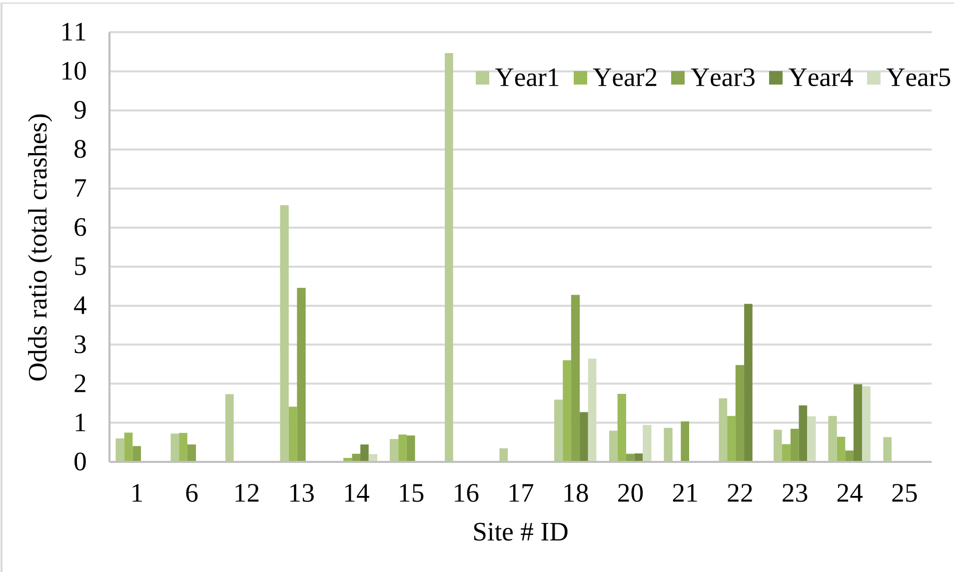


Figure 6-2. Odds ratio year-wise variation of total crashes - TWSC/OWSC intersections converted to mini-roundabouts.

The site ID #s 16, 13, and 18 have the highest odds ratio equal to 5.60, 3.81, and 2.38, respectively. At site ID # 16, the total number of crashes in the before period were zero. At site ID # 13, the eastbound approach has a four-lane undivided road. Also, at site ID # 18, the westbound approach has a four-lane undivided road. However, it was a two-lane undivided road in the before period.

Table 6-11. EB method analysis summary for total crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	Built year	Before period				After period				OR
		# of years	Obs. # of crashes	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	# of years	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	Obs. # of crashes	(Obs. / Exp.)
1	2016	5	56	20.13	49.85	3	19.81	49.05	27	0.55
6	2016	5	25	10.29	22.13	3	9.45	20.33	13	0.64
12	2018	5	12	10.95	11.80	1	2.14	2.31	4	1.73
13	2016	5	2	8.77	3.50	3	4.60	1.84	7	3.81
14*	2014	5	42	9.35	36.60	5	12.61	49.36	8	0.16
15	2016	5	36	28.11	35.36	3	16.96	21.33	14	0.66
16*	2017	5	0	1.36	0.78	2	0.62	0.36	2	5.60
17	2018	5	13	18.25	13.63	1	3.89	2.91	1	0.34
18	2013	5	13	5.00	10.33	5	8.76	18.09	43	2.38
20	2014	5	14	8.79	12.84	5	14.22	20.79	15	0.72
21	2016	5	9	7.68	8.53	3	6.97	7.75	5	0.65
22	2015	5	2	9.28	3.54	4	7.89	3.01	7	2.32
23^{Ψ}	2014	5	18	12.21	16.88	5	14.75	20.39	19	0.93
24^{Ψ}	2014	5	12	10.07	11.56	5	12.82	14.72	17	1.16
25^{Ψ}	2018	5	8	10.89	8.61	1	1.99	1.57	1	0.64

Note: *Three-legged, $^{\Psi}$OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

Table 6-12. EB method analysis summary for FI crashes (fatal and injury type A, B and C) - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	Built year	Before period				After period				OR
		# of years	Obs. # of crashes	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	# of years	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	Obs. # of crashes	(Obs. / Exp.)
1	2016	5	23	7.78	17.69	3	8.26	18.78	5	0.27
6	2016	5	6	3.82	5.23	3	3.85	5.27	2	0.38
12	2018	5	5	5.97	5.25	1	1.26	1.11	0	0.00
13	2016	5	1	4.66	2.13	3	2.39	1.10	0	0.00
14*	2014	5	5	1.29	2.81	5	2.85	6.21	0	0.00
15	2016	5	9	14.57	9.70	3	9.64	6.42	0	0.00
16*	2017	5	0	0.49	0.39	2	0.43	0.34	0	0.00
17	2018	5	8	8.33	8.07	1	1.51	1.46	0	0.00
18	2013	5	2	1.80	1.89	5	4.13	4.34	7	1.61
20	2014	5	5	3.77	4.56	5	6.95	8.40	2	0.24
21	2016	5	6	3.90	4.91	3	2.10	2.65	2	0.75
22	2015	5	2	4.21	2.73	4	3.74	2.43	2	0.82
23^{Ψ}	2014	5	3	3.48	3.18	5	4.45	4.07	4	0.98
24^{Ψ}	2014	5	2	2.39	2.18	5	3.31	3.02	2	0.66
25^{Ψ}	2018	5	3	2.57	2.80	1	0.43	0.47	0	0.00

Note: *Three-legged, $^{\Psi}$OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

Table 6-13. EB method analysis summary for PDO crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	Built year	Before period				After period				OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	# of years	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	Obs. # of crashes	
1	2016	5	33	12.34	27.79	3	11.59	26.10	22.00	0.84
6	2016	5	19	6.47	15.51	3	5.44	13.03	11.00	0.84
12	2018	5	7	5.07	6.36	1	0.86	1.07	4.00	3.72
13	2016	5	1	4.16	2.19	3	2.19	1.15	7.00	6.08
14*	2014	5	37	7.91	31.48	5	9.60	38.21	8.00	0.21
15	2016	5	27	14.16	25.07	3	7.57	13.40	14.00	1.04
16*	2017	5	0	0.82	0.57	2	0.42	0.29	2.00	6.96
17	2018	5	5	10.08	6.01	1	2.29	1.37	1.00	0.73
18	2013	5	11	3.19	7.57	5	4.56	10.83	36.00	3.32
20	2014	5	9	5.07	7.70	5	7.38	11.21	13.00	1.16
21	2016	5	3	3.80	3.42	3	4.88	4.39	3.00	0.68
22	2015	5	0	5.11	1.68	4	4.09	1.34	5.00	3.73
23^{Ψ}	2014	5	15	8.98	13.11	5	10.47	15.27	15.00	0.98
24^{Ψ}	2014	5	10	7.75	9.22	5	9.45	11.24	15.00	1.33
25^{Ψ}	2018	5	5	8.25	6.08	1	1.56	1.15	1.00	0.87

Note: *Three-legged, $^{\Psi}$OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

6.5 Analysis and Comparison of the Safety Effectiveness Computed from HSM SPFs and Jurisdiction-Specific SPFs for TWSC/OWSC Intersections Converted to Mini-Roundabouts

As stated previously, a minimum of three years crash data is recommended for SPF development in the SPF decision guide (Srinivasan et al., 2013). The HSM suggests use of SPFs to predict long-term expected average number of crashes to address regression-to-mean bias. However, the safety effectiveness may vary based on the calibrated HSM SPFs and developed jurisdiction-specific SPFs using 3 years, 5 years and 9 years of crash data. It may also vary with developed jurisdiction-specific SPFs calibrated year-wise to account for temporal variation (due to advancement in automobile technologies focused on traffic safety, policies such as vision zero plan and socio-demographic changes).

Since the SPFs for OWSC (ramp) were not available in the HSM (AASHTO, 2010), the remaining twelve TWSC/OWSC intersections were used for safety effectiveness comparison. Crash data for 3, 5, 7 and 9 year was used for jurisdiction-specific SPF development. Calibration factors for the remaining year were computed separately based on intersection geometric configuration (four-legged/three-legged), control type, and crash severity type. For example, if 3 year crash data (2011-2013) was used for SPF development, calibration factors were computed for the remaining year (2014-2019). The safety effectiveness was computed and compared using:

a) calibrated HSM SPFs year-wise,

b) non-calibrated HSM SPFs,

c) developed jurisdiction-specific SPFs from 3 year crash data and year-wise calibration,

d) developed jurisdiction-specific SPFs from 3 year crash data and no year-wise calibration,

e) developed jurisdiction-specific SPFs from 5 year crash data and year-wise calibration,

f) developed jurisdiction-specific SPFs from 5 year crash data and no year-wise calibration,

g) developed jurisdiction-specific SPFs from 7 year crash data and year-wise calibration,

h) developed jurisdiction-specific SPFs from 7 year crash data and no year-wise calibration, and

i) developed jurisdiction-specific SPFs from 9 year crash data.

Table 6-14 shows the expected number of crashes in after period by severity type computed considering HSM SPFs (calibrated and non-calibrated) and jurisdiction-specific SPFs (calibrated and non-calibrated). The expected number of total crashes varied from 154.96 crashes to 197.12 crashes in the after period. Thus, the odds ratio for total crashes varied from 0.94 to 0.74, a 20.00 difference in the safety effectiveness estimates.

When results from year-wise calibrated HSM SPFs are compared with non-calibrated HSM SPFs, a 12.61 difference in safety effectiveness estimate was observed for the total crashes. Likewise, when results from jurisdiction-specific SPFs are compared with year-wise calibration and no calibration, a 7.48, and a 13.53 difference in safety effectiveness estimated was observed from 3 year and 5 year crash data, respectively. The difference was marginal (0.78) for 7 year crash data. It may be noted that the expected number of total crashes were higher when both HSM SPFs and jurisdiction-specific SPFs are calibrated when compared to non-calibrated SPFs, inferring that the safety benefits are estimated higher when calibration factors are considered in computing safety effectiveness estimate. Further, a difference ranged between 3.37 to 6.34 in safety effectiveness estimate was observed when jurisdiction-specific SPFs developed for different time period data (3, 5, 7 and 9 year) are compared. This difference ranged between 0.29 to 13.21 was observed when SPFs were calibrated for subsequent years. The difference was lowest (0.29) for 3 year and 5 year of crash data calibrated year-wise, and highest (13.21) for 3 year of crash data calibrated year-wise and 9 year of crash data. Similar trends were observed for FI and PDO crash safety effectiveness estimate (Figure 6-3). A two-tailed t-test was conducted to examine the statistical significance of difference between the safety effectiveness estimates. The null hypothesis was defined as the no difference between the safety effectiveness estimates computed from HSM SPFs and jurisdiction-specific SPFs. The alternate hypothesis was defined as the safety effectiveness estimates differs significantly at a 95% confidence level. The computed t-statistic was less than t-critical 2.20, indicating the difference between the safety effectiveness estimates was not statistically significant.

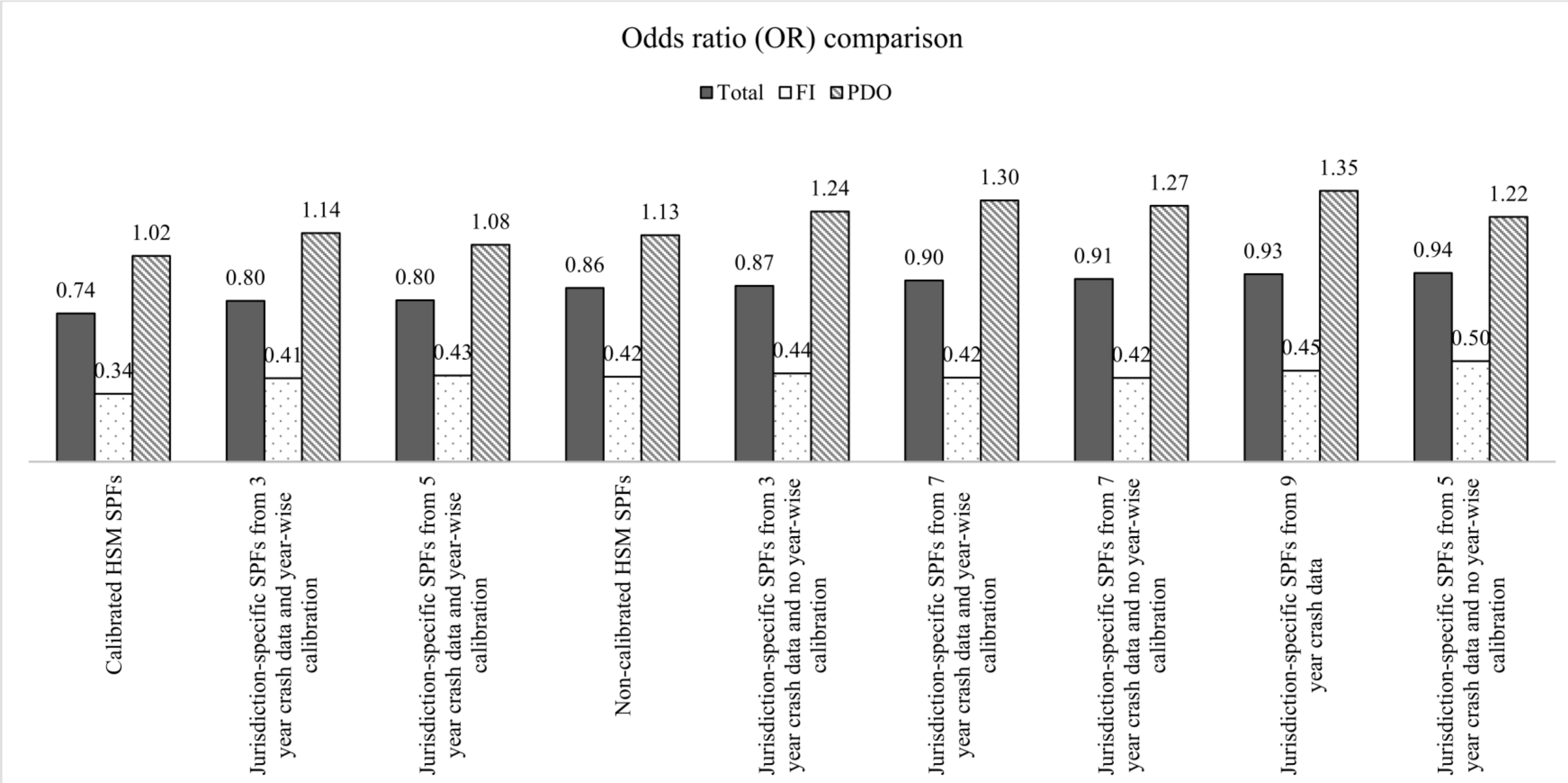


Figure 6-3. Odds ratio comparison for total, FI and PDO crashes computed from HSM and jurisdiction-specific SPFs – twelve TWSC/OWSC intersections converted to mini-roundabouts.

Table 6-14. Expected number of crashes in the after period computed from HSM and jurisdiction-specific SPFs – twelve TWSC/OWSC intersections converted to mini-roundabouts.

Crash severity type	Exp. # of crashes in after period									Obs. # of crashes in after period
	HSM SPFs		Jurisdiction-specific SPFs							
	Calibrated year-wise	Non-calibrated	3 year crash data and year-wise calibration	3 year crash data and no year-wise calibration	5 year crash data and year-wise calibration	5 year crash data and no year-wise calibration	7 year crash data and year-wise calibration	7 year crash data and no year-wise calibration	9 year crash data	
Total	197.12	168.32	181.74	166.21	181.07	154.96	161.44	160.06	155.99	146
FI	58.54	46.79	47.87	45.19	46.21	39.62	47.30	47.42	43.65	20
PDO	122.39	111.12	110.24	100.70	116.11	102.92	96.43	98.52	93.07	126

Note: Computed expected crashes are excluding OWSC (ramp).

Table 6-15. Odds ratio and safety effectiveness estimate computed from HSM and jurisdiction-specific SPFs summary – twelve TWSC/OWSC intersections converted to mini-roundabouts.

Crash severity type	Estimate	HSM SPFs		Jurisdiction-specific SPFs						
		Calibrated year-wise	Non-calibrated	3 year crash data and year-wise calibration	3 year crash data and no year-wise calibration	5 year crash data and year-wise calibration	5 year crash data and no year-wise calibration	7 year crash data and year-wise calibration	7 year crash data and no year-wise calibration	9 year crash data
Total	OR (Obs. / Exp.)	0.74	0.86	0.80	0.87	0.80	0.94	0.90	0.91	0.93
	Standard error (OR)	0.08	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10
	Safety effectiveness SE (%)	26.27	13.66	20.02	12.55	19.73	6.21	9.97	9.18	6.81
	Standard error SE (%)	7.90	9.28	8.54	9.32	8.58	10.02	9.59	9.65	9.91
FI	OR (Obs. / Exp.)	0.34	0.42	0.41	0.44	0.43	0.50	0.42	0.42	0.45
	Standard error (OR)	0.08	0.11	0.10	0.11	0.11	0.12	0.10	0.10	0.11
	Safety effectiveness SE (%)	66.25	57.77	58.57	56.12	57.14	50.04	58.20	58.31	54.70
	Standard error SE (%)	8.47	10.59	10.06	10.66	10.52	12.34	10.43	10.41	11.31
PDO	OR (Obs. / Exp.)	1.02	1.13	1.14	1.24	1.08	1.22	1.30	1.27	1.35
	Standard error (OR)	0.12	0.14	0.13	0.15	0.13	0.15	0.15	0.15	0.16
	Safety effectiveness SE (%)	-2.31	-12.67	-13.63	-24.39	-7.82	-21.66	-29.92	-27.16	-34.62
	Standard error SE (%)	12.23	13.54	13.36	14.70	13.00	14.58	15.24	14.93	15.74

Note: Computed estimates are excluding OWSC (ramp).

6.6 Effectiveness Computation for All-Way Stop-Controlled (AWSC) Intersections Converted to Mini-Roundabouts

The AWSC control type was consistently applied and did not change at the selected mini-roundabouts during the considered before periods. In other words, it was applied as a long term traffic control in the before periods (not as an interim solution) at the selected AWSC intersections converted to mini-roundabouts.

As stated previously, jurisdiction-specific SPFs were developed for total crashes, FI crashes, and PDO crashes at AWSC intersections. They were developed for Georgia, Michigan, Minnesota, and Washington State. SPF regression coefficients and overdispersion parameter were then used for EB before and after analysis. The regression coefficients, overdispersion parameter and goodness-of-fit measures summary is shown in Tables 6-6 to 6-9.

Tables 6-16 to 6-18 summarize the observed number of crashes, predicted number of crashes using SPFs, and the expected number of crashes for the before and after periods for each AWSC intersection converted to a mini-roundabout. A detailed year-wise odds ratio computation for AWSC intersections converted to mini-roundabouts is shown in Tables E-9 to E-11 in Appendix E. The expected number of crashes shown in the abovementioned tables are computed from jurisdiction-specific SPFs developed from 3 year crash data and calibrated year-wise for the subsequent years.

Overall, ten AWSC intersections converted to mini-roundabouts were considered for analysis. In the case of total crashes, the odds ratio was observed to be equal to or greater than 1 at nine AWSC intersections converted to mini-roundabouts. It was observed to be less than 1 at one AWSC intersection converted to a mini-roundabout. In the case of FI crashes, the odds ratio was observed to be equal to or greater than 1 at nine AWSC intersections converted to mini-roundabouts but less than 0.50 at one AWSC intersection converted to a mini-roundabout. In the case of PDO crashes, the odds ratio was observed to be equal to or greater than 1 at nine AWSC intersections converted to mini-roundabouts but less than 0.50 at one AWSC intersection converted to a mini-roundabout. At eight mini-roundabouts (site ID #s 2, 3, 4, 5, 9, 10, 11 and 19), the odds ratio was equal to or greater than 1 for total crashes, FI crashes, and PDO crashes. Figure 6-4 shows the year-wise variation of odds ratio for total crashes. No specific trend in year-wise odds ratio variation was observed from the analysis.

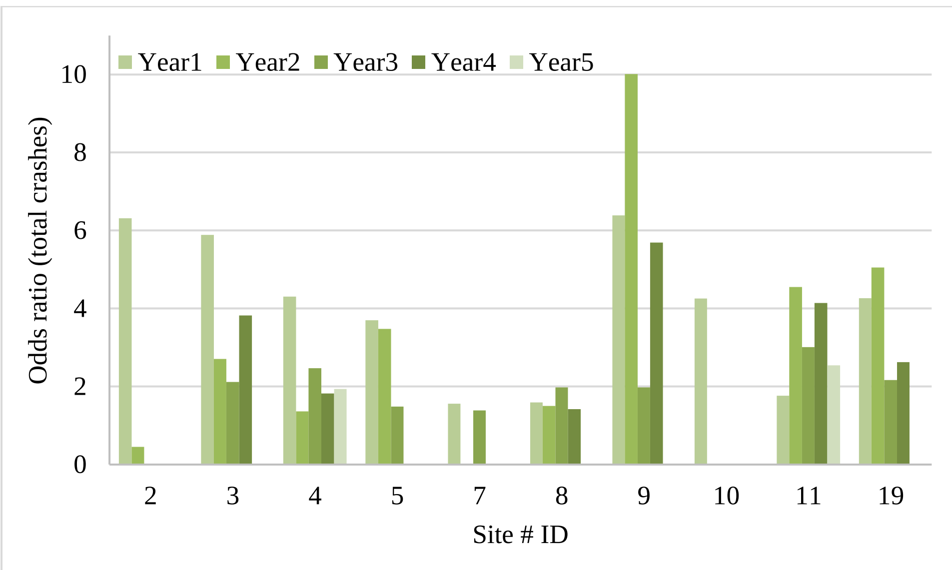


Figure 6-4. Odds ratio year-wise variation of total crashes – AWSC intersections converted to mini-roundabouts.

At one mini-roundabout (site ID # 7), the odds ratio was less than 1 for total crashes and PDO crashes but greater than 1 for FI crashes. It may be noted that the odds ratio was less than 1 for only site ID # 7, indicating that the mini-roundabout design was effective in reducing total and PDO crashes. At this mini-roundabout, the eastbound approach has an unpaved road. Further, at site ID # 19, the satellite images of year 2020 shows that the mini-roundabout was converted to AWSC intersection.

Table 6-16. EB method analysis summary for total crashes – AWSC intersections converted to mini-roundabouts.

Site ID	Built year	Before period				After period				OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	# of years	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	Obs. # of crashes	
2	2017	5	8	10.59	8.61	2	4.48	3.64	10.00	2.75
3	2015	5	18	18.41	18.06	4	19.51	19.15	69.00	3.60
4	2013	5	18	16.89	17.82	5	22.88	24.13	56.00	2.32
5	2016	5	42	31.28	40.99	3	23.47	30.76	85.00	2.76
7	2016	5	3	16.51	5.61	3	11.94	4.05	4.00	0.99
8	2015	5	8	14.32	9.37	4	12.24	8.01	13.00	1.62
9	2015	5	9	13.70	10.05	4	10.91	8.01	48.00	5.99
10	2018	5	12	14.00	12.44	1	3.17	2.82	12.00	4.26
11	2014	5	18	9.56	16.11	5	10.02	16.88	53.00	3.14
19	2015	5	23	6.63	18.16	4	6.13	16.79	57.00	3.40

Note: OR = 0 indicates observed # of crashes in the after period is zero.

Table 6-17. EB method analysis summary for FI crashes (fatal and injury type A, B and C) – AWSC intersections converted to mini-roundabouts.

Site ID	Built year	Before period				After period				OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	# of years	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	Obs. # of crashes	
2	2017	5	2	2.75	2.43	2	0.86	0.76	3.00	3.95
3	2015	5	6	4.95	5.55	4	4.78	5.36	17.00	3.17
4	2013	5	6	4.55	5.35	5	5.45	6.42	11.00	1.71
5	2016	5	8	8.22	8.07	3	5.25	5.16	9.00	1.75
7	2016	5	0	2.29	1.16	3	1.60	0.81	2.00	2.46
8	2015	5	2	2.63	2.30	4	2.41	2.11	1.00	0.47
9	2015	5	2	2.30	2.15	4	1.56	1.46	3.00	2.06
10	2018	5	3	2.56	2.79	1	0.79	0.86	1.00	1.17
11	2014	5	5	2.69	3.51	5	2.69	3.51	6.00	1.71
19	2015	5	7	2.05	5.05	4	1.89	4.66	9.00	1.93

Note: OR = 0 indicates observed # of crashes in the after period is zero.

Table 6-18. EB method analysis summary for PDO crashes – AWSC intersections converted to mini-roundabouts.

Site ID	Built year	Before period				After period				OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	# of years	Pred. # of crashes using SPF and calibration factor	Exp. # of crashes	Obs. # of crashes	
2	2017	5	6	8.98	6.95	2	3.18	2.46	7.00	2.84
3	2015	5	12	13.98	12.46	4	13.76	12.26	52.00	4.24
4	2013	5	12	13.06	12.26	5	18.03	16.93	45.00	2.66
5	2016	5	34	23.96	32.50	3	15.07	20.44	76.00	3.72
7	2016	5	3	13.88	5.73	3	10.22	4.22	2.00	0.47
8	2015	5	6	11.45	7.58	4	9.87	6.53	12.00	1.84
9	2015	5	7	11.17	8.23	4	9.28	6.83	45.00	6.59
10	2018	5	9	11.38	9.69	1	2.44	2.07	11.00	5.30
11	2014	5	13	7.02	11.88	5	7.47	12.64	47.00	3.72
19	2015	5	16	4.42	10.37	4	4.17	9.79	48.00	4.90

Note: OR = 0 indicates observed # of crashes in the after period is zero.

6.7 Analysis and Comparison of the Safety Effectiveness Computed from HSM SPFs and Jurisdiction-Specific SPFs for AWSC Intersections Converted to Mini-Roundabouts

The safety effectiveness of AWSC converted to mini-roundabouts was computed and compared using:

a) developed jurisdiction-specific SPFs from 3 year crash data and year-wise calibration,

b) developed jurisdiction-specific SPFs from 3 year crash data and no year-wise calibration,

c) developed jurisdiction-specific SPFs from 5 year crash data and year-wise calibration,

d) developed jurisdiction-specific SPFs from 5 year crash data and no year-wise calibration,

e) developed jurisdiction-specific SPFs from 7 year crash data and year-wise calibration,

f) developed jurisdiction-specific SPFs from 7 year crash data and no year-wise calibration,

g) developed jurisdiction-specific SPFs from 9 year crash data, and

Table 6-19 shows the expected number of crashes in the after period by severity type computed using jurisdiction-specific SPFs (calibrated and non-calibrated). The expected number of total crashes varied from 124.84 crashes to 134.23 crashes in the after period. Thus, the odds ratio for total crashes varied from 3.24 to 3.01, a 22.64 difference in the safety effectiveness estimates.

A 22.64, 18.57, and 15.40 difference in safety effectiveness estimate was observed for total crashes when jurisdiction-specific SPFs with year-wise calibration and no calibration are compared for 3, 5 and 7 year of crash data, respectively. Similar to TWSC/OWSC analysis based observation, the expected number of total crashes were higher when results using calibration factor for jurisdiction-specific SPFs are compared to non-calibrated SPFs, inferring that the safety benefits are estimated higher when calibration factors are considered in computing safety effectiveness estimate. Further, a 16.22 difference in safety effectiveness estimate was observed when jurisdiction-specific SPFs developed for different time period data (3 year and 9 year) are compared. This difference was lower (6.43) when SPFs developed from 3 year of crash data was calibrated for subsequent years. Thus, it can be inferred that calibration of jurisdiction-specific SPFs for subsequent years yields different safety estimates. This difference was marginal ranged between 0.07 to 1.09 when safety effectiveness estimate for time period 3, 5 and 7 year are compared. Similar trends were observed for FI and PDO crash safety effectiveness estimate (Figure 6-5).

A two-tailed t-test was conducted to examine the statistical significance of difference between the safety effectiveness estimates. The null hypothesis was defined as the no difference between the safety effectiveness estimates computed from jurisdiction-specific SPFs year-wise calibrated and non-calibrated for subsequent years. The alternate hypothesis was defined as the safety effectiveness estimates differs significantly at a 95% confidence level. When the safety effectiveness estimates for total crashes from jurisdiction-specific SPFs developed from 3 year crash data year-wise and calibrated (OR = 3.01) are compared with non-calibrated (OR = 3.24) for subsequent years, the computed t-statistic was 4.75, greater than the t-critical value = 2.26 (p-value less than 0.01). This indicates that the difference between the safety effectiveness estimates are statistically significant. For other combinations of safety effectiveness estimates, t-statistic was less than t-critical, indicating that the difference between the safety effectiveness estimates was not statistically significant.

Table 6-19. Expected number of crashes in the after period computed from HSM and jurisdiction-specific SPFs – AWSC intersections converted to mini-roundabouts.

Crash severity type	Exp. # of crashes in after period							Obs. # of crashes in after period
	Jurisdiction-specific SPFs							
	3 year crash data and year-wise calibration	3 year crash data and no year-wise calibration	5 year crash data and year-wise calibration	5 year crash data and no year-wise calibration	7 year crash data and year-wise calibration	7 year crash data and no year-wise calibration	9 year crash data	
Total	134.23	124.84	132.97	125.31	131.12	124.89	131.51	407
FI	31.11	31.04	30.67	32.05	29.69	30.45	32.01	62
PDO	94.17	92.89	101.57	91.90	100.97	93.45	99.36	345

Table 6-20. Odds ratio and safety effectiveness estimate computed from HSM and jurisdiction-specific SPFs summary – AWSC intersections converted to mini-roundabouts.

Crash severity type	Estimate	Jurisdiction-specific SPFs						
		3 year crash data and year-wise calibration	3 year crash data and no year-wise calibration	5 year crash data and year-wise calibration	5 year crash data and no year-wise calibration	7 year crash data and year-wise calibration	7 year crash data and no year-wise calibration	9 year crash data
Total	OR (Obs. / Exp.)	3.01	3.24	3.04	3.23	3.09	3.24	3.08
	Standard error (OR)	0.27	0.30	0.27	0.29	0.27	0.29	0.27
	Safety effectiveness SE (%)	-201.45	-224.10	-204.44	-223.01	-208.78	-224.17	-207.88
	Standard error SE (%)	27.48	29.72	27.09	28.93	27.17	28.67	26.98
FI	OR (Obs. / Exp.)	1.96	1.97	1.99	1.90	2.06	2.01	1.91
	Standard error (OR)	0.35	0.36	0.36	0.34	0.36	0.36	0.34
	Safety effectiveness SE (%)	-96.20	-96.61	-98.90	-90.38	-105.75	-100.61	-90.90
	Standard error SE (%)	35.40	35.57	36.19	34.43	36.50	35.63	33.73
PDO	OR (Obs. / Exp.)	3.64	3.69	3.38	3.73	3.40	3.67	3.45
	Standard error (OR)	0.37	0.37	0.33	0.36	0.33	0.35	0.33
	Safety effectiveness SE (%)	-263.68	-268.71	-237.51	-272.95	-239.56	-266.85	-245.12
	Standard error SE (%)	36.87	37.41	32.63	36.43	32.53	35.33	32.87

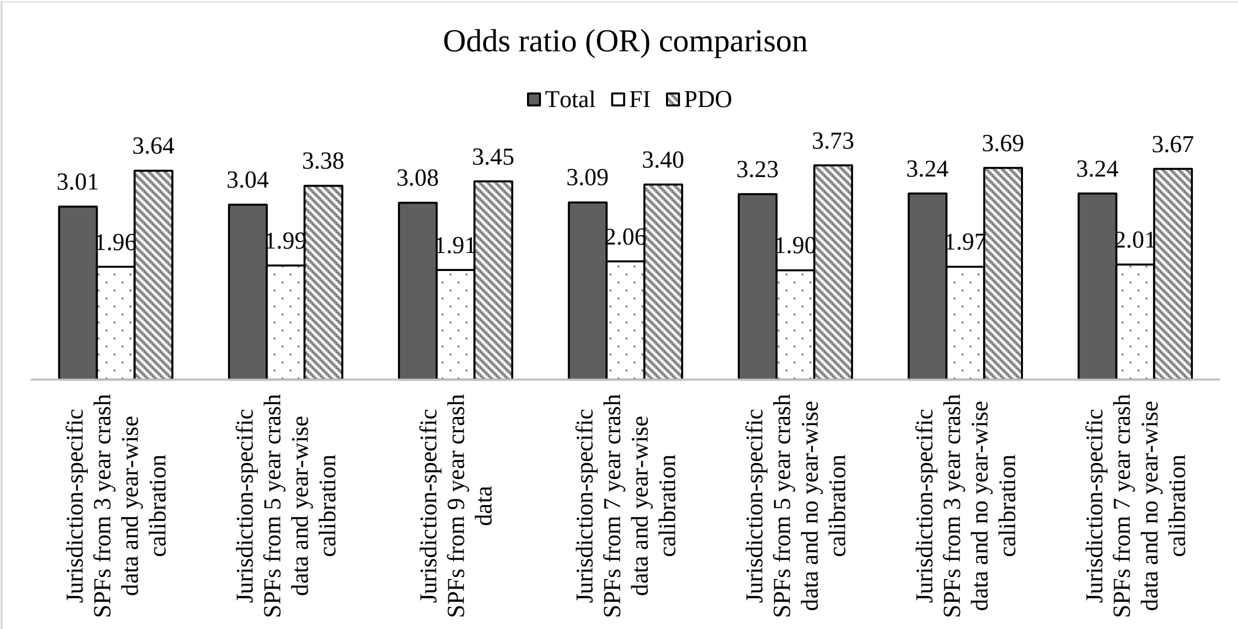


Figure 6-5. Odds ratio comparison for total, FI and PDO crashes computed from jurisdiction-specific SPFs – AWSC intersections converted to mini-roundabouts.

6.8 EB Before and After Analysis Summary

Table 6-21 summarize results from the EB method. The results are summarized based on calibrated HSM SPFs (TWSC and OWSC), and year-wise calibrated developed jurisdiction-specific SPFs (OWSC (ramp) and AWSC). A 22.03% decrease in total crashes, a 61.08% decrease in FI crashes, and a 4.11% increase in PDO crashes was observed when TWSC/OWSC intersections were converted to mini-roundabouts. The standard error was 7.56% in total crashes, 8.72% in FI crashes, and 11.18% in PDO crashes. The ratio of the absolute value of safety effectiveness to standard error of safety effectiveness gives statistical significance. This ratio was greater than 2 for total crashes and FI crashes, indicating safety effectiveness (positive - treatment is effective) was statistically significant at a 95% confidence level. However, the ratio was less than 2 in the case of PDO crashes, indicating that mini-roundabout installation is not effective in reducing PDO crashes (not statistically significant at a 95% confidence level).

A 201.05% increase in total crashes, a 96.20% increase FI crashes, and a 263.68% increase in PDO crashes was observed when AWSC intersections were converted to mini-roundabouts. The standard error was 27.48% in total crashes, 35.40% in FI crashes, and 36.87% in PDO crashes. The ratio of absolute value of safety effectiveness to standard error of safety effectiveness was greater than 2 for total crashes, FI crashes, and PDO crashes, indicating that the mini-roundabout installation is not effective (statistically significant at a 95% confidence level).

Table 6-21. EB analysis summary.

Crash severity type	Odds ratio (OR)	Standard error (OR)	Safety effectiveness (%)	Standard error (safety effectiveness)	Abs [Safety effectiveness/Standard error (safety effectiveness)]	Statistical significance
15 TWSC/OWSC intersections converted to mini-roundabouts						
Total	0.78	0.08	22.03	7.56	2.92	Significant at 95% confidence level
FI	0.39	0.09	61.08	8.72	7.00	Significant at 95% confidence level
PDO	1.04	0.11	-4.11	11.18	0.37	Not significant
10 AWSC intersections converted to mini-roundabouts						
Total	3.01	0.27	-201.45	27.48	7.33	Significant at 95% confidence level
FI	1.96	0.35	-96.20	35.40	2.72	Significant at 95% confidence level
PDO	3.64	0.37	-263.68	36.87	7.15	Significant at 95% confidence level

Table 6-22 shows the number of intersections with odds ratio less than 1, and greater than or equal to 1. The results are summarized based on calibrated HSM SPFs (TWSC and OWSC), and year-wise calibrated developed jurisdiction-specific SPFs (OWSC (ramp) and AWSC). When TWSC/OWSC intersections are converted to mini-roundabouts, the installation of mini-roundabouts was found to be effective in the reduction of total crashes at 60% of the selected sites (9 out of 15). They are found to be more effective in the reduction of FI crashes - at 90% of the selected sites (14 out of 15). However, they are found to be less effective in the reduction of PDO crashes - at less than 50% of sites (7 out of 15). When AWSC intersections converted to mini-roundabouts, the installation of mini-roundabouts was found to be effective at only 10% of the selected sites (1 out of 10) for total, FI and PDO crashes.

Table 6-22. EB method summary - # of intersections with odds ratio less than 1, and greater or equal to 1.

Prior control type	Crash severity type	# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1
TWSC/OWSC	Total	9	6
	FI	14	1
	PDO	7	8
AWSC	Total	1	9
	FI	1	9
	PDO	1	9

CHAPTER 7 EFFECT OF TRAFFIC, GEOMETRIC, ON-NETWORK AND OFF-NETWORK CHARACTERISTICS ON SAFETY AT MINI-ROUNDABOUTS

An analysis was conducted to identify characteristics that may affect the safety effectiveness of mini-roundabouts. Also, how the crashes at mini-roundabouts are related to traffic characteristics and on-network and off-network characteristics was examined. The scatter plots and heat maps are used to examine the trend between the selected mini-roundabout characteristics and odds ratio. The statistical significance of the trends was evaluated using the Pearson correlation coefficient analysis.

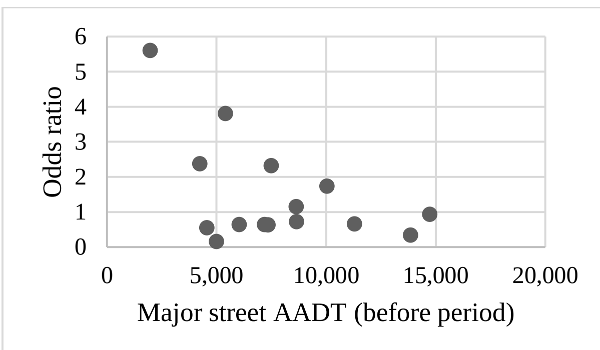
7.1 Examining the Effect of Traffic, On-Network and Off-Network Characteristics on the Safety Effectiveness

The results summarizing the effect of various characteristics on the safety effectiveness of mini-roundabouts are discussed next.

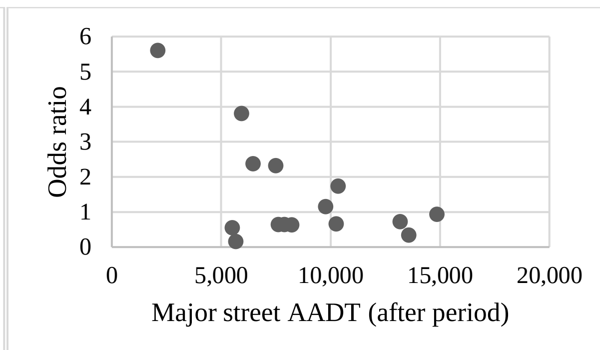
7.1.1 Effect of Traffic Volume on the Safety Effectiveness

The effect of traffic volume on the safety effectiveness was examined using scatter plots. Figure 7-1 shows the scatter plots between odds ratio and before and after period traffic volume (major-street volume, cross-street volume, and cross-street volume share) for TWSC/OWSC intersections converted to mini-roundabouts. No specific trend between the odds ratio with major street and cross-street traffic volume was observed. The odds ratio was less than one for a wide range of major street and cross-street traffic volumes. This indicates that the conversion of a TWSC/OWSC intersection to a mini-roundabout could be effective for the range of major road and cross-street traffic volumes considered in this research. A high odds ratio was observed in the case of before period cross-street volume share at around 0.4.

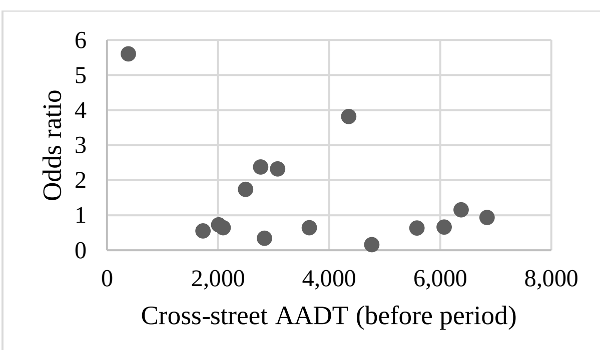
Figure 7-2 shows the scatter plots between the odds ratio and before and after period traffic volume (major-street volume, cross-street volume, and cross-street volume share) for AWSC intersections converted to mini-roundabouts. No specific trend between the odds ratio with major street and cross-street traffic volume was observed. Also, no specific trend between the odds ratio and cross-street volume share was observed.



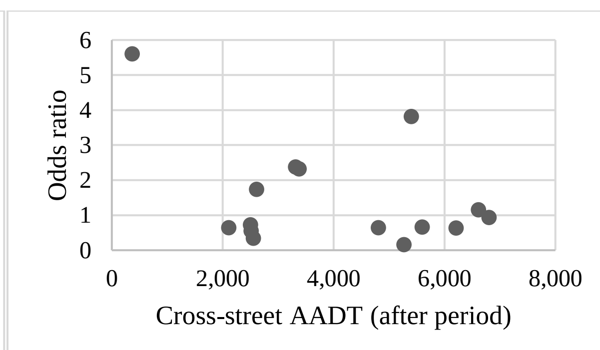
(a) Major street AADT (before period)



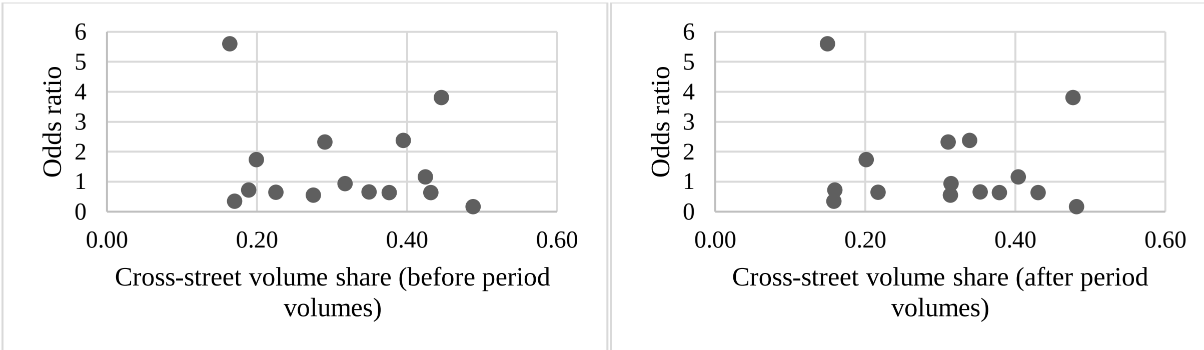
(b) Major street AADT (after period)



(c) Cross-street AADT (before period)



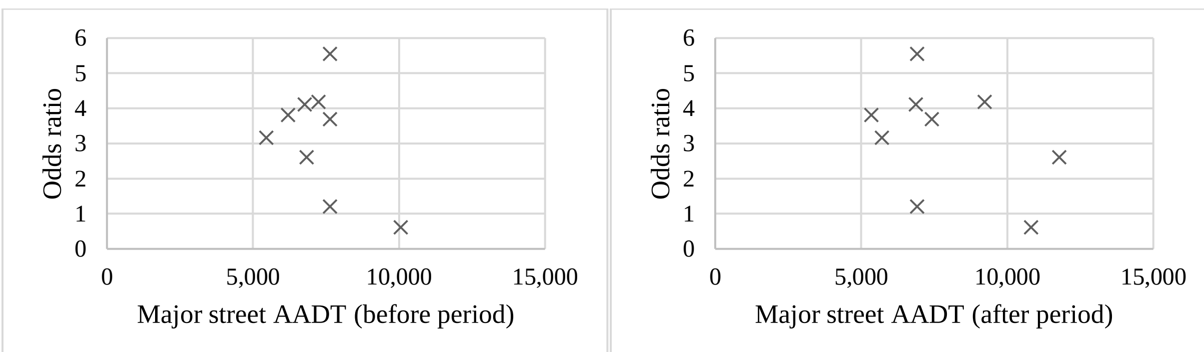
(d) Cross-street AADT (after period)



(e) Cross-street share (before period)

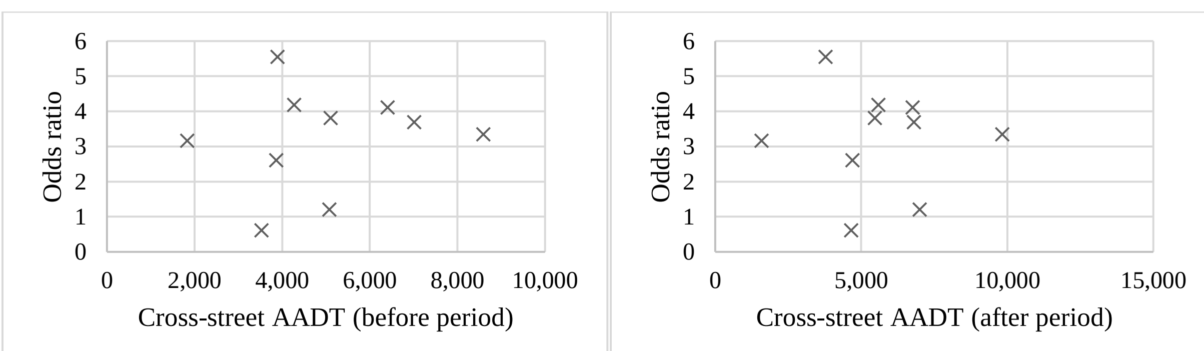
(f) Cross-street share (after period)

Figure 7-1. Scatterplot between odds ratio and AADT for TWSC/OWSC intersections converted to mini-roundabouts.



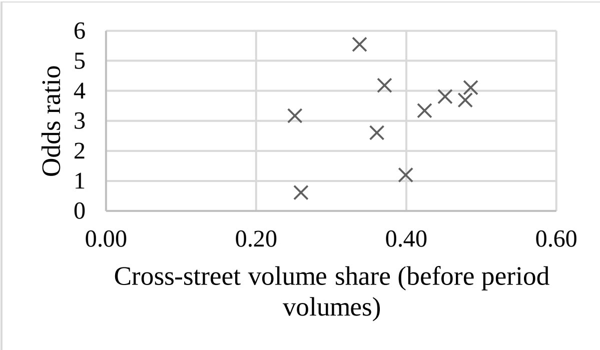
(a) Major street AADT (before period)

(b) Major street AADT (after period)

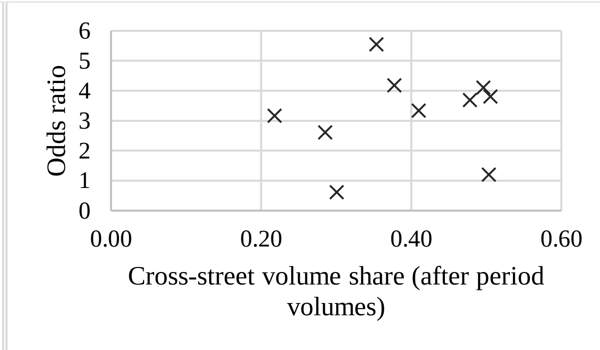


(c) Cross-street AADT (before period)

(d) Cross-street AADT (after period)



(e) Cross-street share (before period)



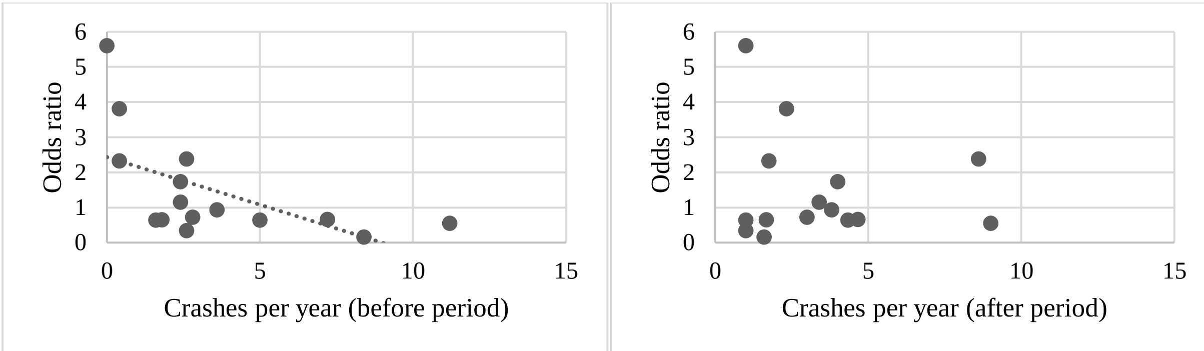
(f) Cross-street share (after period)

Figure 7-2. Scatterplot between odds ratio and AADT for AWSC intersections converted to mini-roundabouts.

7.1.2 Effect of Before and After Period Crashes on the Safety Effectiveness

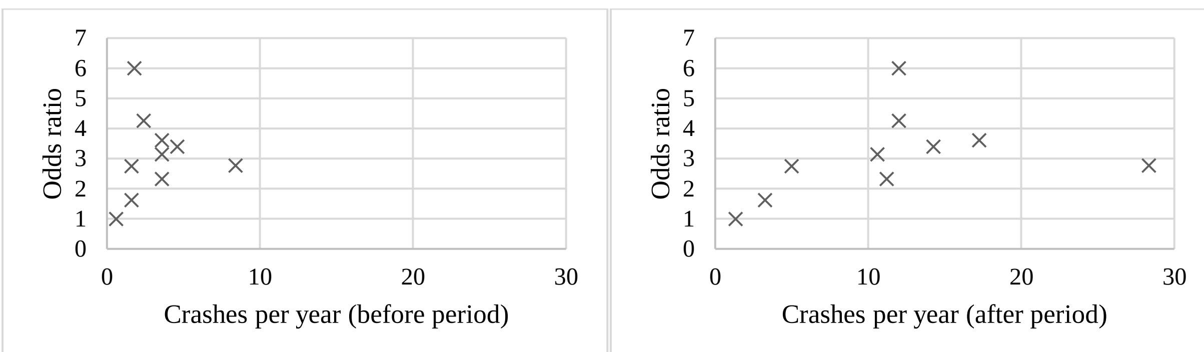
The effect of before period crash history on the safety effectiveness was examined using scatter plots. Figure 7-3 shows the scatter plots between the odds ratio and before period crashes per year for TWSC/OWSC intersections converted to mini-roundabouts. A negative trend was observed for the odds ratio and crashes per year in the before period. However, no specific trend was observed for the odds ratio and crashes per year in the after period.

For AWSC intersections converted to mini-roundabouts, Figure 7-4 (b) shows a positive trend between the odds ratio and after period crashes.



(a) Crashes per year (before period) (b) Crashes per year (after period)

Figure 7-3. Scatter plot between odds ratio and crashes for TWSC/OWSC intersections converted to mini-roundabouts.

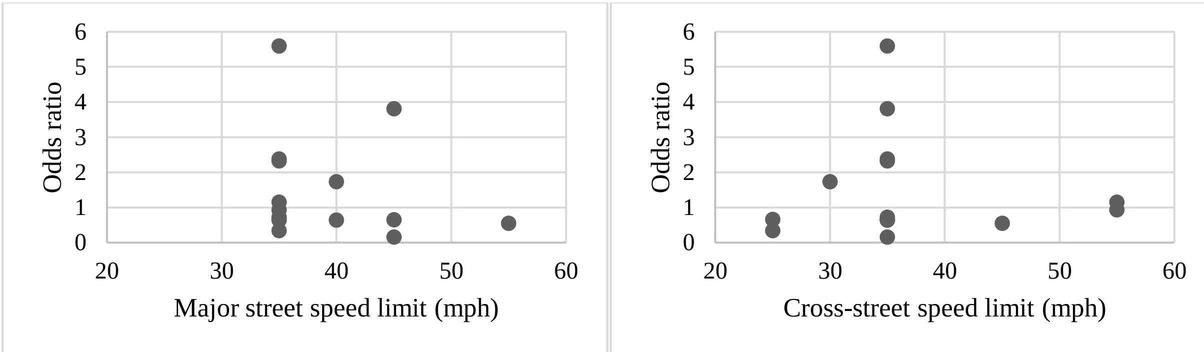


(a) Crashes per year (before period) (b) Crashes per year (after period)

Figure 7-4. Scatter plot between odds ratio and crashes for AWSC intersections converted to mini-roundabouts.

7.1.3 Effect of Speed Limit on the Safety Effectiveness

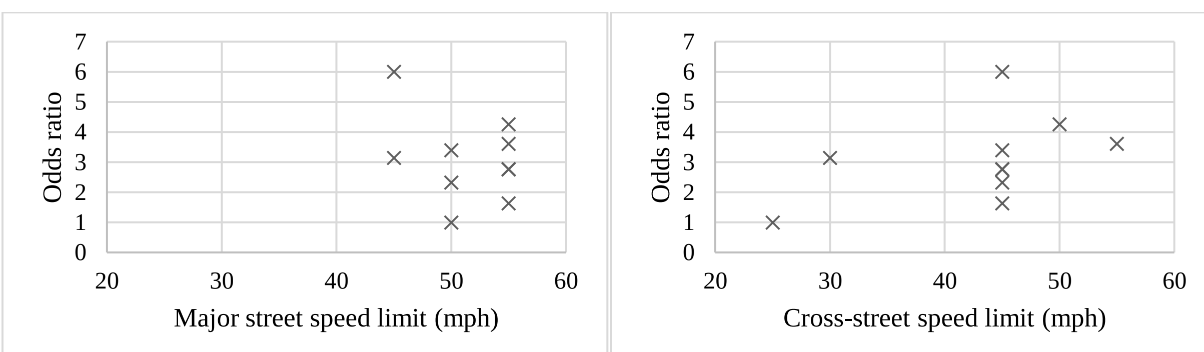
Figure 7-5 shows the effect of the speed limit on the odds ratio for TWSC/OWSC intersections converted to mini-roundabouts. No specific trend was observed between the odds ratio and major street and cross-street speed limits. However, an odds ratio of less than one was observed for all the speed limits at major streets, ranging from 35 to 55 mph.



(a) Major street speed limit (b) Cross-street speed limit

Figure 7-5. Scatter plot between odds ratio and speed limit for TWSC/OWSC intersections converted to mini-roundabouts.

Figure 7-6 shows the effect of speed limit on the odds ratio for AWSC intersections converted to mini-roundabouts. No specific trend was observed between the odds ratio and major street speed limit. However, a positive trend can be seen between the odds ratio and cross-street speed limit, indicating that safety effectiveness decreases with an increase in cross-street speed limit.



(a) Major street speed limit (b) Cross-street speed limit

Figure 7-6. Scatter plot between odds ratio and speed limit for AWSC intersections converted to mini-roundabouts.

7.1.4 Effect of Area Type and Land use on the Safety Effectiveness

The odds ratio was observed to be less than 1 at three out of four TWSC/OWSC intersections when converted to mini-roundabouts in rural areas. Similarly, the odds ratio was observed to be less than 1 at six out of eleven TWSC/OWSC intersections when converted to mini-roundabouts in urban/suburban areas (Figure 7-7). The odds ratio was observed to be greater than 1 when AWSC intersections were converted to mini-roundabouts in both rural and urban/suburban areas, except at one intersection located in urban/suburban area. The majority of the mini-roundabouts were located in the urban/suburban areas (Figure7-8).

While looking into the land use types, the majority of the mini-roundabouts were installed in mixed land use areas. No specific trend between land use and odds ratio was observed for TWSC/OWSC and AWSC intersections converted to mini-roundabouts (Figure 7-9).

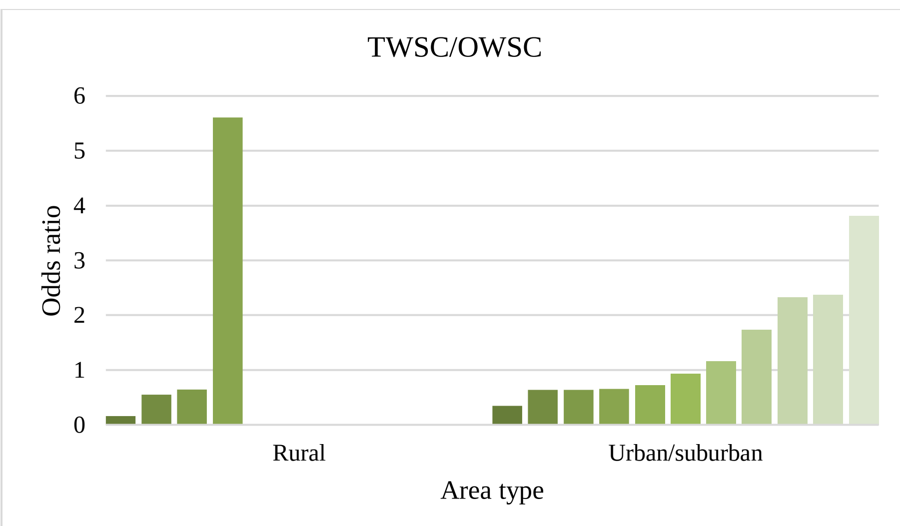


Figure 7-7. Odds ratio and area type for TWSC/OWSC intersections converted to mini-roundabouts.

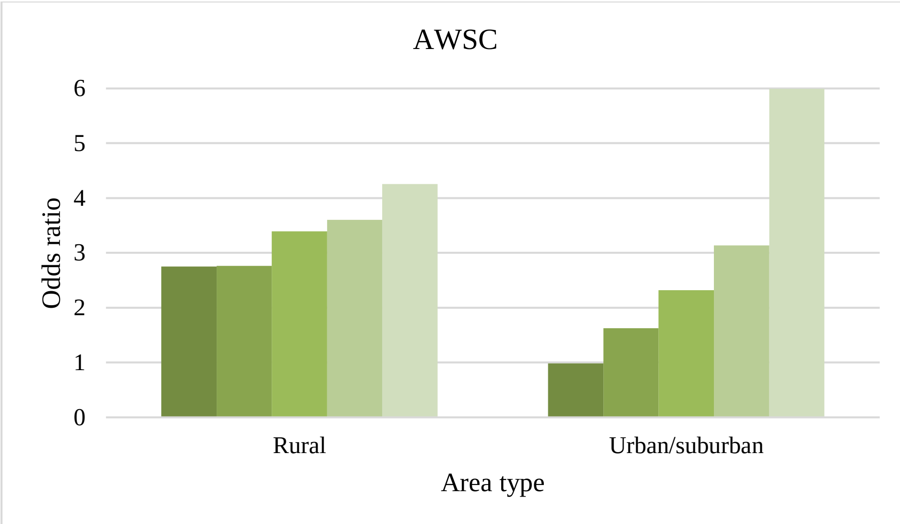


Figure 7-8. Odds ratio and area type for AWSC intersections converted to mini-roundabouts.

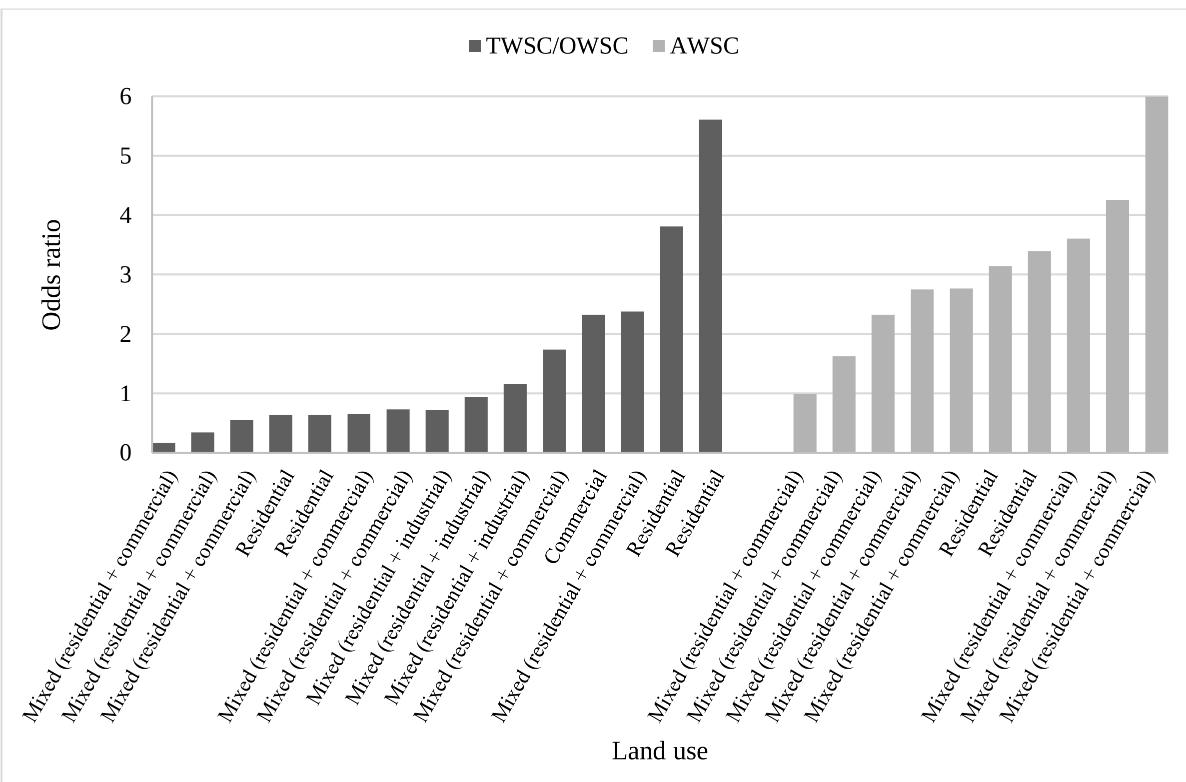
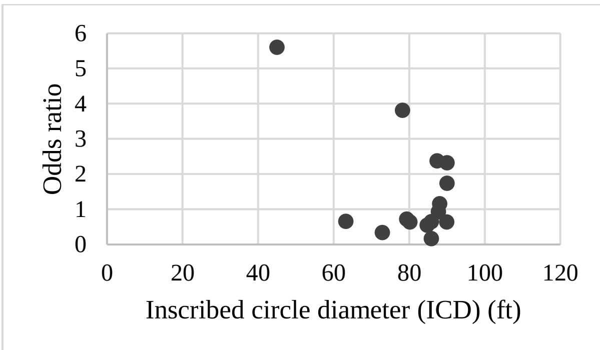


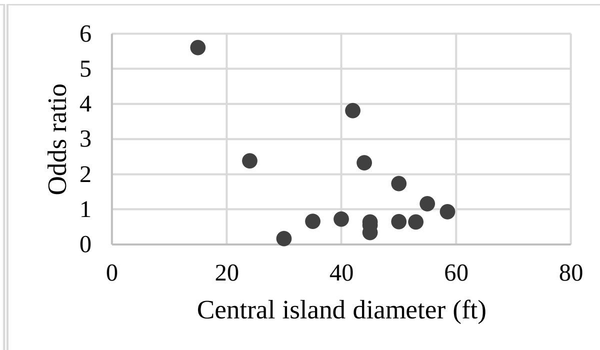
Figure 7-9. Odds ratio and land use for TWSC/OWSC/AWSC intersections converted to mini-roundabouts.

7.1.5 Effect of Geometric Characteristics on the Safety Effectiveness

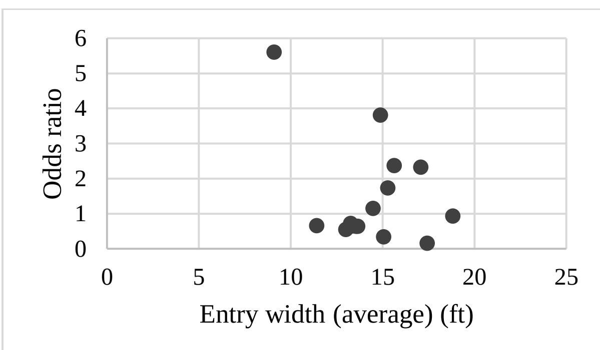
Figures 7-10 shows the effect of selected geometric characteristics on the safety effectiveness of TWSC/OWSC converted to mini-roundabouts.



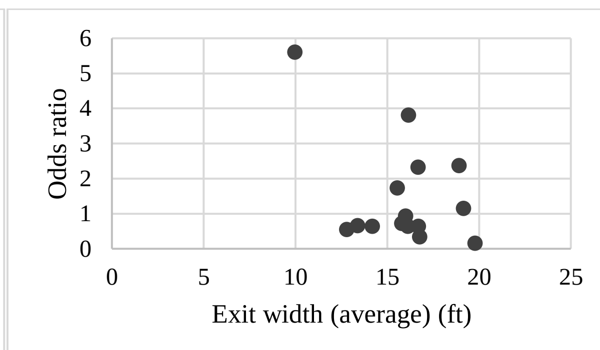
(a) Inscribed circle diameter



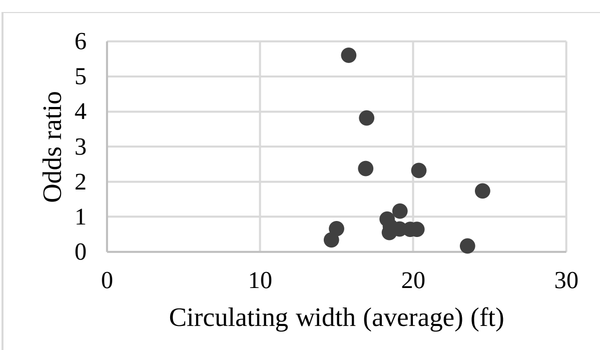
(b) Central island diameter



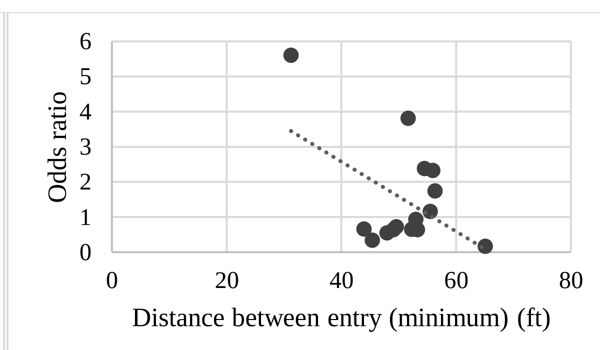
(c) Entry width (average)



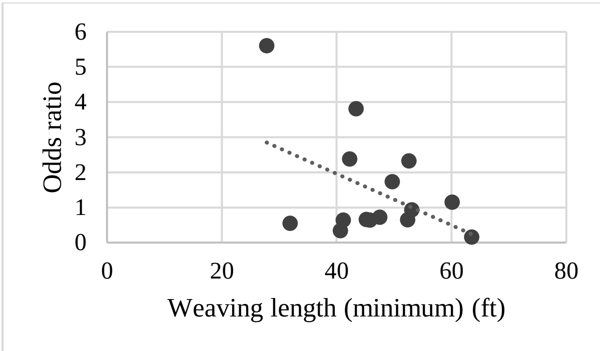
(d) Exit width (average)



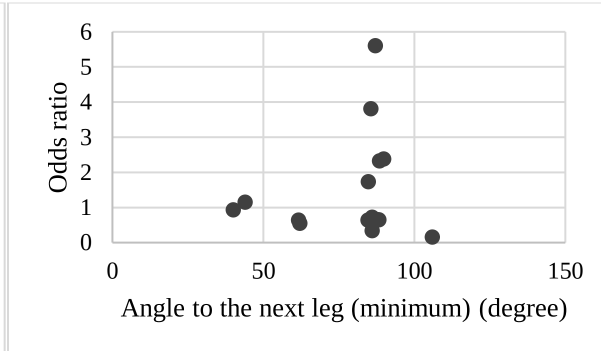
(e) Circulating width (average)



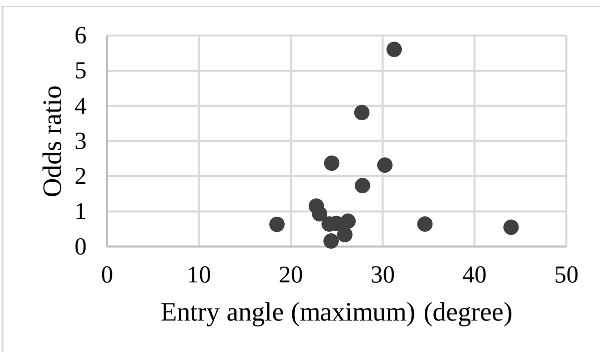
(f) Distance between entry to the next leg (minimum)



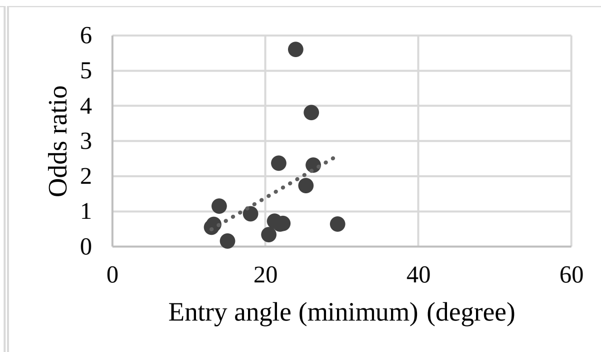
(g) Weaving length (minimum)



(h) Angle to the next leg (minimum)



(i) Entry angle (maximum)



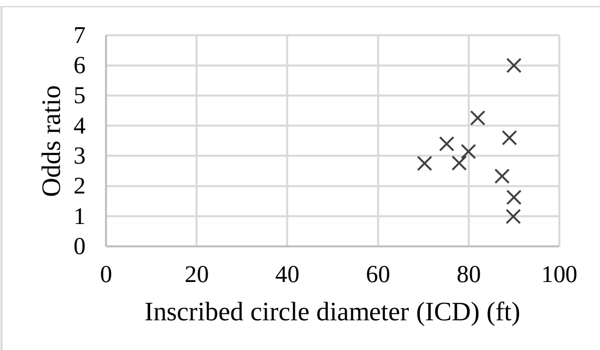
(j) Entry angle (minimum)

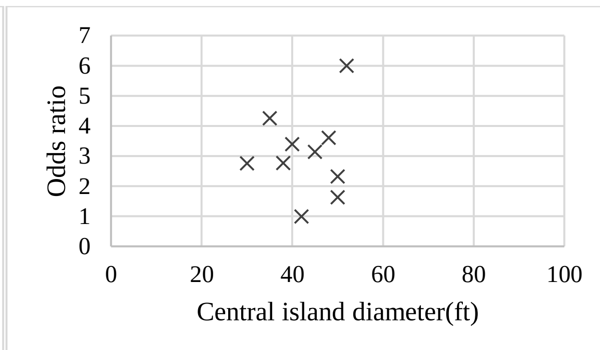
Figure 7-10. Scatter plot between odds ratio and selected geometric characteristics for TWSC/OWSC intersections converted to mini-roundabouts.

Note: 1 meter = 3.28 feet.

The geometric characteristics such as circulating width (average), distance between entry to the next leg (minimum), weaving length (minimum), and entry angle (minimum) have an effect on the odds ratio (Figure 7-10). A negative trend was observed, indicating odds ratio increases (a decrease in the safety effectiveness) with a decrease in the circulating width, distance between entry to the next leg (minimum), weaving length (minimum), and entry angle (minimum).

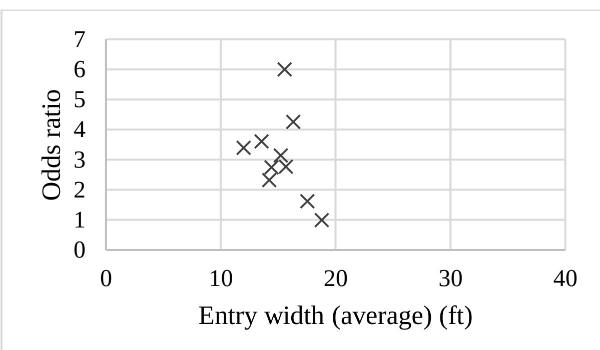
Likewise, entry width (average), circulating width (average), distance between entry to the next leg (minimum), weaving length (minimum), angle to the next leg (minimum), and entry angle (minimum) have an effect on the odds ratio in the case of AWSC intersections converted to mini-roundabouts (Figure 7-11 c, e, f, g, h & j). A negative trend was observed, indicating odds ratio increases (a decrease in the safety effectiveness) with a decrease in the circulating width, distance between entry to the next leg (minimum), weaving length (minimum), and entry angle (minimum). Also, exit width (average) and entry angle (maximum) show a positive trend with the odds ratio, indicating an increase in odds ratio with an increase in exit width (average) and entry angle (maximum) (Figure 7-11 d & i).

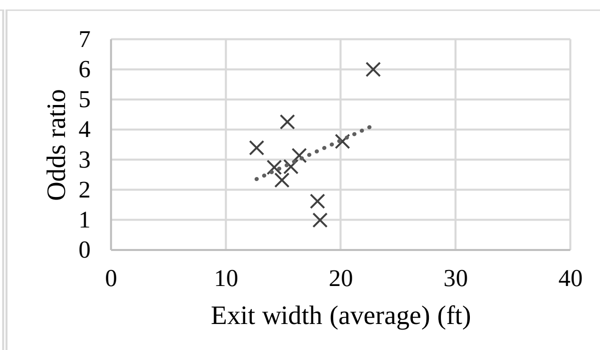




(a) Inscribed circle diameter

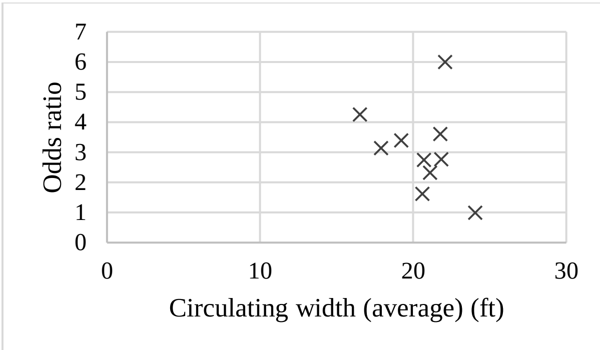
(b) Central island diameter



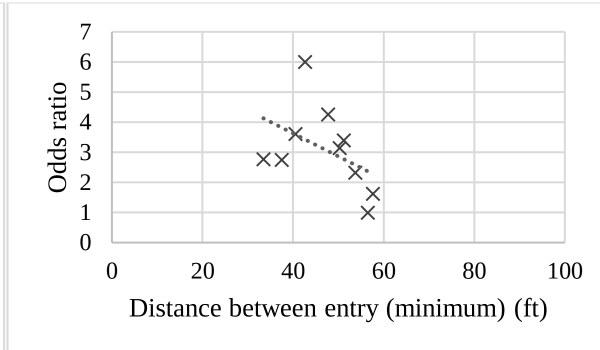


(c) Entry width (average)

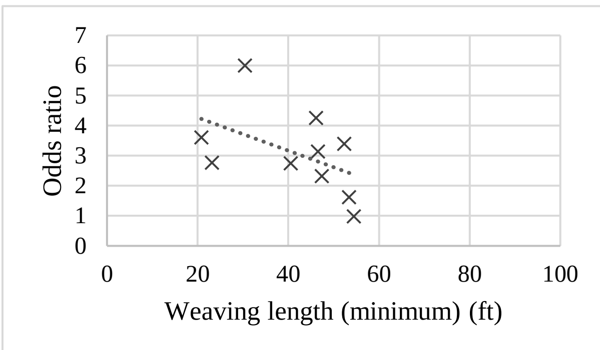
(d) Exit width (average)



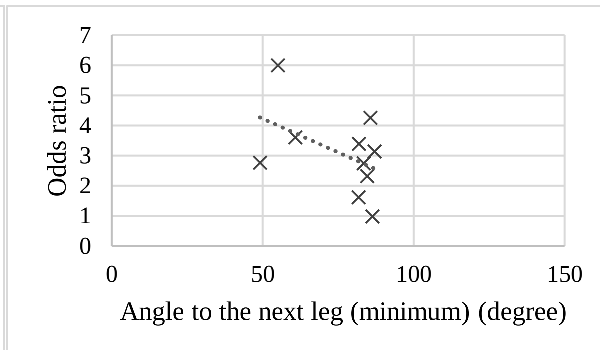
(e) Circulating width (average)



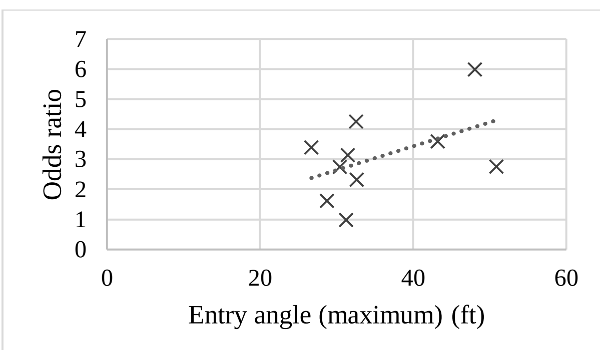
(f) Distance between entry to the next leg (minimum)



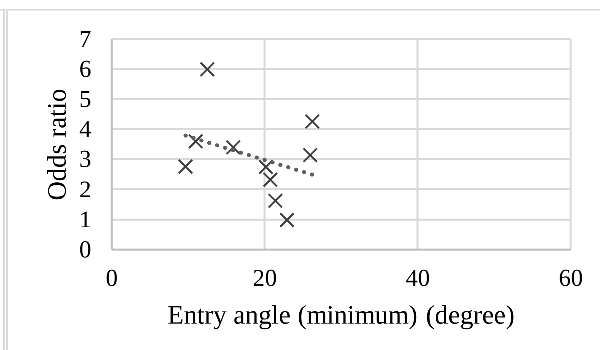
(g) Weaving length (minimum)



(h) Angle to the next leg (minimum)



(i) Entry angle (maximum)



(j) Entry angle (minimum)

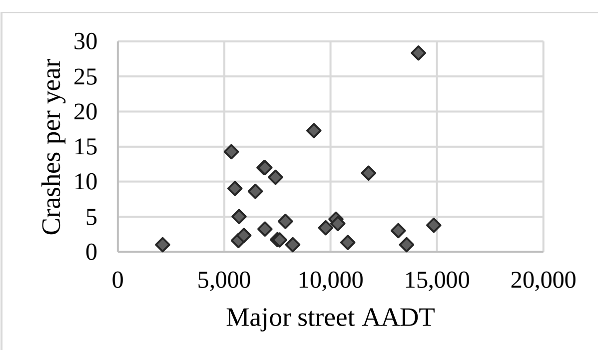
Figure 7-11. Scatter plot between odds ratio and selected geometric characteristics for AWSC intersections converted to mini-roundabouts.

7.2 Examining the Effect of Traffic, On-Network and Off-Network Characteristics on After Period Crashes

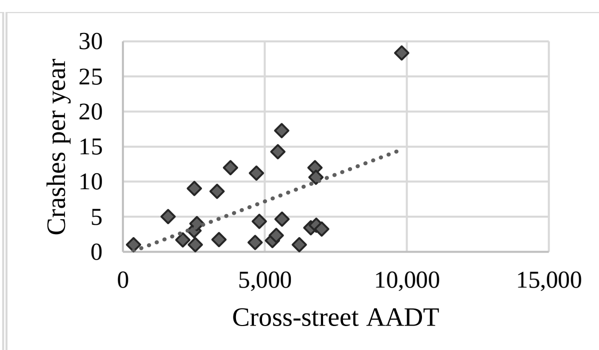
In this section, crashes at mini-roundabouts (after period) were examined with respect to traffic characteristics, on-network characteristics, and off-network characteristics. All the locations were considered together in the analysis as crashes after installing the mini-roundabout are the interest variable.

From the scatter plots, no specific trend was observed between after period crashes per year at mini-roundabouts and major street traffic volumes (Figure 7-12 a). However, cross-street traffic volume and total intersection traffic volume (major + cross-street AADT) show a positive trend with after period crashes per year (Figure 7-12 b & c). Also, cross-street volume share shows a positive trend with after period crashes per year (Figure 7-12 d).

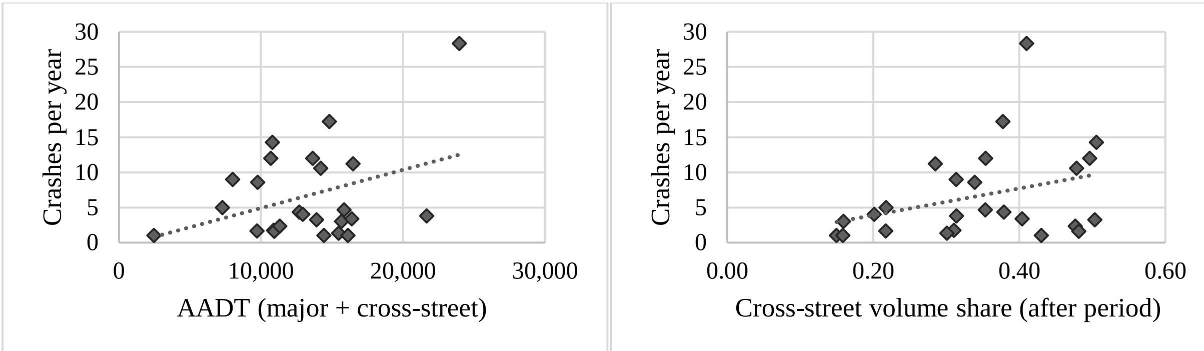
Likewise, scatter plot between after period crashes per year at mini-roundabouts and speed limit (major street and cross-street) shows a positive trend indicating number of crashes per year increases with an increase in the speed limit (Figure 7-13 a & b). The positive trend between after period crashes per year and major street speed limit is steeper, implying that major street speed limit may have more influence on crashes per year at mini-roundabouts.



(a) Major street AADT



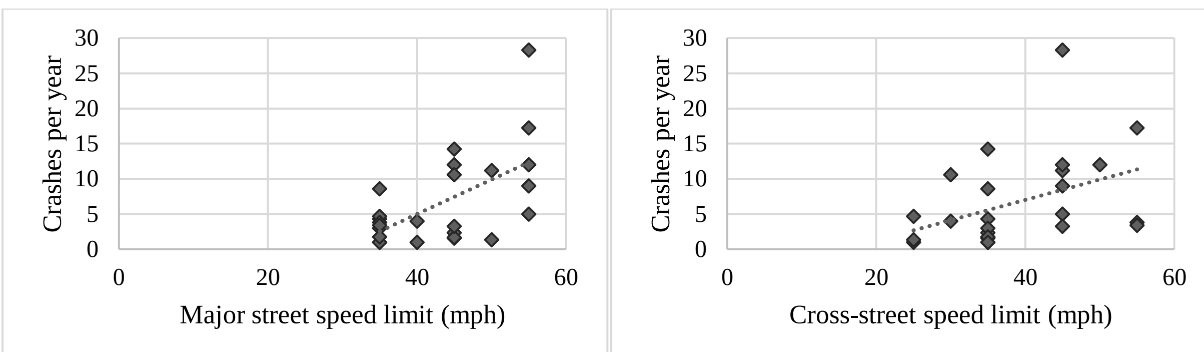
(b) Cross-street AADT



(c) Total AADT (major + cross-street)

(d) Cross-street volume share

Figure 7-12. Scatter plots between after period crashes and traffic volume for all mini-roundabouts.



(a) Major street speed limit

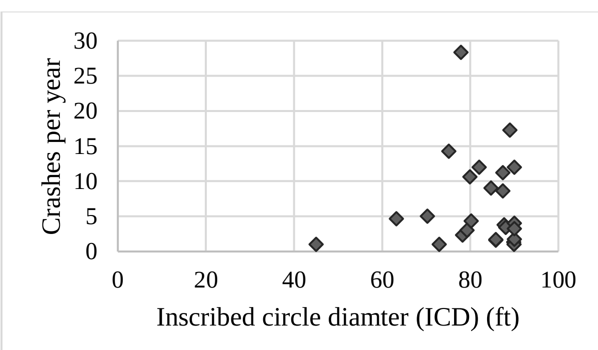
(b) Cross-street speed limit

Figure 7-13. Scatter plots between after period crashes and speed limit at major street and cross-street.

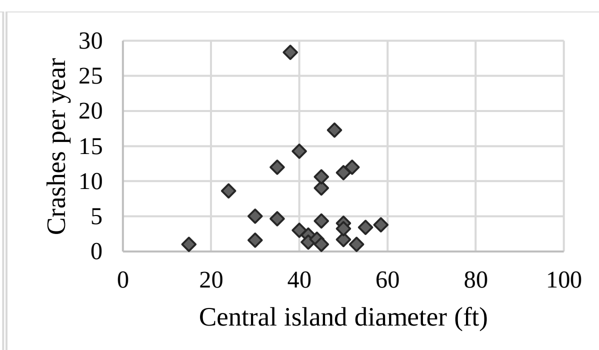
While looking into the geometric characteristics, inscribed circle diameter (ICD) and central island diameter show no trend with after period crashes per year (Figure 7-14 a & b). Likewise, entry width, exist width and circulating width (average of all approaches) show no trend with after period crashes per year (Figure 7-14 c, d & e). However, distance between entry to the next leg and weaving length (minimum of all approaches) show a negative trend with after period crashes per year (Figure 7-14 f & g). Similarly, angle to the next leg and entry angle (minimum of all approaches) show a negative trend, indicating crashes per year increases with skewness at mini-roundabouts (Figure 7-14 h & j). The angle to the next leg indicates the skew at a mini-roundabout. Entry angle (maximum) also shows a notable effect on after period crashes (Figure 7-14 i).

Tables 7-1 to 7-4 summarize the variation of odds ratio based on traffic characteristics, on-network characteristics, and off-network characteristics by the prior control type. From Tables 7-1 and 7-2, low crashes per year in the before period, entry width, exit width, and entry angle increase the odds ratio (reduce the safety effectiveness) at TWSC/OWSC intersections converted to mini-roundabouts.

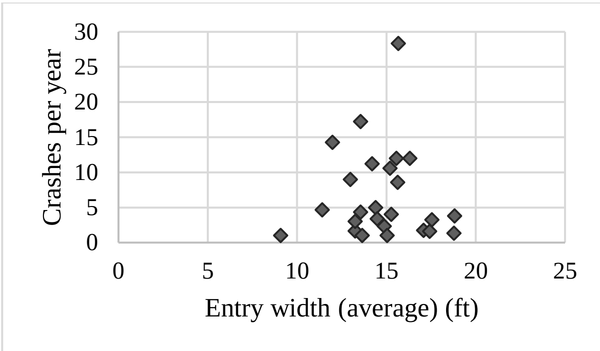
In the case of AWSC intersections converted to mini-roundabouts, high cross-street volume share, high speed limit at major street and cross-street, and exit width (average) have an increasing effect on the odds ratio. Also, weaving length (minimum), entry angle (minimum), and angle to the next leg (minimum) show negative trend, indicating an increase in the odds ratio with a decrease in aforementioned variables (Tables 7-3 and 7-4).



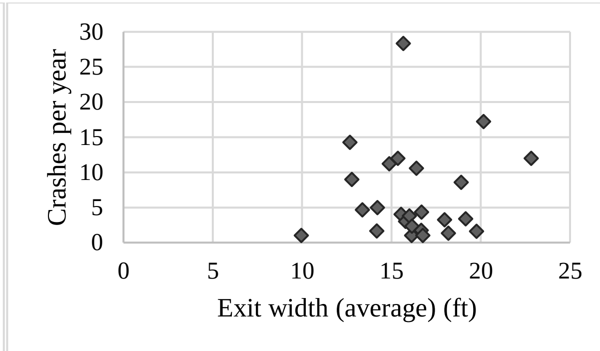
(a) Inscribed circle diameter



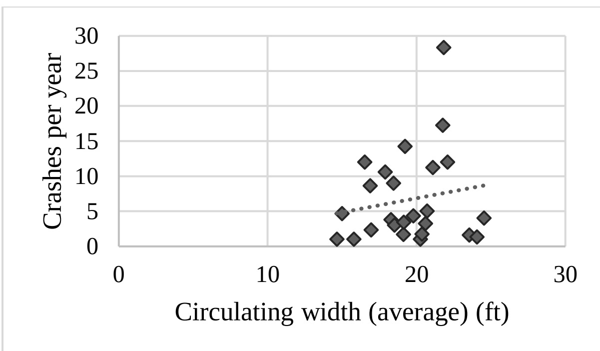
(b) Central island diameter



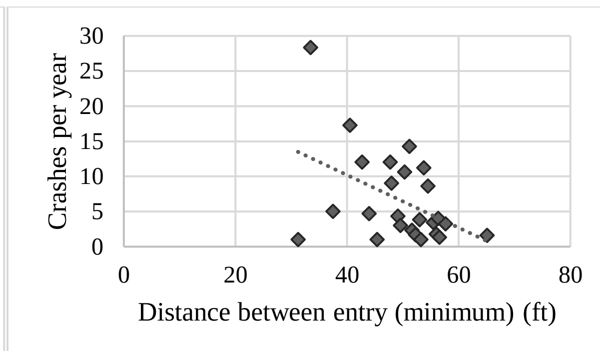
(c) Entry width (average)



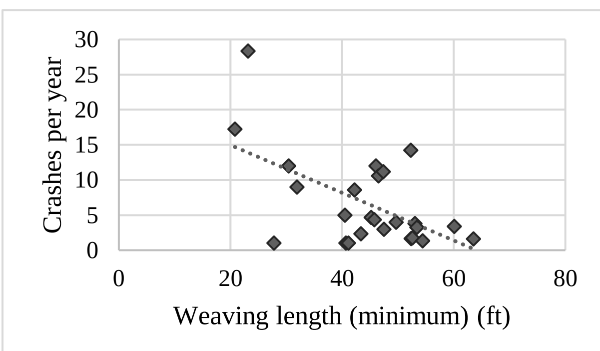
(d) Exit width (average)



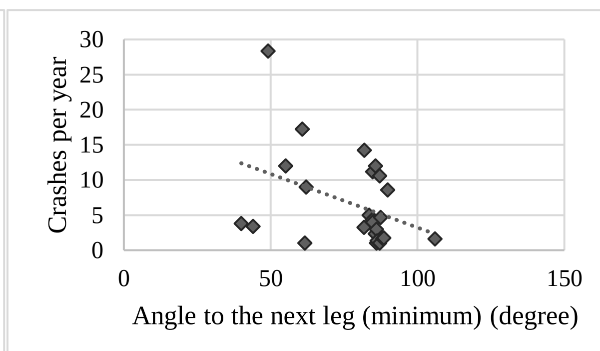
(e) Circulating width (average)



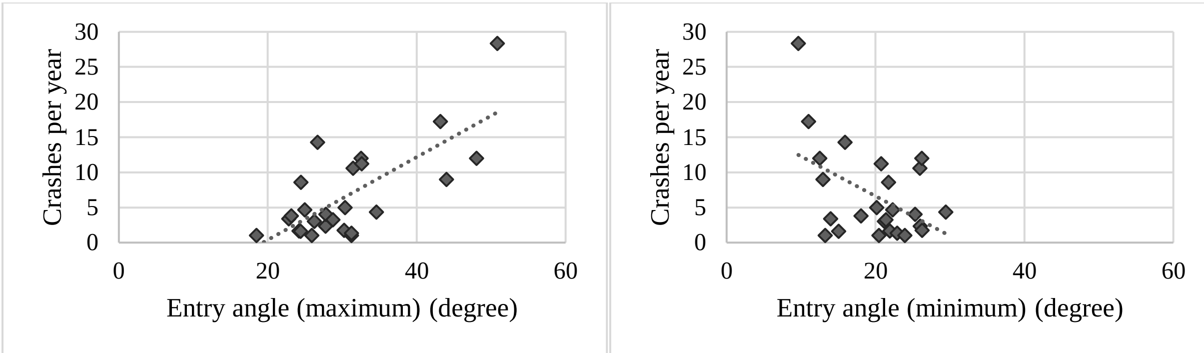
(f) Distance between entry to the next leg (minimum)



(g) Weaving length (minimum)



(h) Angle to the next leg (minimum)



(i) Entry angle (maximum)

(j) Entry angle (minimum)

Figure 7-14. Scatter plots between crashes per year and selected geometric characteristics for TWSC/OWSC intersections converted to mini-roundabouts.

Note: 1 meter = 3.28 feet.

Table 7-1. Examining total crashes odds ratio variation with crashes, traffic volume, and speed limit for TWSC/OWSC intersections converted to mini-roundabouts.

Site # ID	Odds ratio computed by total crashes	Total crashes per year before period	Total crashes per year after period	Major Street AADT before period	Cross- Street AADT before period	Cross-street volume share before period	Total AADT (major + cross-street) before period	Major Street AADT after period	Cross- Street AADT after period	Cross-street volume share after period	Total AADT (major + cross-street) after period	Speed limit major street	Speed limit cross-street
14*	0.16	8.40	1.60	5,000	4,768	0.49	9,768	5,673	5,269	0.48	10,942	45	35
17	0.34	2.60	1.00	13,849	2,837	0.17	16,686	13,568	2,551	0.16	16,119	35	25
1	0.55	11.20	9.00	4,550	1,726	0.28	6,276	5,503	2,513	0.31	8,015	55	45
25$^{\Psi}$	0.64	1.60	1.00	7,345	5,578	0.43	12,923	8,226	6,212	0.43	14,438	40	35
6	0.64	5.00	4.33	6,035	3,643	0.38	9,678	7,883	4,808	0.38	12,691	35	35
21	0.65	1.80	1.67	7,192	2,090	0.23	9,282	7,605	2,109	0.22	9,714	45	35
15	0.66	7.20	4.67	11,300	6,070	0.35	17,370	10,250	5,600	0.35	15,850	35	25
20	0.72	2.80	3.00	8,653	2,013	0.19	10,666	13,176	2,499	0.16	15,675	35	35
23$^{\Psi}$	0.93	3.60	3.80	14,726	6,846	0.32	21,573	14,854	6,806	0.31	21,660	35	35
24$^{\Psi}$	1.16	2.40	3.40	8,635	6,374	0.42	15,009	9,766	6,615	0.40	16,380	35	35
12	1.73	2.40	4.00	10,038	2,498	0.20	12,536	10,342	2,608	0.20	12,950	40	30
22	2.32	0.40	1.75	7,500	3,072	0.29	10,572	7,500	3,380	0.31	10,880	35	35
18	2.38	2.60	8.60	4,237	2,767	0.40	7,004	6,458	3,313	0.34	9,771	35	35
13	3.81	0.40	2.33	5,405	4,350	0.45	9,755	5,925	5,400	0.48	11,325	45	35
16*	5.60	0	1.00	1,970	386	0.16	2,356	2,100	370	0.15	2,470	35	35

Note: *Three-legged, $^{\Psi}$OWSC (ramp).

Low High

Table 7-2. Examining total crashes odds ratio variation with mini-roundabout geometry characteristics for TWSC/OWSC intersections converted to mini-roundabouts.

Site # ID	Odds ratio (total crashes)	Inscribed Circle Dia. (ft)	Central Island Dia. (ft)	Entry width (ft)			Exit width (ft)			Circulating width (ft)	Weaving length (ft)			Entry angle (degree)			Angle to the next leg (degree)		
				Max.	Min.	Avg.	Max.	Min.	Avg.		Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
14*	0.16	86	30	19	16	17.42	22	18	19.77	24	78	64	68.46	24	15	19	137	106	120
17	0.34	73	45	16	14	15.05	19	14	16.77	15	49	41	46.71	26	20	24	93	86	89
1	0.55	85	45	13	12	12.99	13	12	12.79	18	51	32	43.26	44	13	26	108	62	82
25$^{\Psi}$	0.64	90	53	15	13	13.65	17	15	16.13	20	64	41	53.88	19	13	16	110	62	89
6	0.64	80	45	14	13	13.55	19	15	16.69	20	54	46	50.83	35	29	32	93	85	91
21	0.65	86	50	14	12	13.25	15	14	14.18	19	57	52	55.08	24	22	23	91	88	90
15	0.66	63	35	12	11	11.42	14	12	13.38	15	51	45	47.26	25	22	24	95	87	91
20	0.72	79	40	15	12	13.26	22	12	15.79	19	52	48	49.5	26	21	24	88	86	87
23$^{\Psi}$	0.93	88	59	21	15	18.83	19	14	16	18	122	53	79.41	23	18	21	142	40	85
24$^{\Psi}$	1.16	88	55	16	13	14.48	22	13	19.16	19	60	60	60.29	23	14	19	205	44	105
12	1.73	90	50	16	15	15.28	17	15	15.55	25	60	50	54.73	28	25	26	95	85	90
22	2.32	90	44	19	14	17.08	21	14	16.67	20	54	53	53.2	30	26	29	90	89	89
18	2.38	87	24	16	15	15.63	21	17	18.91	17	52	42	47.84	24	22	23	93	90	91
13	3.81	78	42	16	14	14.89	17	15	16.15	17	51	43	47.86	28	26	27	95	86	92
16*	5.60	44	15	10	8	9.09	11	10	9.96	16	46	28	34.52	31	24	27	89	87	88

Note: *Three-legged, $^{\Psi}$OWSC (ramp); 1 meter = 3.28 feet; maximum, minimum and average is the maximum, minimum and average values considering all approaches.

Low — High

Table 7-3. Examining total crashes odds ratio variation with crashes, traffic volume, and speed limit for AWSC intersections converted to mini-roundabouts.

Site # ID	Odds ratio computed by total crashes	Total crashes per year before period	Total crashes per year after period	Major Street AADT before period	Cross- Street AADT before period	Cross-street volume share before period	Total AADT (major + cross-street) before period	Major Street AADT after period	Cross- Street AADT after period	Cross-street volume share after period	Total AADT (major + cross-street) after period	Speed limit major street	Speed limit cross-street
7	0.99	0.60	1.33	10,062	3,530	0.26	13,592	10,813	4,655	0.30	15,468	50	25
8	1.62	1.60	3.25	7,641	5,078	0.40	12,719	6,910	7,001	0.50	13,910	55	45
4	2.32	3.60	11.20	6,836	3,860	0.36	10,696	11,780	4,702	0.29	16,482	50	45
2	2.75	1.60	5.00	5,454	1,834	0.25	7,288	5,704	1,588	0.22	7,291	55	45
5	2.76	8.40	28.33	11,640	8,590	0.42	20,230	14,133	9,823	0.41	23,957	55	45
11	3.14	3.60	10.60	7,636	7,010	0.48	14,646	7,414	6,800	0.48	14,214	45	30
19	3.40	4.60	14.25	6,199	5,107	0.45	11,306	5,344	5,461	0.51	10,805	50	45
3	3.60	3.60	17.25	7,238	4,274	0.37	11,512	9,221	5,590	0.38	14,811	55	55
10	4.26	2.40	12.00	6,775	6,409	0.49	13,184	6,867	6,764	0.50	13,631	55	50
9	5.99	1.80	12.00	7,641	3,896	0.34	11,537	6,910	3,784	0.35	10,693	45	45

Low — High

Table 7-4. Examining total crashes odds ratio variation with mini-roundabout geometry characteristics for AWSC intersections converted to mini-roundabouts.

Site # ID	Odds ratio (total crashes)	Inscribed Circle Dia. (ft)	Central Island Dia. (ft)	Entry width (ft)			Exit width (ft)			Circulating width (ft)	Weaving length (ft)			Entry angle (degree)			Angle to the next leg (degree)		
				Max.	Min.	Avg.	Max.	Min.	Avg.		Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
7	0.99	90	42	20	18	18.78	19	17	18.2	24	59	54	57.22	31	23	28	92	86	90
8	1.62	90	50	18	17	17.54	19	17	17.97	21	58	53	55.66	29	21	26	98	82	89
4	2.32	87	50	15	13	14.2	16	14	14.89	21	55	47	51.15	33	21	28	91	85	88
2	2.75	70	30	17	13	14.41	15	14	14.22	21	45	41	42.22	30	20	27	92	84	90
5	2.76	78	38	16	15	15.68	16	15	15.67	22	67	23	45.56	51	10	31	133	49	90
11	3.14	80	45	16	14	15.21	18	15	16.4	18	50	47	47.92	31	26	28	91	87	89
19	3.40	75	40	13	12	11.99	14	12	12.67	19	57	52	55.01	27	16	22	96	82	88
3	3.60	89	48	14	13	13.55	28	13	20.16	22	72	21	51.24	43	11	27	135	61	110
10	4.26	82	35	17	16	16.31	16	14	15.36	17	48	46	46.86	33	26	30	93	86	89
9	5.99	90	52	19	13	15.56	30	17	22.84	22	79	30	54.68	48	13	26	125	55	75

Low — High

7.3 Correlation Analysis

The Pearson correlation coefficient analysis was carried out to understand the relationship between the computed odds ratio with crashes, traffic characteristics, on-network characteristics, and off-network characteristics of mini-roundabouts. The Pearson correlation coefficient indicates a linear relationship between two variables and shows the confidence level at which the coefficient is significant. The Pearson correlation coefficient ranges between -1 to +1, and values closer to -1 or +1 indicates a strong correlation. A positive correlation suggests an increase in one variable would increase another variable. The analysis was carried out separately for all the selected mini roundabouts, TWSC intersections converted to mini-roundabouts, and AWSC intersections converted to mini-roundabouts. The correlation analysis results for TWSC/OWSC intersections converted to mini- roundabouts based on total crashes, FI crashes, and PDO crashes are summarized in Table 7-5. A 90% confidence level was considered to check the statistical significance.

From Table 7-5, the odds ratio for total crashes and PDO crashes have a statistically significant negative correlation with before period per year crashes. It indicates that odds ratio decreases at intersections with high crash history. The FI based odds ratio has a statistically significant positive correlation with after period per year crashes. It indicates that FI based odds ratio increases with after period crashes at a mini-roundabout.

Table 7-6 shows the correlation analysis results for AWSC intersections converted to mini-roundabouts based on total crashes, FI crashes, and PDO crashes. The odds ratio for total crashes and PDO crashes have a statistically significant negative correlation with the entry width. It indicates that odds ratio decreases with an increase in the entry width. For FI based odds ratio, no variables show statistically significant correlation.

Table F-1 in Appendix F shows the correlation analysis based on after period crashes per year for TWSC/OWSC intersections converted to mini-roundabouts. Total and PDO crashes per year in the after period have a statistically significant positive correlation with before period total and PDO crashes per year, respectively. It indicates high crash frequency at mini-roundabouts if an intersection possess high crash history in the before period.

Table F-2 in Appendix F shows the correlation analysis based on after period crashes per year for AWSC intersections converted to mini-roundabouts. Total and PDO crashes per year in the after period have a statistically significant positive correlation with before period crashes, cross-street traffic volume in the before period, entry angle (maximum), and angle to the next leg (maximum). Additionally, PDO crashes per year also have a statistically significant positive correlation with total intersection volume (major + cross-street AADT) in the before period and cross-street traffic volume in the after period. Hence, crashes at a mini-roundabout increase with an increase in the before period crash history, cross-street traffic volume, and intersection skewness. Also, total and PDO crashes per year in the after period have a statistically significant negative correlation with the entry angle (minimum), distance between entry to the next leg (minimum), and weaving length (minimum). Similarly, FI crashes per year in the after period have a statistically significant positive correlation with before period FI crashes, and statistically significant negative correlation with the entry angle (minimum) and weaving length (minimum). Also, it is negatively correlated with the entry width (maximum) and exit width (minimum).

Table 7-7 shows the correlation analysis based on the after period crashes per year considering all mini-roundabouts. Total and PDO crashes per year in the after period have a statistically significant positive correlation with before period crashes, cross-street traffic volume in the before and after period, major street and cross-street speed limit. This indicates that an increase in the aforementioned variables increases the number of crashes at mini-roundabouts. Additionally, PDO crashes per year have a statistically significant positive correlation with cross-street volume share in the before period. Also, total and PDO crashes per year in the after period have a statistically significant negative correlation with the entry angle (minimum), distance between entry to the next leg (minimum), and weaving length (minimum). However, it has a statistically significant positive correlation with the entry angle (maximum). The FI crashes per year in the after period have a statistically significant positive correlation with major street and cross-street speed limit, indicating FI crashes increases at high speed limit roads. Also, it is negatively correlated with the entry angle (minimum) and weaving length (minimum).

In summary, it may be inferred that crashes at mini-roundabout increases with an increase in the before period crash history, cross-street traffic volume, speed limit at major street and cross-street, and intersection skewness.

Table 7-5. Pearson correlation analysis based on odds ratio – TWSC/OWSC converted to mini-roundabouts.

Variable	Odds ratio		
	Total crashes	FI crashes	PDO crashes
Total crashes per year before period	-0.560*	-	-
Total crashes per year after period	0.152	-	-
FI crashes per year before period	-	-0.285	-
FI crashes per year after period	-	0.645*	-
PDO crashes per year before period	-	-	-0.536*
PDO crashes per year after period	-	-	0.094
Major street AADT (before period)	-0.277	-0.160	-0.228
Cross-street AADT (before period)	-0.044	-0.037	-0.117
Cross-street share (before period)	0.232	0.123	0.125
Total AADT (major + cross-street) (before period)	-0.232	-0.139	-0.225
Major street AADT (after period)	-0.289	-0.060	-0.271
Cross-street AADT (after period)	0.036	-0.027	-0.044
Cross-street share after period	0.239	-0.012	0.170
Total AADT (major + cross-street) (after period)	-0.227	-0.063	-0.250
Speed limit major street	-0.194	-0.301	-0.121
Speed limit cross -street	-0.001	0.341	-0.102
Speed limit difference between major and cross-street	-0.139	-0.184	-0.134
Inscribed circle diameter	0.201	0.372	0.154
Center island diameter	-0.171	-0.273	-0.113
Entry width (max.)	0.214	0.366	0.141
Entry width (min.)	0.310	0.338	0.283
Entry width (avg.)	0.267	0.376	0.207
Exit width (max.)	0.166	0.419	0.050
Exit width (min.)	0.250	0.303	0.200
Exit width (avg.)	0.203	0.373	0.092
Circulating width (max.)	-0.177	-0.266	-0.066
Circulating width (min.)	-0.043	-0.067	0.030
Circulating width (avg.)	-0.092	-0.170	0.017
Distance between entry to the next leg (max.)	-0.143	0.108	-0.219
Distance between entry to the next leg (min.)	0.160	0.177	0.139
Distance between entry to the next leg (avg.)	-0.110	0.113	-0.171
Weaving length (max.)	-0.158	0.165	-0.226
Weaving length (min.)	-0.050	0.040	-0.086
Weaving length (avg.)	-0.160	0.128	-0.224
Entry angle (max.)	-0.028	-0.093	0.027
Entry angle (min.)	0.424	0.033	0.498
Entry angle (avg.)	0.305	0.010	0.375
Angle-to-the-next-leg (max.)	-0.124	0.079	-0.219
Angle-to-the-next-leg (min.)	0.065	-0.139	0.147
Angle-to-the-next-leg (avg.)	-0.137	-0.128	-0.155

Note: * indicates statistical significance at a 90% confidence level. Highlighted cell indicates Pearson correlation (r) greater/less or equal to ±0.4. Max., min., and avg. are the maximum, minimum and average values considering all approaches.

Table 7-6. Pearson correlation analysis based on odds ratio – AWSC converted to mini-roundabouts.

Variable	Odds ratio		
	Total crashes	FI crashes	PDO crashes
Total crashes per year before period	0.274	-	-
Total crashes per year after period	0.534	-	-
FI crashes per year before period	-	-0.005	-
FI crashes per year after period	-	0.512	-
PDO crashes per year before period	-	-	0.340
PDO crashes per year after period	-	-	0.513
Major street AADT (before period)	-0.303	-0.267	-0.326
Cross-street AADT (before period)	0.156	-0.483	0.258
Cross-street share (before period)	0.350	-0.438	0.540
Total AADT (major + cross-street) (before period)	-0.075	-0.430	-0.029
Major street AADT (after period)	-0.288	-0.079	-0.387
Cross-street AADT (after period)	-0.063	-0.561	0.063
Cross-street share after period	0.143	-0.555	0.440
Total AADT (major + cross-street) (after period)	-0.220	-0.333	-0.222
Speed limit major street	0.044	0.483	-0.246
Speed limit cross -street	0.444	0.156	0.117
Speed limit difference between major and cross-street	-0.491	0.107	-0.284
Inscribed circle diameter	-0.211	-0.179	-0.362
Center island diameter	0.022	-0.250	-0.020
Entry width (max.)	-0.372	-0.226	-.653*
Entry width (min.)	-.698*	-0.558	-.725*
Entry width (avg.)	-0.588	-0.400	-.755*
Exit width (max.)	0.428	0.356	0.079
Exit width (min.)	-0.443	-0.483	-0.600
Exit width (avg.)	0.216	0.154	-0.146
Circulating width (max.)	-0.446	0.149	-0.522
Circulating width (min.)	-0.349	0.154	-0.391
Circulating width (avg.)	-0.362	0.212	-0.448
Distance between entry to the next leg (max.)	0.287	0.159	0.147
Distance between entry to the next leg (min.)	-0.586	-0.483	-0.273
Distance between entry to the next leg (avg.)	-0.109	-0.154	-0.071
Weaving length (max.)	0.335	0.118	0.200
Weaving length (min.)	-0.592	-0.459	-0.224
Weaving length (avg.)	-0.306	-0.271	-0.029
Entry angle (max.)	0.498	0.199	0.147
Entry angle (min.)	-0.408	-0.259	-0.353
Entry angle (avg.)	-0.088	-0.045	-0.462
Angle-to-the-next-leg (max.)	0.471	0.254	0.235
Angle-to-the-next-leg (min.)	-0.490	-0.150	-0.258
Angle-to-the-next-leg (avg.)	-0.132	0.434	-0.144

Note: * indicates statistical significance at a 90% confidence level. Highlighted cell indicates Pearson correlation (r) greater/less or equal to ±0.4. Max., min., and avg. are the maximum, minimum and average values considering all approaches.

Table 7-7. Pearson correlation analysis based on crashes per year (after period) – all mini-roundabouts.

Variable	Crashes per year (after period)		
	Total crashes	FI crashes	PDO crashes
Total crashes per year before period	0.432*	-	-
Total crashes per year after period	1	-	-
FI crashes per year before period	-	0.318	-
FI crashes per year after period	-	1	-
PDO crashes per year before period	-	-	0.438*
PDO crashes per year after period	-	-	1
Major street AADT (before period)	0.060	-0.060	0.080
Cross-street AADT (before period)	.473*	0.202	.506*
Cross-street share (before period)	0.390	0.225	.406*
Total AADT (major + cross-street) (before period)	0.263	0.053	0.293
Major street AADT (after period)	0.168	0.119	0.171
Cross-street AADT (after period)	.507*	0.280	.530*
Cross-street share after period	0.339	0.176	0.357
Total AADT (major + cross-street) (after period)	0.368	0.222	0.382
Speed limit major street	.581*	.629*	.550*
Speed limit cross -street	.405*	.492*	.374
Speed limit difference between major and cross-street	-0.110	-0.101	-0.107
Inscribed circle diameter	0.069	0.151	0.051
Center island diameter	-0.014	0.037	-0.023
Entry width (max.)	-0.091	-0.116	-0.083
Entry width (min.)	0.052	-0.032	0.065
Entry width (avg.)	-0.037	-0.074	-0.029
Exit width (max.)	0.128	0.171	0.116
Exit width (min.)	-0.035	-0.139	-0.013
Exit width (avg.)	0.080	0.065	0.080
Circulating width (max.)	0.111	0.145	0.100
Circulating width (min.)	0.159	0.249	0.136
Circulating width (avg.)	0.164	0.226	0.147
Distance between entry to the next leg (max.)	-0.071	-0.032	-0.076
Distance between entry to the next leg (min.)	-.452*	-0.369	-.450*
Distance between entry to the next leg (avg.)	-0.182	-0.124	-0.186
Weaving length (max.)	0.088	0.099	0.082
Weaving length (min.)	-.561*	-.519*	-.548*
Weaving length (avg.)	-0.198	-0.137	-0.202
Entry angle (max.)	.729*	.608*	.724*
Entry angle (min.)	-.478*	-.475*	-.460*
Entry angle (avg.)	.446*	0.365	.444*
Angle-to-the-next-leg (max.)	0.142	0.111	0.143
Angle-to-the-next-leg (min.)	-0.390	-0.334	-0.385
Angle-to-the-next-leg (avg.)	-0.081	0.086	-0.109

Note: * indicates statistical significance at a 90% confidence level. Highlighted cell indicates Pearson correlation (r) greater/less or equal to ±0.4. Max., min., and avg. are the maximum, minimum and average values considering all approaches.

Table 7-8 summarizes the Pearson correlation coefficient analysis. Some of the mini-roundabout characteristics may have influenced crashes that occurred after the installation. The Pearson correlation analysis results indicated that an increase in crash history, cross-street traffic volume, and major street and cross-street speed limits increases the number of crashes in the mini-roundabout area. Similarly, an increase in the weaving length (minimum), entry angle (minimum), and reduction in intersection skewness may improve the safety effectiveness of mini-roundabouts.

Table 7-8. Pearson correlation coefficient analysis summary.

Variable	Odds ratio – TWSC/OWSC intersection converted to a mini-roundabout			Odds ratio – AWSC intersection converted to a mini-roundabout			Crashes per year (after period) – all mini-roundabouts		
	Total	FI	PDO	Total	FI	PDO	Total	FI	PDO
Total crashes per year before period	N						P		
FI crashes per year after period		P							
PDO crashes per year before period			N						P
Cross-street AADT (before period)							P		P
Cross-street share (before period)									P
Cross-street AADT (after period)							P		P
Speed limit major street							P	P	P
Speed limit cross - street							P	P	P
Entry width (maximum)						N			
Entry width (minimum)				N		N			
Entry width (average)						N			
Weaving length (minimum)							N	N	N
Entry angle (maximum)							P	P	P
Entry angle (minimum)							N	N	N

Note: P/N indicates statistically significant positive/negative correlation and greater/less or equal to ±0.4 at a 90% confidence level; blank cell indicates no statistically significant correlation; maximum, minimum, and average are the maximum, minimum, and average values considering all the approaches.

CHAPTER 8 MINI-ROUNDABOUT CRASH MODIFICATION FACTORS

This chapter provides a summary and comparison of CMFs from naïve and EB method.

8.1 Crash Modification Factors (CMFs)

CMFs are used to compute the expected number of crashes after implementing a countermeasure on a road or at an intersection. The CMF is defined in HSM (AASHTO, 2010) as "the relative change in crash frequency due to a change in one specific condition (when all other conditions and site characteristics remain constant). CMFs are the ratio of the crash frequency of a site under two different conditions. Therefore, a CMF may serve as an estimate of the effect of a particular geometric design or traffic control feature or the effectiveness of a particular treatment or condition" (AASHTO, 2010). The safety impacts in terms of CMF on converting regular intersections to mini-roundabouts are unknown. CMFs are used by practitioners to recommend countermeasures. CMF less than 1 indicates that implementing a countermeasure would result in the reduction of the number of crashes, whereas CMF greater than 1 indicates that it would result in an increase in the number of crashes. The subsequent sections provide the summary and comparison of CMF and standard error estimates based on crash severity type for TWSC/OWSC, and AWSC intersections converted to mini-roundabouts.

8.2 Crash Modification Factors (CMFs) Comparison from Naïve and EB Method

Table 8-1 shows the estimated CMFs and standard error for TWSC/OWSC and AWSC intersections converted to mini-roundabouts based on naïve and EB method. CMFs were computed considering HSM SPFs (calibrated and non-calibrated) and jurisdiction-specific SPFs (calibrated and non-calibrated) employing EB method. Using naïve method, CMFs were computed using metrics crashes per year and crash rate.

CMFs for total crashes varied from 0.78 to 0.99, and the standard error varied from 0.08 to 0.10 for TWSC/OWSC intersections converted to mini-roundabouts. For FI crashes, CMFs varied from 0.39 to 0.56, and the standard error varied from 0.09 to 0.12. CMFs for PDO crashes varied from 0.99 to 1.35, and the standard error varied from 0.11 to 0.14. CMFs computed for total and FI crashes from EB method using calibrated HSM SPFs were lowest, compared to HSM non-calibrated SPFs, jurisdiction-specific SPFs (calibrated and non-calibrated), and naïve method. CMFs for total and FI crashes were highest using crashes per year metrics employing naïve method. CMF for PDO crashes was nearly 1 using crash rate metrics employing naïve method. It was greater than 1 using the EB method. Figure 8-1 shows the CMF comparison for total, FI and PDO crashes computed from naïve and EB methods when TWSC/OWSC intersections are converted to mini-roundabouts.

The standard errors computed from both naïve and EB method were comparable for total, FI and PDO crashes. The standard error computed from the EB method using calibrated HSM SPFs were lowest. Equations used for the odds ratio standard error computation from the simple naïve analysis and with traffic volume correction are referred from Hauer (1997) and Tsapakis et al. (2019), and are presented in Appendix C and D.

CMFs for total crashes varied from 3.01 to 3.51, and the standard error varied from 0.27 to 0.34 for AWSC intersections converted to mini-roundabouts. For FI crashes, CMFs varied from 1.67 to 2.06, and the standard error varied from 0.34 to 0.39. CMFs for PDO crashes varied from 3.38 to 4.06, and the standard error varied from 0.33 to 0.44. CMFs computed for total crashes from the EB method using year-wise calibrated jurisdiction-specific SPFs were lowest, compared to non-calibrated SPFs. CMFs for total, FI and PDO crashes were highest using crashes per year metrics employing naïve method. Figure 8-2 shows the CMF comparison for total, FI and PDO crashes computed from naïve and EB methods when AWSC intersections converted to mini-roundabouts.

The standard errors computed from the EB method were consistently less than the standard error computed from the naïve method for total, FI and PDO crashes.

Table 8-1. CMF and standard error estimates computed from naïve and EB method – summary.

Crash severity type	CMF (standard error) based on EB method									CMF (standard error) based on Naïve method	
	HSM SPFs		Jurisdiction-specific SPFs								
	Calibrated year-wise	Non-calibrated	3 year crash data and year-wise calibration	3 year crash data and no year-wise calibration	5 year crash data and year-wise calibration	5 year crash data and no year-wise calibration	7 year crash data and year-wise calibration	7 year crash data and no year-wise calibration	9 year crash data	Crashes per year	Crash rate (crashes per year/traffic volume)
15 TWSC/OWSC converted to mini-roundabouts											
Total	0.78 (0.08)	0.91 (0.09)	0.84 (0.08)	0.92 (0.09)	0.84 (0.08)	0.98 (0.09)	0.94 (0.09)	0.95 (0.09)	0.98 (0.09)	0.99 (0.10)	0.85 (0.09)
FI	0.39 (0.09)	0.48 (0.11)	0.47 (0.10)	0.50 (0.11)	0.48 (0.11)	0.56 (0.12)	0.48 (0.11)	0.47 (0.11)	0.52 (0.11)	0.53 (0.12)	0.44 (0.10)
PDO	1.04 (0.11)	1.15 (0.12)	1.13 (0.12)	1.25 (0.13)	1.09 (0.12)	1.22 (0.13)	1.28 (0.14)	1.26 (0.13)	1.35 (0.14)	1.15 (0.13)	0.99 (0.12)
10 AWSC intersections converted to mini-roundabouts											
Total	-	-	3.01 (0.27)	3.24 (0.30)	3.04 (0.27)	3.23 (0.29)	3.09 (0.27)	3.24 (0.29)	3.08 (0.27)	3.51 (0.34)	3.04 (0.34)
FI	-	-	1.96 (0.35)	1.97 (0.36)	1.99 (0.36)	1.90 (0.34)	2.06 (0.36)	2.01 0.36)	1.91 (0.34)	1.96 (0.39)	1.67 (0.35)
PDO	-	-	3.64 (0.37)	3.69 (0.37)	3.38 (0.33)	3.73 (0.36)	3.40 (0.33)	3.67 (0.35)	3.45 (0.33)	4.06 (0.44)	3.53 (0.43)

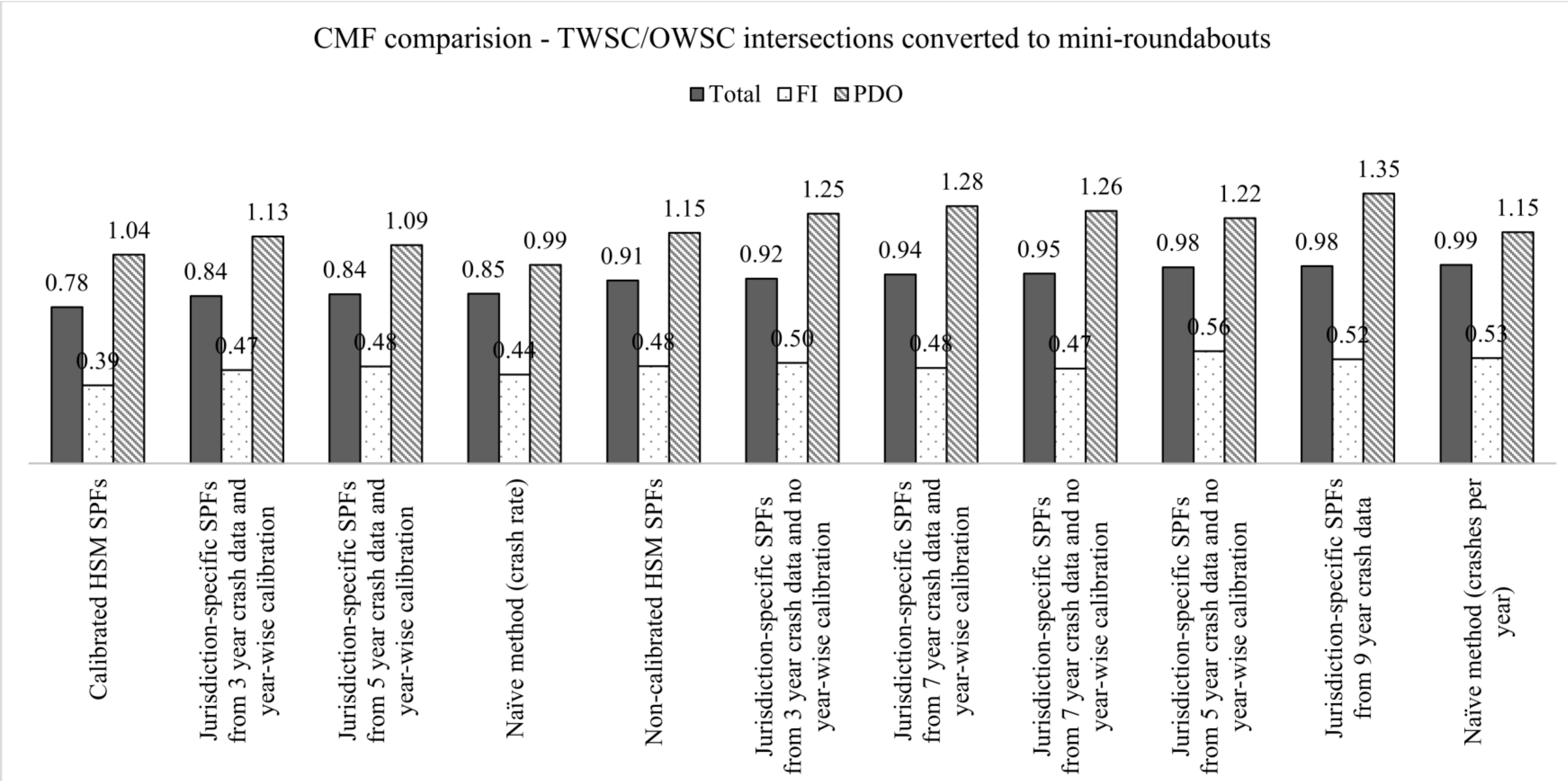


Figure 8-1. CMF comparison for total, FI and PDO crashes computed from naïve and EB method – TWSC/OWSC intersections converted to mini-roundabouts.

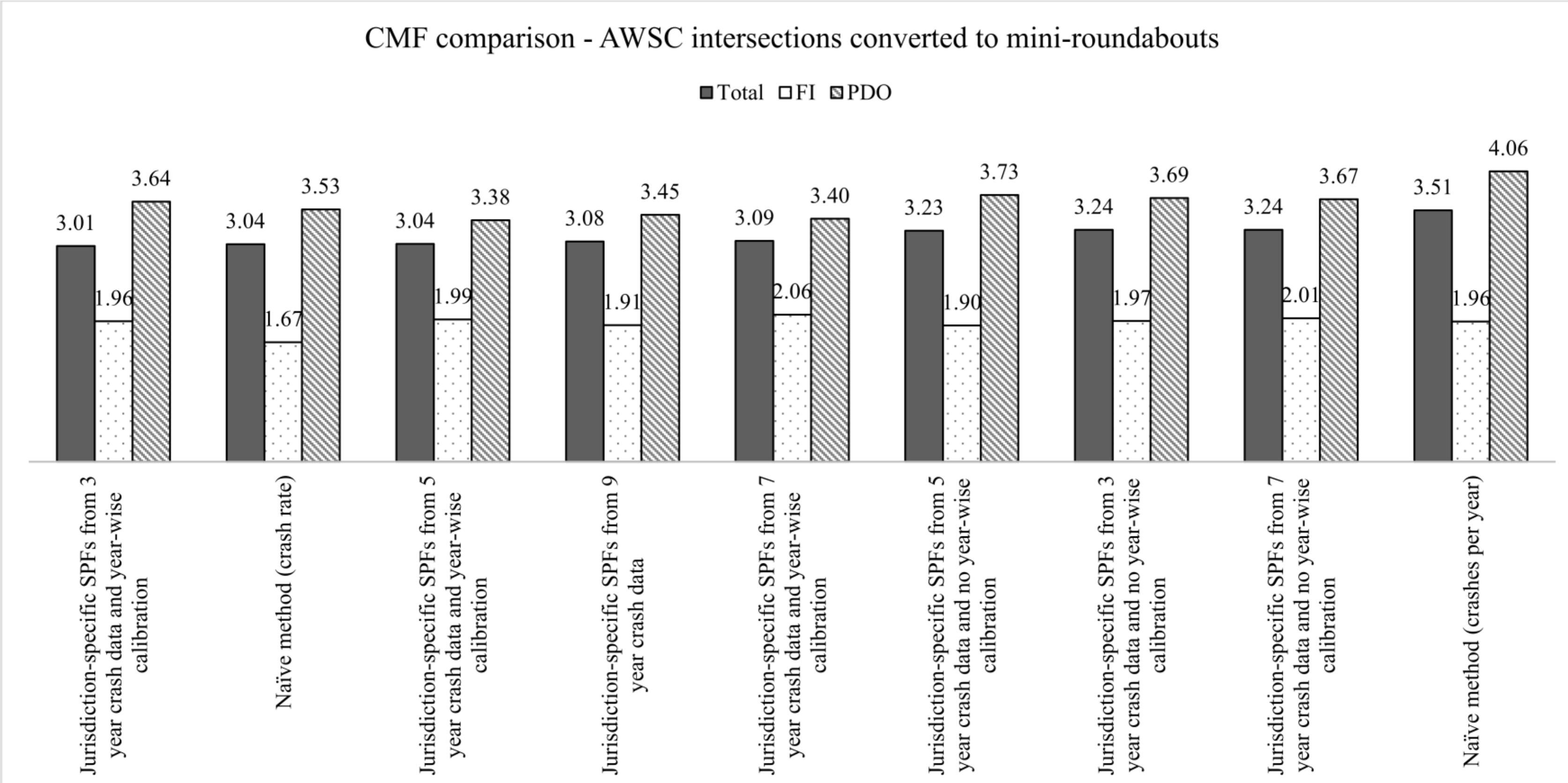


Figure 8-2. CMF comparison for total, FI and PDO crashes computed from naïve and EB method – AWSC intersections converted to mini-roundabouts.

8.3 Recommended Crash Modification Factors (CMFs)

CMFs for converting a TWSC/OWSC and AWSC intersection to a mini-roundabout are recommended based on before and after analysis using EB method. CMFs are recommended based on calibrated HSM SPFs (TWSC and OWSC), and year-wise calibrated developed jurisdiction-specific SPFs (OWSC (ramp) and AWSC). Table 8-2 shows the recommended CMFs for converting a TWSC/OWSC intersection and AWSC intersection to a mini-roundabout.

Table 8-2. Recommended CMFs for a mini-roundabout.

Crash severity type	CMF	Standard error	Confidence interval	Lower limit	Upper limit	Statistical significance
			TWSC/OWSC intersection			
Total	0.78	0.08	± 1.96	0.63	0.93	Significant at α=0.05
FI	0.39	0.09	± 1.96	0.22	0.56	Significant at α=0.05
PDO	1.04	0.11	± 1.96	0.82	1.26	Not significant
			AWSC intersection			
Total	3.01	0.27	± 1.96	2.48	3.55	Significant at α=0.05
FI	1.96	0.35	± 1.96	1.27	2.66	Significant at α=0.05
PDO	3.64	0.37	± 1.96	2.91	4.36	Significant at α=0.05

8.4 CMF Comparison for Mini-roundabouts and Roundabouts

The CMFs recommended for converting a TWSC/OWSC and AWSC intersection to a mini-roundabout from this research are compared to CMFs for a single-lane roundabout, and are summarized in Table 8-3. The CMFs for total crashes and FI crashes when a TWSC/OWSC intersection converted to a mini-roundabout are higher than when converted to a single-lane roundabout. Hence, it can be inferred that converting a TWSC/OWSC intersection to a mini-roundabout on higher speed limit roads (>=35 mph) is less effective than converting to a single-lane roundabout. However, it is still effective in reducing total crashes and FI crashes when a TWSC/OWSC intersection is converted to a mini-roundabout.

Similarly, the CMFs for total crashes and FI crashes when an AWSC interaction converted to a mini-roundabout are higher than when converted to a roundabout. Hence, it can be inferred that converting an AWSC intersection to a mini-roundabout on higher speed limit roads (>=35 mph) is less effective than converting to a roundabout.

Table 8-3. Comparison of CMFs for mini-roundabouts and single-lane roundabouts.

Study title	Prior condition	# of sites	Setting	Crash severity type	CMF	Standard error	Source
Modeling and evaluating the safety effectiveness of mini-roundabouts	TWSC/OWSC	15	All	All	0.78	0.08	This research
				K, A, B & C	0.39	0.09	
				O	1.04	0.11	
	AWSC	10	All	All	3.01	0.27	
				K, A, B & C	1.96	0.35	
				O	3.64	0.37	
NCHRP report 572: applying roundabouts in the United States	TWSC	9	Rural	All	0.29	0.04	Rodegerdts et al. (2007)
				K, A & B	0.13	0.03	
		16	Urban / suburban	All	0.44	0.06	
				K, A & B	0.22	0.07	
	AWSC	10*	All	All	1.03	0.15	
				K, A & B	1.28	0.41	
Statistical analysis and development of crash prediction model for roundabouts on high-speed rural roadways	TWSC	16	Rural	All	0.26	N/A	Isebrands and Hallmark (2012)
				K, A, B & C	0.11	N/A	
	OWSC	2	Rural	All	0.74	N/A	
				K, A, B & C	0.28	N/A	
Evaluation of roundabouts on high-speed roadways	TWSC	13	All	All	0.59	0.10	NCDOT (2020)
			All	K, A, B & C	0.21	0.08	

Note: K is fatal, A is serious injury, B is minor injury, C is possible injury, and O is property damage only; *including one 2-lane roundabout.

CHAPTER 9 CONCLUSIONS

Mini-roundabout intersection design implementation is relatively new in the United States. Over the past two decades, mini-roundabouts have been installed in various states. They provide an alternative intersection design option in areas with constraints and requiring additional land acquisition. Also, they are better suited for traffic calming and reducing delay, thereby reducing emissions. However, their safety benefits are not very well documented. This research work focuses on evaluating and quantifying the safety benefits of implementing mini-roundabouts in terms of safety effectiveness and CMFs.

The methodology starts with identifying mini-roundabout installation locations across the United States. Extensive research was conducted to identify mini-roundabouts in different states. The FHWA technical summary report on mini-roundabouts (FHWA, 2010) suggests mini-roundabouts installation at intersections with speed limits of 30 mph (~48.28 kmph) or less at all approaches and an 85th-percentile speed of less than 35 mph (~56.33 kmph) near the proposed yield line. Although the mini-roundabout installation location database indicates that the majority of mini-roundabouts were installed at intersections with speed limits of 30 mph (~48.28 kmph) or less, there were a few mini-roundabouts that were installed at intersections having speed limits of 35 mph (~56.33 kmph) or higher at major streets. In this research, mini-roundabouts with at least one approach with a speed limit equal to 35 mph (~56.33 kmph) or higher were selected.

Crash, traffic volume, and geometry data for the identified 25 mini-roundabouts in eight states (Georgia, Iowa, Michigan, Minnesota, Missouri, North Carolina, Virginia, Washington State) was collected. Further, 767 reference intersections based on prior control types (TWSC, OWSC, and AWSC) were identified in the selected eight states, and 723 intersections with available crash and traffic volume data used for calibration and jurisdiction-specific SPF development.

An observational before and after study was conducted to compute safety effectiveness and CMFs based on prior control type. Naïve and EB method were explored. For prior control type TWSC/OWSC, SPFs available in the HSM were calibrated for the considered time period and jurisdiction. The jurisdiction-specific SPFs were developed separately for total crashes, FI crashes, and PDO crashes based on control types [TWSC (four-legged), OWSC (three-legged), OWSC (ramp) (four-legged) and AWSC (four-legged)]. The safety effectiveness estimates were computed and compared using a) calibrated HSM SPFs, b) non-calibrated HSM SPFs, c) developed jurisdiction-specific SPFs from 3 year crash data with year-wise calibration, d) developed jurisdiction-specific SPFs from 3 year crash data without year-wise calibration, e) developed jurisdiction-specific SPFs from 5 year crash data with year-wise calibration, f) developed jurisdiction-specific SPFs from 5 year crash data without year-wise calibration, g) developed jurisdiction-specific SPFs from 7 year crash data with year-wise calibration, h) developed jurisdiction-specific SPFs from 7 year crash data without year-wise calibration, and i) developed jurisdiction-specific SPFs from 9 year crash data. The following are the concluding remarks.

- The results from the naïve before and after analysis indicated a decrease in the number of total crashes and FI crashes per year as well as the crash rate when TWSC/OWSC intersections were converted to mini-roundabouts. However, PDO crashes per year increased, and PDO crash rate remained nearly the same after the mini-roundabout installation.
- The results from the naïve before and after analysis indicated an increase in the number of total crashes, FI crashes and PDO crashes per year and the crash rate when AWSC intersections

were converted to mini-roundabouts.

- Jurisdiction-specific SPFs developed in this research for total crashes, FI crashes, and PDO crashes based on control types [TWSC (four-legged), OWSC (three-legged), OWSC (ramp) (four-legged) and AWSC (four-legged)] could be used by agencies, practitioners and researchers for network screening, predicting crashes and evaluating alternative intersection designs.
- The EB method results indicated a decrease in total crashes and FI crashes when TWSC/OWSC intersections were converted to mini-roundabouts. However, an increase in PDO crashes was observed.
- The EB method results indicated an increase in total number of crashes, FI crashes, and PDO when AWSC intersections were converted to mini-roundabouts.
- The safety effectiveness from the EB method differed when HSM SPFs and jurisdiction-specific SPFs were used. The safety effectiveness estimate difference ranged from 1.11 to 20.00.
- The safety effectiveness from the EB method also differed when jurisdiction-specific SPFs were used and calibrated for subsequent years. The difference between the safety effectiveness estimate ranged from 7.48 to 22.64. The difference between the safety effectiveness estimates (22.64) was statistically significant at a 95% confidence level for total crashes when AWSC intersections converted to mini-roundabouts.
- The safety effectiveness from the EB method also differed when jurisdiction-specific SPFs were developed and compared for 3, 5, 7 and 9 years of crash data. The difference between the safety effectiveness estimate ranged from 3.37 to 16.22 when temporal variation not considered (jurisdiction-specific SPFs without year-wise calibration). This difference was

ranged from 0.29 to 13.21 when SPFs were calibrated for subsequent years.

- When calibration factors were applied for either HSM or jurisdiction-specific SPFs, the estimated safety benefits are higher. The findings are consistent for both TWSC/OWSC and AWSC as prior control types. In other words, computing safety effectiveness without calibration may yield a conservative estimate of safety effectiveness.
- Calibration of jurisdiction-specific SPFs are recommended to account for temporal changes in estimating the expected number of crashes in before and after periods.
- The standard error of safety effectiveness computed from the EB method are either lower or comparable with the naïve method. The lower standard error from the EB method yields a better estimate of safety effectiveness.
- A 22.03% and 61.08% reduction in the number of total crashes and FI crashes but a 4.11% increase in the number PDO crashes is expected when a TWSC/OWSC intersection is converted to a mini-roundabout.
- A 201.45%, 96.20%, and 263.68% increase in the number of total crashes, FI crashes, and PDO crashes is expected when an AWSC intersection is converted to a mini-roundabout.
- The EB method results indicated that when TWSC/OWSC intersections are converted to mini-roundabouts, the installation of mini-roundabouts was found to be effective in the reduction of total crashes at 60% of the selected sites (9 out of 15). They are found to be more effective in the reduction of FI crashes - at 90% of the selected sites (14 out of 15). However, they are found to be less effective in the reduction of PDO crashes - at less than 50% of sites (7 out of 15).
- Likewise, when AWSC intersections are converted to mini-roundabouts, the installation of mini-roundabouts was found to be effective at only 10% of the selected sites (1 out of 10) for

total, FI and PDO crashes.

- No specific trend was observed between the odds ratio and traffic volume for all considered prior control types (intersection AADT, major street AADT, cross-street AADT, and cross-street volume share).
- No specific trend was observed between the odds ratio and speed limits. However, mini-roundabouts installed at speed limits of 45 mph (~72.42 kmph) or higher seems to be effective in reducing crashes at TWSC/OWSC intersections when converted.
- Mini-roundabout installation seems to be effective at TWSC/OWSC intersections exhibiting high crash frequency during the before period.
- The relationship between after period crashes at mini-roundabouts and weaving length (minimum of all approaches) shows a negative trend. It indicates an increase in crashes per year with a decrease in weaving length.
- After period crashes at mini-roundabouts and the entry angle (minimum and maximum of all approaches) trends show an increase in crashes per year with too low or too high entry angles at approaches.
- The relationship between after period crashes at mini-roundabouts and angle to the next leg (skew intersection) shows a positive trend, indicating an increase in crashes with an increase in angle to the next leg.
- The results from Pearson correlation analysis for TWSC/OWSC intersections converted to mini-roundabouts shows that the odds ratio for total crashes and PDO crashes are negatively correlated with the before period per year crashes. It indicates the odds ratio decreases at intersections with a high crash history. The odds ratio for FI crashes shows positive correlation with after period per year crashes. It indicates the odds ratio for FI crashes increases with an

increase in after period crashes at a mini-roundabout.

- The results from Pearson correlation analysis for AWSC intersections converted to mini-roundabouts shows that the odds ratio for total crashes and PDO crashes are negatively correlated with entry width. It indicates the odds ratio decreases with an increase in the entry width. No variables showed a statistically significant correlation with the odds ratio for FI crashes at a 90% confidence level.
- The Pearson correlation analysis results indicated crashes at mini-roundabout increases with an increase in before period crash history, cross-street traffic volume, speed limit at major street and cross-street, and intersection skewness.
- The recommended CMFs for converting a TWSC/OWSC intersection to a mini-roundabout are 0.78 for total crashes, 0.39 for FI crashes, and 1.04 for PDO crashes.
- The recommended CMFs for converting an AWSC intersection to a mini-roundabout are 3.01 for total crashes, 1.96 for FI crashes, and 3.64 for PDO crashes.

The safety effectiveness based on total crashes at TWSC/OWSC intersections converted to mini-roundabouts are comparable to percentage reductions mentioned in Lalani (1975), Green (1977), Ibrahim and Metcalfe (1993), and Brilon (2011). However, they differ based on FI crashes and PDO crashes or for AWSC intersections converted to mini-roundabouts. Overall, converting a TWSC/OWSC intersection to a mini-roundabout could result in better safety benefits than converting an AWSC intersection to a mini-roundabout. The odds ratio is lower for TWSC/OWSC intersections with high crash history. However, FI-based odds ratio is higher for mini-roundabouts with a greater number of crashes in the after period. The odds ratio for the number of total crashes and PDO crashes is lower if entry width is higher at AWSC intersections converted to mini-roundabouts. The number of crashes in the before period, cross-street traffic volume, speed limit at major street and cross-street, and intersection skewness have a statistically significant influence on the safety effectiveness of mini-roundabouts (number of crashes in the after period) at a 90% confidence level.

9.1 Policy/Practice Recommendations

The recommended CMFs could be used by practitioners at intersections with safety implications. For example, if a TWSC/OWSC intersection experiences an average of nine crashes per year (total crashes), converting it to a mini-roundabout may result in an average of seven crashes per year (using total crashes CMF = 0.78). Likewise, if an AWSC intersection experiences an average of three crashes per year (total number of crashes), converting it to a mini-roundabout may result in an average of nine crashes per year (using total crashes CMF = 3.01). Likewise, priority could be given to TWSC/OWSC intersections with relatively higher number of crashes in the before period to maximize derived benefits. The findings from this research could be used in the updated version of technical documents such as mini-roundabout technical summary report, roundabout informational guide, and HSM. Also, recommended CMFs can be included in the CMF clearinghouse database.

9.2 Limitations and Scope for Future Work

In this research, data for 25 mini-roundabouts converted from TWSC/OWSC and AWSC intersections were considered for safety effectiveness evaluation. The number of intersections converted from TWSC/OWSC and AWSC to mini-roundabouts are relatively limited. The HSM and jurisdiction-specific SPFs used in this research considered major street and cross-street AADT as explanatory variables. For SPF development, other variables can be considered such as, speed limit of major street and cross-street, intersection skewness, presence of turning lanes, lighting condition, area type, and land use type. In general, the AWSC intersections converted to mini-roundabouts do not have a high crash history (crashes per year in the before period). The safety effectiveness of AWSC intersections, with high crash history, converted to mini-roundabouts should be further studied in the future. Further, before-after analysis by crash type e.g., angle crashes, rear-end crashes, etc. when converted to mini-roundabouts would provide insights for large-scale implementation. Also, analyzing using larger sample size and comparing the safety effectiveness with mini-roundabouts installed at intersections with speed limit less than 35 mph (56.3 kmph) by area type in the United States merits further investigation.

REFERENCES

Abbess, C., D. Jarrett, and C.C. Wright. Accidents at Blackspots: Estimating the Effectiveness of Remedial Treatment, with Special Reference to the "Regression-To-Mean" Effect. *Traffic Engineering & Control*, Vol. 22(10), 1981, pp. 535-542.

American Association of State Highway and Transportation Officials (AASHTO). *Highway Safety Manual*, 1st edition. AASHTO, Washington, D.C., 2010.

American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*. 7th Edition, Washington, D.C., 2018.

Austroads. *Improving the Performance of Safe System Infrastructure: Final Report*. Publication No. AP- R498-15, Austroads, Sydney, NSW, 2015.

Avelar, R., K. Dixon, and P. Escobar. Evaluation of Signalized-Intersection Crash Screening Methods Based on Distance from Intersection. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2514, 2015, pp. 177-186

Badgley, J., J. Condon, L. Rainville, and D. Li. *FHWA Research and Technology Evaluation: Roundabout Research.* Final Report # FHWA-HRT-17-040, FHWA, U.S. Department of Transportation, 2018.

Brilon, W. Studies on Roundabouts in Germany: Lessons Learned. In *3rd International TRB-Roundabout Conference*, 2011, May 18-20, Carmel, Indiana.

CMF Clearinghouse. Crash Modification Factor (CMF) Clearinghouse Homepage. Federal Highway Administration U.S. Department of Transportation. www.cmfclearinghouse.org, Accessed on December 20, 2019.

Cowhig, M. Traffic Safety Monitoring Report – 3 Years. North Carolina Department of Transportation (NCDOT) - Safety Evaluation Group, Raleigh, NC, 2019.

Delbosc, A., R. Shafi, D. Wanninayake, and J. Mascaro. Understanding Safety and Driver Behaviour Impacts of Mini-Roundabouts on Local Roads. In *Australasian Transport Research Forum Proceedings*, 2017, Auckland, New Zealand.

Department for Transport. *Mini Roundabouts, Good Practice Guidance*. Department for Transport and the County Surveyors Society, United Kingdom, November 27, 2006. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/561491/mini-roundabouts-report.pdf, Accessed on December 15, 2019.

Elvik, R. Effects on Road Safety of Converting Intersections to Roundabouts: Review of Evidence from Non-US Studies. *Transportation Research Record: Journal of the Transportation Research Board*, # 1847, 2003, pp. 1-10.

FHWA (Federal Highway Administration). About Intersection Safety. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 2021. https://safety.fhwa.dot.gov/intersection/about/, Accessed on November 15, 2021.

FHWA (Federal Highway Administration). Intersection Safety. U.S. Department of Transportation, Federal Highway Administration, Turner-Fairbank Highway Research Center McLean, VA, 2021. https://highways.dot.gov/research/research-programs/safety/intersection-safety, Accessed on November 15, 2021.

FHWA (Federal Highway Administration). Roundabouts and Mini Roundabouts. U.S. Department of Transportation, Washington D.C., 2018, https://safety.fhwa.dot.gov/intersection/innovative/roundabouts/, Accessed on December 15, 2019.

FHWA (Federal Highway Administration). *Technical Summary Mini-Roundabouts*. FHWA-SA-10-007, U.S. Department of Transportation, Washington D.C., 2010. https://safety.fhwa.dot.gov/intersection/innovative/roundabouts/fhwasa10007/fhwasa10007.pdf, Accessed on December 15, 2019.

Green, H. *Accidents at Off-Side Priority Roundabouts with Mini or Small Islands*. TRRL Laboratory Report 774, TRRL, Department of Transport, Berkshire, UK, 1977.

Gross, F., B. Persaud, and C. Lyon. *A Guide to Developing Quality Crash Modification Factors*. FHWA-SA-10-032, U.S. Department of Transportation, Federal Highway Administration (FHWA), 2010.

Gross, F., C. Lyon, B. Persaud, and R. Srinivasan, R. Safety Effectiveness of Converting Signalized Intersections to Roundabouts. *Accident Analysis & Prevention*, Vol. 50, 2013, pp. 234-241.

Hauer, E. *Observational Before–After Studies in Road Safety*. Pergamon Press, Oxford, United Kingdom, 1997.

HNTB Corporation. Mini-Roundabouts Overland Park Kansas, 2017. https://www.marc2.org/tr_cfp/UploadedFiles/962_ProjID-OP%20Mini%20Roundabouts_DRAFT%20v%209-1-17.pdf, Accessed on December 15, 2019.

Ibrahim, K. B., and A.V. Metcalfe. Bayesian Overview for Evaluation of Mini-Roundabouts as a Road Safety Measure. *Journal of the Royal Statistical Society: Series D (The Statistician)*, Vol. 42(5), 1993, pp. 525-540.

Isebrands, H. Crash Analysis of Roundabouts at High-Speed Rural Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, # 2096, 2009, pp. 1-7.

Isebrands, H., and S. Hallmark, S. Statistical Analysis and Development of Crash Prediction Model for Roundabouts on High-Speed Rural Roadways. *Transportation Research Record: Journal of the Transportation Research Board*, # 2312, 2012, pp. 3-13.

Kennedy, J.V., R.D. Hall, and S. R. Barnard. Accidents at Urban Mini-Roundabouts. In *25th European Transport Forum Annual Meeting*, Brunel University, England, 1997, pp. 117-130. https://aetransport.org/public/downloads/Assp0/2176-514ec4430a879.pdf

Kittelson & Associates, Inc. Roundabouts Database: The Online Inventory Database of Roundabouts and Other Circular Intersections, 2019. https://roundabouts.kittelson.com/ Accessed on Dec 15, 2019.

Lalani, N. *Roundabouts: Impact on Accidents*. Greater London Intelligence Quarterly, London, Greater London Council, 1975.

Lochrane, T. W. P., N. Kronprasert, J. Bared, D. J. Dailey, and W. Zhang. Determination of Mini-Roundabout Capacity in the United States. *Journal of Transportation Engineering*, Vol. 140(10), 2014. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000700.

Mandavilli, S., A.T. McCartt, and R. A. Retting. Crash Patterns and Potential Engineering Countermeasures at Maryland Roundabouts. *Traffic Injury Prevention*, Vol. 10(1), 2009, pp. 44-50.

Montella, A. Identifying Crash Contributory Factors at Urban Roundabouts and Using Association Rules to Explore their Relationships to Different Crash Types. *Accident Analysis & Prevention*, Vol. 43(4), 2011, pp. 1451-1463.

Montella, A. Roundabout In-Service Safety Reviews: Safety Assessment Procedure. *Transportation Research Record: Journal of the Transportation Research Board*, # 2019, 2007, pp. 40-50.

North Carolina Department of Transportation (NCDOT). Evaluation of Roundabouts on High-Speed Roadways. NCDOT Traffic Safety Unit Programs 2020. https://connect.ncdot.gov/resources/safety/TrafficSafetyResources/One%20Pager_Highspeed%20Roundabouts.pdf, Accessed on May, 2021.

Persaud, B. N., R. A. Retting, P. E. Garder, and D. Lord. Safety Effect of Roundabout Conversions in the United States: Empirical Bayes Observational before-after Study. *Transportation Research Record: Journal of the Transportation Research Board*, # 1751, 2001, pp. 1-8.

Pochowski, A., A. Paul, and L.A. Rodegerdts. *Roundabout Practices A Synthesis of Highway Practice*. NCHRP Synthesis 488, National Cooperative Highway Research Program Synthesis Program, Transportation Research Board, Washington D.C., 2016. DOI 10.17226/23477 Accessed on November 20, 2021.

Qin, X., A. Bill, M. Chitturi, and D. Noyce. Evaluation of Roundabout Safety. In *92nd Annual Meeting of the Transportation Research Board*, Washington, D.C., 2013.

Rhodes, B. Frank Blackmore Determined, Maverick Traffic Engineer Who Invented the Mini-Roundabout. The Guardian, 2008. https://www.theguardian.com/theguardian/2008/jun/21/6, Accessed on December 20, 2019.

Robinson, B. W., L. Rodegerdts, W. Scarbrough, W. Kittelson, R. Troutbeck, W. Brilon, L. Bondzio, K. Courage, M. Kyte, J. Mason, A. Flannery, E. Myers, J. Bunker, and G. Jacquemart. *Roundabouts: An Informational Guide*. Report FHWA-RD-00-067. FHWA, U.S. Department of Transportation, June 2000.

Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O’Brien. *Roundabouts:*

An Informational Guide, 2nd Edition. NCHRP Report # 672, Transportation Research Board, Washington, D.C., 2010.

Rodegerdts, L., M. Blogg, E. Wemple, E. Myres, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter. *Roundabouts in the United States*. NCHRP Report # 572, Transportation Research Board, Washington, D.C., 2007.

Sawers, C. Mini-Roundabouts for the United States. *Institute of Transportation Engineers, ITE Journal*, Vol. 79(2), 2009, pp. 46-50.

Srinivasan, R., and K. Bauer. *Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs*. Report # FHWA-SA-14-005 Federal Highway Administration Office of Safety, Washington, D.C., 2013. https://safety.fhwa.dot.gov/rsdp/downloads/spf_developde_final.pdf, Accessed on May 2022.

Srinivasan, R., D. Carter, and K. Bauer. *Safety Performance Function Decision Guide: SPF Calibration vs SPF Development*. Report # FHWA-SA-14-004 Federal Highway Administration Office of Safety, Washington, D.C., 2013. https://rosap.ntl.bts.gov/view/dot/49504, Accessed on May 2022.

Stein, W., (2018). Mini-Roundabouts in Minnesota: Benefits of Roundabouts with a Smaller Footprint and Lower Cost. *Institute of Transportation Engineers, ITE Journal*, Vol. 88(8), 2018, pp. 35-39. https://www.proquest.com/scholarly-journals/mini-roundabouts-minnesota-benefits-with-smaller/docview/2099845840/se-2

Šurdonja, S., S. Babić, A. Deluka-Tibljaš, and M. Cuculić. Mini-Roundabouts in Urban Areas. In *2nd International Conference on Road and Rail Infrastructure (CETRA)*, 2012, Dubrovnik, Croatia, pp. 997-1003.

Tsapakis, I., S. Sharma, B. Dadashova, S. Geedipally, A. Sanchez, M. Le, L. Cornejo, S. Das, and K. Dixon. *Evaluation of Highway Safety Improvement Projects and Countermeasures: Technical Report*. Report # FHWA/TX-19/0-6961-R1 Texas Department of Transportation Research and Technology Implementation Office, Austin, Texas, 2019. http://tti.tamu.edu/documents/0-6961-R1.pdf, Accessed on April 2021.

Waddell, E., and J. Albertson. The Dimondale Mini: America's First Mini-Roundabout. In *International Conference on Roundabouts*, Transportation Research Board, Subcommittee on Roundabouts, Vail Colorado, 2005.

Walker, J. S., and S. R. Pittam. *Accidents at Mini-Roundabouts: Frequencies and Rates.* TRRL Contractor Report 161, Department of Transport, TRRL, Berkshire, UK, 1989.

Wang, X., M. Abdel-Aty, A. Nevarez, and J. B. Santos. Investigation of Safety Influence Area for Four-Legged Signalized Intersections: Nationwide Survey and Empirical Inquiry. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2083, 2008, pp. 86-95. https://doi.org/10.3141/2083-10.

Wilkinson, B. Compact and Mini-Roundabouts: Maximized Safety at Minimum Size. MSA Professional Services, 2020. https://www.msa-ps.com/compact-and-mini-roundabouts-maximized-safety-at-minimum-size/, Accessed May 15, 2021.

Yap, Y. H., H. M. Gibson, and B. J. Waterson. An International Review of Roundabout Capacity Modelling. *Transport Reviews*, Vol. 33(5), 2013, pp. 593–616. https://doi.org/10.1080/01441647.2013.830160.

Zhang, W., and N. Kronprasert. Mini-Roundabout Case Studies. In 4th *International Roundabout Conference,* Seattle, Washington, 2014.

Zhang, W., J. Bared, and R. Jaganathan. Mini-Roundabouts. Year Unknown, https://www.dot.state.mn.us/stateaid/trafficsafety/roundabout/fhwa-brochure.pdf, Accessed on December 15, 2019.

Zito, R., and M. A. P. Taylor. Speed Profiles and Vehicles Fuel Consumption at LATM Devices. *In Proceedings of ARRB Conference*, 1996, pp. 391-406.

APPENDIX A: QUESTIONNAIRE

Mini-Roundabout Questionnaire

Division number :

Date :

1. Are there any mini-roundabouts constructed in your division? If yes, please list each location (street name, cross-street name, nearest landmark, etc.) and the year of construction.

2. Are there any ongoing mini-roundabout construction projects or plans to construct in the future in your division? If yes, please list each location (street name, cross-street name, nearest landmark, etc.) and the planned year of construction.

3. Do you think that mini-roundabouts are safe?

4. What do you think about the safety of vulnerable road users (pedestrians and bicyclist) at mini-roundabouts?

For more information about mini-roundabouts, please refer to Federal Highway Administration (FHWA), U.S. DOT. Technical Summary - Mini-Roundabouts. FHWA-SA-10-007, Washington DC, 2010. https://safety.fhwa.dot.gov/intersection/innovative/roundabouts/fhwasa10007/fhwasa10007.pdf.

APPENDIX B: DATA SOURCES AND MINI-ROUNDABOUT DETAILS

Table B-1. Crash data sources.

State	Sources
Georgia	GDOT: Georgia Electronic Accident Reporting System (GEARS)
Iowa	IOWADOT: Iowa Crash Analysis Tool (ICAT) (online)
Michigan	Michigan State Police, Criminal Justice Information Center
Minnesota	MnDOT: MnDOT Office of Traffic Engineering (OTE)
Missouri	MoDOT: Public Record Request Portal
North Carolina	NCDOT: Transportation Mobility & Safety Division
Virginia	VDOT Crash Analysis Tool (online)
Washington State	WSDOT: Public Disclosure Request Portal

Table B-2. Traffic volume data sources.

State	Source
Georgia	GDOT traffic volume maps, HPMS database
Iowa	IOWADOT traffic volume maps, HPMS database
Michigan	MDOT traffic volume maps, Genesee County traffic count database, Washtenaw County traffic count database, Southeast Michigan Council of Governments (SEMCOG) traffic count database, HPMS database
Minnesota	MnDOT traffic volume maps, HPMS database
Missouri	MoDOT traffic volume maps, HPMS database
North Carolina	NCDOT traffic volume maps, HPMS database
Virginia	VDOT traffic volume maps, HPMS database
Washington State	WSDOT traffic volume maps, Skagit County traffic count database, Snohomish County traffic count database, Whatcom County traffic counts database, HPMS database

Table B-3. List of selected mini-roundabouts.

Site # ID	State	County	City	Latitude	Longitude	Intersection name	Prior control type	# of legs	Built year	Speed limit (mph)
1	GA	Henry	McDonough	33.462826	-83.96864	GA 81 / Snapping Shoals Rd / Jackson Lake Rd	TWSC	4	2016	55
2	GA	Butts	Jackson	33.38354	-83.90331	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	AWSC	4	2017	55
3	GA	Newton	Covington	33.429632	-83.84706	GA36 / GA212	AWSC	4	2015	55
4	GA	Jackson	Jefferson	34.091894	-83.61568	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	AWSC	4	2013	50
5	GA	Coweta	Turin	33.329808	-84.64482	GA 16 / GA 54	AWSC	4	2016	55
6	IA	Linn	Marion	42.050433	-91.57448	29th Ave / 35th St	TWSC	4	2016	35
7	MI	Washtenaw	Saline	42.19859	-83.79691	Ann Arbor-Saline Rd / Textile Rd	AWSC	4	2016	50
8	MI	Washtenaw	Ypsilanti	42.201706	-83.62094	Textile Rd / Hitchingham Rd	AWSC	4	2015	45
9	MI	Washtenaw	Ypsilanti	42.20173	-83.62312	Textile Rd / Stony Creek Rd	AWSC	4	2015	45
10	MI	Washtenaw	Saline	42.170612	-83.73831	Moon Rd / Bemis Rd	AWSC	4	2018	55
11	MN	Scott	Shakopee	44.783334	-93.52014	Vierling Dr E / Rd 79	AWSC	4	2014	45
12	MN	Olmsted	Rochester	44.071671	-92.48882	18th Ave NW (County Road 112) / 48th St	TWSC	4	2018	40
13	MN	Scott	Savage	44.7393	-93.36903	S Park Dr / Louisiana Ave S	TWSC	4	2016	45
14	MO	Miller	Lakeland	38.21423	-92.62436	US 54 Business / N Shore Dr	OWSC	3	2014	45
15	NC	Durham	Durham	36.040047	-78.90842	Carver St / Broad St / Kenan Rd	TWSC	4	2016	35
16	NC	Wilkes	Wilkesboro	36.19561	-81.14437	Fairplains Rd / Reynolds Rd	OWSC	3	2017	35
17	VA	Fairfax	Annandale	38.82629	-77.19992	Ravensworth Rd / Jayhawk St / Fountain Head Dr	TWSC	4	2018	35
18	WA	Skagit	Mount Vernon	48.399471	-122.3281	Anderson Rd / Cedardale Rd	TWSC	4	2013	35
19	WA	Whatcom	Bellingham	48.833025	-122.3767	Everson Goshen Rd / E Smith Rd	AWSC	4	2015	50
20	WA	Whatcom	Ferndale	48.817168	-122.5443	Slater Rd / Pacific Hwy	TWSC	4	2014	35
21	WA	Whatcom	Lynden	48.964108	-122.4075	SR 546 / Northwood Rd	TWSC	4	2016	45
22	WA	Skagit	Burlington	48.452	-122.3317	E George Hopper Rd / S Walnut St	TWSC	4	2015	35
23	WA	Whatcom	Ferndale	48.81707	-122.5505	Slater Rd / I-5 SB Ramps	OWSC (ramp)	4	2014	55
24	WA	Whatcom	Ferndale	48.817358	-122.5460	Slater Rd / I-5 NB Ramps	OWSC (ramp)	4	2014	55
25	WA	Whatcom	Ferndale	48.858362	-122.5861	Portal Way / I-5 NB Ramps	OWSC (ramp)	4	2018	40

Note: Speed limit indicated is the posted approach speed limit (maximum); 1 mph = 1.61 kmph.

Table B-4. Selected mini-roundabouts – area and land use type.

Site # ID	State	Intersection name	Prior control type	# of legs	Built year	Area type	Land use
1	GA	GA 81 / Snapping Shoals Rd / Jackson Lake Rd	TWSC	4	2016	Rural	Mixed (Residential + Commercial)
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	AWSC	4	2017	Rural	Mixed (Residential + Commercial)
3	GA	GA36 / GA212	AWSC	4	2015	Rural	Mixed (Residential + Commercial)
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	AWSC	4	2013	Urban/suburban	Mixed (Residential + Commercial)
5	GA	GA 16 / GA 54	AWSC	4	2016	Rural	Mixed (Residential + Commercial)
6	IA	29th Ave / 35th St	TWSC	4	2016	Urban/suburban	Residential
7	MI	Ann Arbor-Saline Rd / Textile Rd	AWSC	4	2016	Urban/suburban	Mixed (Residential + Commercial)
8	MI	Textile Rd / Hitchingham Rd	AWSC	4	2015	Urban/suburban	Mixed (Residential + Commercial)
9	MI	Textile Rd / Stony Creek Rd	AWSC	4	2015	Urban/suburban	Mixed (Residential + Commercial)
10	MI	Moon Rd / Bemis Rd	AWSC	4	2018	Rural	Mixed (Residential + Commercial)
11	MN	Vierling Dr E / Rd 79	AWSC	4	2014	Urban/suburban	Residential
12	MN	18th Ave NW (County Road 112) / 48th St	TWSC	4	2018	Urban/suburban	Mixed (Residential + Commercial)
13	MN	S Park Dr / Louisiana Ave S	TWSC	4	2016	Urban/suburban	Residential
14	MO	US 54 Business / N Shore Dr	OWSC	3	2014	Rural	Mixed (Residential + Commercial)
15	NC	Carver St / Broad St / Kenan Rd	TWSC	4	2016	Urban/suburban	Mixed (Residential + Commercial)
16	NC	Fairplains Rd / Reynolds Rd	OWSC	3	2017	Rural	Residential
17	VA	Ravensworth Rd / Jayhawk St / Fountain Head Dr	TWSC	4	2018	Urban/suburban	Mixed (Residential + Commercial)
18	WA	Anderson Rd / Cedardale Rd	TWSC	4	2013	Urban/suburban	Mixed (Residential + Commercial)
19	WA	Everson Goshen Rd / E Smith Rd	AWSC	4	2015	Rural	Residential
20	WA	Slater Rd / Pacific Hwy	TWSC	4	2014	Urban/suburban	Mixed (Residential + Industrial)
21	WA	SR 546 / Northwood Rd	TWSC	4	2016	Rural	Mixed (Residential + Commercial)
22	WA	E George Hopper Rd / S Walnut St	TWSC	4	2015	Urban/suburban	Commercial
23	WA	Slater Rd / I-5 SB Ramps	OWSC (ramp)	4	2014	Urban/suburban	Mixed (Residential + Industrial)
24	WA	Slater Rd / I-5 NB Ramps	OWSC (ramp)	4	2014	Urban/suburban	Mixed (Residential + Industrial)
25	WA	Portal Way / I-5 NB Ramps	OWSC (ramp)	4	2018	Urban/suburban	Residential

Table B-5. Traffic volume at the selected mini-roundabouts.

Site # ID	State	Prior control type	Before period			After period		
			Major street traffic volume	Cross-street traffic volume	Total traffic volume (major + cross-street)	Major street traffic volume	Cross-street traffic volume	Total traffic volume (major + cross-street)
1	GA	TWSC	4,550	1,726	6,276	5,503	2,513	8,015
6	IA	TWSC	6,035	3,643	9,678	7,883	4,808	12,691
12	MN	TWSC	10,038	2,498	12,536	10,342	2,608	12,950
13	MN	TWSC	5,405	4,350	9,755	5,925	5,400	11,325
14	MO	OWSC	5,000	4,768	9,768	5,673	5,269	10,942
15	NC	TWSC	11,300	6,070	17,370	10,250	5,600	15,850
16	NC	OWSC	1,970	386	2,356	2,100	370	2,470
17	VA	TWSC	13,849	2,837	16,686	13,568	2,551	16,119
18	WA	TWSC	4,237	2,767	7,004	6,458	3,313	9,771
20	WA	TWSC	8,653	2,013	10,666	13,176	2,499	15,675
21	WA	TWSC	7,192	2,090	9,282	7,605	2,109	9,714
22	WA	TWSC	7,500	3,072	10,572	7,500	3,380	10,880
23	WA	OWSC (ramp)	14,726	6,846	21,573	14,854	6,806	21,660
24	WA	OWSC (ramp)	8635	6,374	15,009	9,766	6,615	16,380
25	WA	OWSC (ramp)	7345	5,578	12,923	8,226	6,212	14,438
2	GA	AWSC	5,454	1,834	7,288	5,704	1,588	7,291
3	GA	AWSC	7,238	4,274	11,512	9,221	5,590	14,811
4	GA	AWSC	6,836	3,860	10,696	11,780	4,702	16,482
5	GA	AWSC	11,640	8,590	20,230	14,133	9,823	23,957
7	MI	AWSC	10,062	3,530	13,592	10,813	4,655	15,468
8	MI	AWSC	7,641	5,078	12,719	6,910	7,001	13,910
9	MI	AWSC	7,641	3,896	11,537	6,910	3,784	10,693
10	MI	AWSC	6,775	6,409	13,184	6,867	6,764	13,631
11	MN	AWSC	7,636	7,010	14,646	7,414	6,800	14,214
19	WA	AWSC	6,199	5,107	11,306	5,344	5,461	10,805

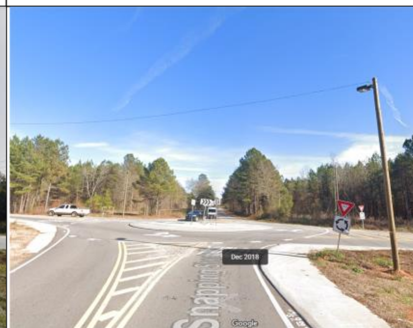
Before	After	Before	After
			
Site ID # 1		Site ID # 6	
			
Site ID # 12		Site ID # 13	

Figure B-1(A). Before and after pictures of TWSC intersections converted to mini-roundabouts (© Google street view).

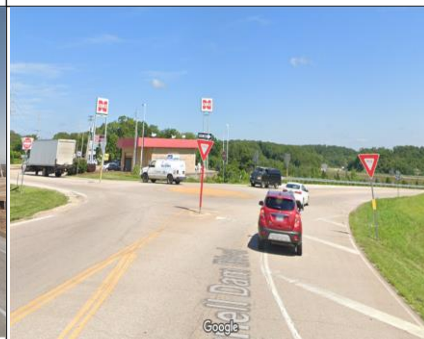
Before	After	Before	After
			
Site ID # 14 (3-legged)		Site ID #15	
			
Site ID # 16 (3-leeged)		Site ID # 17	

Figure B-1(B). Before and after pictures of TWSC/OWSC intersections converted to mini-roundabouts (© Google street view).

Before	After	Before	After
			
Site ID # 18		Site ID # 20	
			
Site ID # 21		Site ID # 22	

Figure B-1(C). Before and after pictures of TWSC intersections converted to mini-roundabouts (© Google street view).

Before	After
	
Site ID # 23 (OWSC ramp)	
	
Site ID # 24 (OWSC ramp)	
	
Site ID # 25 (OWSC ramp)	

Figure B-1(D). Before and after pictures of OWSC ramp intersections converted to mini-roundabouts (© Google street view).

Before	After	Before	After
			
Site ID # 2		Site ID # 3	
			
Site ID # 4		Site ID # 5	

Figure B-2(A). Before and after pictures of AWSC intersections converted to mini-roundabouts (© Google street view).

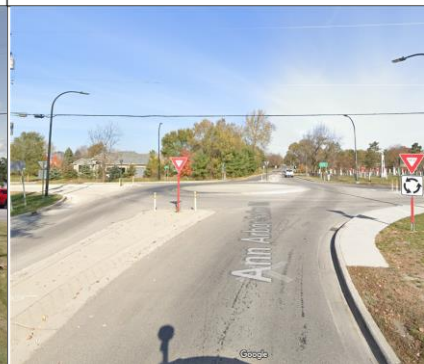
Before	After	Before	After
			
Site ID # 7		Site ID # 8	
			
Site ID # 9		Site ID # 10	

Figure B-2(B). Before and after pictures of AWSC intersections converted to mini-roundabouts (© Google street view).

Before	After	Before	After
			
Site ID # 11		Site ID # 19	

Figure B-2(C). Before and after pictures of AWSC intersections converted to mini-roundabouts (© Google street view).

APPENDIX C: NAÏVE BEFORE-AFTER ANALYSIS EQUATIONS

Equations used for odds ratio and standard error computation are reproduced from Hauer (1997) and Tsapakis et al. (2019).

$N_{Observed,B}$ = observed number of crashes at intersection *i* in the before period.

$N_{Observed,A}$ = observed number of crashes at intersection *i* in the after period.

$N_{Expected,A}$ = expected number of crashes at intersection *i* in the after period.

$$r_{duration} = \frac{Duration\ of\ after\ period}{Duration\ of\ before\ period} \tag{C.1}$$

where $r_{duration}$ = ratio of duration of after period to duration of before period.

$$N_{Expected,A} = r_{duration} \times N_{Observed,B} \tag{C.2}$$

where $r_{duration}$ is from equation (C.1).

$$V_{Expected,A} = r_{\text{duration}}^2 \times N_{Observed,B}$$

where $V_{Expected,A}$ = variance of the expected crashes in the after period.

$$OR_i = \frac{N_{Observed,A}}{N_{Expected,A}} \tag{C.3}$$

where OR_i = odds ratio for intersection *i*, and,

$$\text{Safety Effectiveness}_i = 100 \times (1 - OR_i) \tag{C.4}$$

where Safety Effectiveness$_i$ = safety effectiveness at intersection *i*.

$$\text{OR}' = \frac{\sum_{All\ sites} N_{Observed,A}}{\sum_{All\ sites} N_{Expected,A}} \quad \text{(C.5)}$$

where OR′ = odds ratio of all intersections combined.

$$OR = \frac{OR'}{1+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}} \quad \text{(C.6)}$$

where OR = unbiased odd ratio estimated of effectiveness,

$$Var\left(\sum_{All\ sites} N_{Expected,A}\right) = \sum_{All\ sites} V_{Expected,A}$$

Safety Effectiveness = 100 × (1- OR) (C.7)

where Safety Effectiveness = overall unbiased safety effectiveness.

$$\text{Var(OR)} = \frac{(OR')^2\left[\frac{1}{N_{Observed,A}}+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]}{\left[1+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]^2} \quad \text{(C.8)}$$

where Var(OR) = variance of the unbiased estimated safety effectiveness.

$$\text{SE(OR)} = \sqrt{Var(OR)} \quad \text{(C.9)}$$

where SE(OR) = Standard error.

SE (Safety Effectiveness) = 100 × SE(OR) (C.10)

where SE (Safety Effectiveness) = standard error of safety effectiveness.

APPENDIX D: NAÏVE BEFORE-AFTER ANALYSIS WITH VOLUME CORRECTION EQUATIONS

Equations used for odds ratio and standard error computation with volume correction are reproduced from Hauer (1997) and Tsapakis et al. (2019).

$N_{Observed,B}$ = observed number of crashes at intersection *i* in the before period.

$N_{Observed,A}$ = observed number of crashes at intersection *i* in the after period.

$N_{Expected,A}$ = expected number of crashes at intersection *i* in the after period.

$$r_{duration} = \frac{Duration\ of\ after\ period}{Duration\ of\ before\ period} \quad (D.1)$$

where $r_{duration}$ = ratio of duration of after period to duration of before period.

$$r_{volume} = \frac{Average\ traffic\ volume\ after}{Average\ traffic\ volume\ before} \quad (D.2)$$

where Average traffic volume after = Average total intersection traffic volume (major street + cross-street) in the after period, and,

Average traffic volume before = Average total intersection traffic volume (major street + cross-street) in the before period.

$$N_{Expected,A} = r_{duration} \times r_{volume} \times N_{Observed,B} \quad (D.3)$$

where $r_{duration}$ and r_{volume} are from equations (D.1) and (D.2).

$$Var(r_{volume}) = 1 + (7.7/\text{number of count days}) + (1650/AADT^{0.82}) \quad (D.4)$$

where $Var(r_{volume})$ = variance of volume ratio.

$$V_{Expected,A} = r_{duration}^2 \times (r_{volume}^2 \times N_{Observed,B} + Var(r_{volume}) \times N_{Observed,B}^2) \quad \text{(D.5)}$$

where $V_{Expected,A}$ = variance of expected crash in the after period, and,

$r_{duration}$, r_{volume}, and $Var(r_{volume})$ are from equation (D.1), (D.2) and (D.4).

$$OR_i = \frac{N_{Observed,A}}{N_{Expected,A}} \quad \text{(D.6)}$$

where OR_i = odds ratio for intersection i.

$$\text{Safety Effectiveness}_i = 100 \times (1- OR_i) \quad \text{(D.7)}$$

where Safety Effectiveness$_i$ = safety effectiveness at intersection i.

$$OR' = \frac{\sum_{All\ sites} N_{Observed,A}}{\sum_{All\ sites} N_{Expected,A}} \quad \text{(D.8)}$$

where OR′ = odds ratio of all intersections combined.

$$OR = \frac{OR'}{1+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}} \quad \text{(D.9)}$$

where OR = unbiased odd ratio estimated of effectiveness,

$Var\left(\sum_{All\ sites} N_{Expected,A}\right) = \sum_{All\ sites} V_{Expected,A}$

$$\text{Safety Effectiveness} = 100 \times (1- OR) \quad \text{(D.10)}$$

where Safety Effectiveness = overall unbiased safety effectiveness.

$$\text{Var(OR)} = \frac{(OR')^2\left[\frac{1}{N_{Observed,A}}+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]}{\left[1+\frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]^2} \quad \text{(D.11)}$$

where Var(OR) = variance of the unbiased estimated safety effectiveness.

$$\text{SE(OR)} = \sqrt{Var(OR)} \quad \text{(D.12)}$$

where SE(OR) = Standard error.

$$\text{SE (Safety Effectiveness)} = 100 \times \text{SE(OR)} \quad \text{(D.13)}$$

where SE (Safety Effectiveness) = standard error of safety effectiveness.

APPENDIX E: REFERENCE INTERSECTIONS AND EB ANALYSIS

Table E-1. Reference intersections descriptive statistics crashes per year – TWSC/OWSC.

State	Intersection type	# of intersections	Minimum	Median	Mean	Maximum	IQR	Std. dev.
Total								
Georgia	4ST	47	0	1	1.51	12	2	1.94
Iowa	4ST	59	0	1	1.39	13	2	1.61
Minnesota	4ST	50	0	1	1.09	6	2	1.40
Missouri	3ST	38	0	0	0.51	6	1	0.93
North Carolina	3ST	57	0	0	0.84	9	1	1.38
	4ST	57	0	1	1.59	11	2	1.63
Virginia	4ST	40	0	1	2.01	14	3	2.38
Washington State	4ST	74	0	1	1.11	7	2	1.45
	4ST (ramp)	55	0	1	1.33	11	2	1.69
FI								
Georgia	4ST	47	0	0	0.61	8	1	1.03
Iowa	4ST	59	0	0	0.53	6	1	0.86
Minnesota	4ST	50	0	0	0.55	4	1	0.89
Missouri	3ST	38	0	0	0.10	3	0	0.37
North Carolina	3ST	57	0	0	0.29	4	0	0.66
	4ST	57	0	0	0.75	5	1	1.00
Virginia	4ST	40	0	0	0.85	9	1	1.26
Washington State	4ST	74	0	0	0.48	6	1	0.86
	4ST (ramp)	55	0	0	0.38	6	1	0.72
PDO								
Georgia	4ST	47	0	0	0.90	8	0	1.32
Iowa	4ST	59	0	1	0.86	7	1	1.11
Minnesota	4ST	50	0	0	0.53	5	1	0.85
Missouri	3ST	38	0	0	0.41	5	1	0.79
North Carolina	3ST	57	0	0	0.52	6	1	0.99
	4ST	57	0	0	0.82	8	1	1.10
Virginia	4ST	40	0	1	1.15	8	2	1.58
Washington State	4ST	74	0	0	0.63	5	1	0.96
	4ST (ramp)	55	0	1	0.95	9	1	1.30

Note: Crash data 2011-2019, IQR is interquartile range (range between the 25th and 75th values for the given measurement), 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street.

Table E-2. Reference intersections descriptive statistics crashes per year – AWSC.

State	Intersection type	# of intersections	Minimum	Median	Mean	Maximum	IQR	Std. dev.
				Total				
Georgia	AWSC	49	0	1	1.54	10	2	1.87
Michigan	AWSC	50	0	1	1.76	10	3	1.72
Minnesota	AWSC	55	0	1	1.35	9	2	1.54
Washington State	AWSC	43	0	1	1.21	9	2	1.43
				FI				
Georgia	AWSC	49	0	0	0.41	6	1	0.78
Michigan	AWSC	50	0	0	0.32	5	0	0.64
Minnesota	AWSC	55	0	0	0.45	4	1	0.75
Washington State	AWSC	43	0	0	0.40	5	1	0.73
				PDO				
Georgia	AWSC	49	0	1	1.12	9	2	1.47
Michigan	AWSC	50	0	1	1.44	10	2	1.46
Minnesota	AWSC	55	0	0	0.89	7	1	1.22
Washington State	AWSC	43	0	0	0.79	8	1	1.13

Note: Crash data 2011-2019, four-legged all-way stop-controlled intersection, IQR is interquartile range (range between the 25th and 75th values for the given measurement).

Table E-3. Reference intersections descriptive statistics traffic volume – TWSC/OWSC.

State	Intersection type	# of intersections	Minimum	Median	Mean	Maximum	IQR	Std. dev.
				Major street				
Georgia	4ST	47	170	1,570	2,527	11,700	2,940	2,286
Iowa	4ST	59	164	3,856	4,328	12,000	3,250	2,405
Minnesota	4ST	50	560	4,750	4,991	14,400	3,542	2,427
Missouri	3ST	38	134	2,141	2,776	10,550	2,005	2,112
North Carolina	3ST	57	280	3,300	3,800	22,500	2,400	3,095
	4ST	57	500	3,200	4,044	15,500	3,350	3,044
Virginia	4ST	40	688	6,689	7,801	26,028	6,981	5,200
Washington State	4ST	74	1,025	3,564	4,787	15,101	4,344	3,529
	4ST (ramp)	55	552	4,257	5,582	25,842	5,558	4,692
				Cross-street				
Georgia	4ST	47	80	430	636	2,450	745	525
Iowa	4ST	59	52	1,777	1,875	5,600	1,492	1,147
Minnesota	4ST	50	80	1,300	1,634	5,400	1,322	1,140
Missouri	3ST	38	122	419	793	5,461	733	931
North Carolina	3ST	57	90	850	1,297	4,700	1,370	1,082
	4ST	57	160	1,075	1,300	5,100	1,200	989
Virginia	4ST	40	175	1,710	1,843	6,222	1,846	1,268
Washington State	4ST	74	162	1,182	1,548	4,676	1,262	1,127
	4ST (ramp)	55	423	2,537	2,893	10,626	2,953	2,143

Note: Traffic volume 2011-2019, IQR is interquartile range (range between the 25th and 75th values for the given measurement), 4ST – four-legged stop-controlled at cross-street, 3ST – three-legged stop-controlled at cross-street.

Table E-4. Reference intersections descriptive statistics traffic volume – AWSC.

State	Intersection type	# of intersections	Minimum	Median	Mean	Maximum	IQR	Std. dev.
				Major street				
Georgia	AWSC	49	640	2,350	2,739	10,200	2,670	1,817
Michigan	AWSC	50	500	4,149	4,383	11,302	2,850	2,100
Minnesota	AWSC	55	1,150	6,130	6,036	17,200	2,417	2,172
Washington State	AWSC	43	732	4,915	5,138	16,170	4,257	3,184
				Cross-street				
Georgia	AWSC	49	350	1,200	1,551	7,540	1,530	1,291
Michigan	AWSC	50	348	2,417	2,647	6,590	2,246	1,480
Minnesota	AWSC	55	632	3,209	3,825	8,433	2,575	1,787
Washington State	AWSC	43	464	2,258	2,736	9,280	2,473	1,945

Note: Traffic volume 2011-2019, IQR is interquartile range (range between the 25th and 75th values for the given measurement).

Table E-5. Comparing multiple-vehicle and single-vehicle crash estimates from SPFs for TWSC intersections in urban/suburban areas.

Site ID	Pred. # of multiple-vehicle crashes	Pred. # of single-vehicle crashes	Pred. # of crashes using SPF and calibration factor	Pred. # of multiple-vehicle crashes	Pred. # of single-vehicle crashes	Pred. # of crashes using SPF and calibration factor
	Before period (crashes per year)			After period (crashes per year)		
Considering both multiple-vehicle and single-vehicle crashes SPFs						
6	1.32	0.23	1.98	1.78	0.26	2.92
12	1.84	0.26	2.07	1.91	0.26	2.03
13	1.27	0.23	1.71	1.45	0.24	1.49
15	2.54	0.30	5.09	2.29	0.29	5.20
17	2.48	0.29	3.49	2.37	0.29	3.75
18	0.93	0.20	1.13	1.38	0.23	1.61
20	1.54	0.24	1.78	2.30	0.28	2.59
22	1.53	0.24	1.77	1.57	0.24	1.81
Sum	13.45	1.98	19.02	15.05	2.09	21.39
Considering only multiple-vehicle crashes SPF						
6	1.32	-	2.06	1.78	-	3.15
12	1.84	-	2.19	1.91	-	2.14
13	1.27	-	1.75	1.45	-	1.53
15	2.54	-	5.62	2.29	-	5.65
17	2.48	-	3.65	2.37	-	3.89
18	0.93	-	0.93	1.38	-	1.38
20	1.54	-	1.54	2.30	-	2.30
22	1.53	-	1.53	1.57	-	1.57
Sum	13.45	-	19.28	15.05	-	21.61

Table E-6(A). EB analysis for total crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Intersection name	Latitude	Longitude	Built year	Before period: # of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor: Y1	Y2	Y3	Y4	Y5	Total	Total exp. # of crashes	Exp. # of crashes per year
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	GA	GA 81 / Snapping Shoals Rd / Jackson Lake Rd	33.462826	-83.968645	2016	5	56	11.20	3.64	4.02	3.46	3.84	5.17	20.13	49.85	9.97
6	IA	29th Ave / 35th St	42.050433	-91.574481	2016	5	25	5.00	1.36	1.54	1.89	2.71	2.80	10.29	22.13	4.43
12	MN	18th Ave / 48th St	44.071671	-92.488824	2018	5	12	2.40	2.57	2.33	2.73	1.75	1.58	10.95	11.80	2.36
13	MN	S Park Dr / Louisiana Ave S	44.7393	-93.36903	2016	5	2	0.40	1.91	1.41	1.78	1.68	1.99	8.77	3.50	0.70
14*	MO	US 54 Business / N Shore Dr	38.21423	-92.62436	2014	5	42	8.40	1.96	2.86	1.48	1.87	1.18	9.35	36.60	7.32
15	NC	Carver St / Broad St / Kenan Rd	36.040047	-78.908427	2016	5	36	7.20	5.27	5.68	3.97	6.39	6.80	28.11	35.36	7.07
16*	NC	Fairplains Rd / Reynolds Rd	36.19561	-81.14437	2017	5	0	0	0.25	0.20	0.36	0.23	0.32	1.36	0.78	0.16
17	VA	Ravensworth Rd / Jayhawk St / Fountain Head Dr	38.82629	-77.19992	2018	5	13	2.60	3.60	4.47	3.47	3.60	3.10	18.25	13.63	2.73
18	WA	Anderson Rd / Cedardale Rd	48.399471	-122.328164	2013	5	13	2.60	0.95	0.95	1.19	0.97	0.95	5.00	10.33	2.07
20	WA	Slater Rd / Pacific Hwy	48.817168	-122.544338	2014	5	14	2.80	1.49	1.92	1.56	1.66	2.16	8.79	12.84	2.57
21	WA	SR 546 / Northwood Rd	48.964108	-122.407553	2016	5	9	1.80	1.24	1.15	2.08	1.48	1.72	7.68	8.53	1.71
22	WA	E George Hopper Rd / S Walnut St	48.452	-122.33174	2015	5	2	0.40	1.97	1.60	1.57	2.00	2.12	9.28	3.54	0.71
23$^{\Psi}$	WA	Slater Rd / I-5 SB Ramps	48.81707	-122.5505	2014	5	18	3.60	2.65	2.65	1.99	2.25	2.66	12.21	16.88	3.38
24$^{\Psi}$	WA	Slater Rd / I-5 NB Ramps	48.817358	-122.546092	2014	5	12	2.40	2.18	2.18	1.64	1.87	2.21	10.07	11.56	2.31
25$^{\Psi}$	WA	Portal Way / I-5 NB Ramps	48.858362	-122.586126	2018	5	8	1.60	1.78	1.92	2.03	2.43	2.72	10.89	8.61	1.72

Note: *Three-legged, $^{\Psi}$OWSC (ramp).

Table E-6(B). EB analysis for total crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	Built year	After period															Odds ratio (observed crashes/expected crashes)					
		# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Exp. # of crashes											
					Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total (observed crashes/expected crashes)
1	2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
1	2016	3	27	9.00	5.40	5.40	9.01			19.81	13.37	13.37	22.31			49.05	0.60	0.75	0.40			0.55
6	2016	3	13	4.33	3.20	3.13	3.12			9.45	6.88	6.74	6.71			20.33	0.73	0.74	0.45			0.64
12	2018	1	4	4.00	2.14					2.14	2.31					2.31	1.73					1.73
13	2016	3	7	2.33	1.14	1.77	1.69			4.60	0.46	0.71	0.67			1.84	6.57	1.42	4.46			3.81
14*	2014	5	8	1.60	3.38	2.46	2.45	1.73	2.59	12.61	13.25	9.64	9.58	6.76	10.14	49.36	0	0.10	0.21	0.44	0.20	0.16
15	2016	3	14	4.67	5.46	5.64	5.85			16.96	6.87	7.10	7.36			21.33	0.58	0.70	0.68			0.66
16*	2017	2	2	1.00	0.33	0.29				0.62	0.19	0.17				0.36	10.47	0				5.60
17	2018	1	1	1.00	3.89					3.89	2.91					2.91	0.34					0.34
18	2013	5	43	8.60	1.82	1.30	1.36	1.90	2.38	8.76	3.76	2.69	2.81	3.92	4.92	18.09	1.60	2.60	4.28	1.27	2.64	2.38
20	2014	5	15	3.00	2.58	2.36	3.27	3.12	2.88	14.22	3.77	3.45	4.78	4.57	4.22	20.79	0.80	1.74	0.21	0.22	0.95	0.72
21	2016	3	5	1.67	2.06	2.32	2.59			6.97	2.29	2.58	2.88			7.75	0.87	0	1.04			0.65
22	2015	4	7	1.75	1.61	2.22	2.11	1.94		7.89	0.62	0.85	0.81	0.74		3.01	1.62	1.18	2.48	4.05		2.32
23$^{\Psi}$	2014	5	19	3.80	2.64	3.20	3.43	2.99	2.48	14.75	3.65	4.42	4.74	4.14	3.43	20.39	0.82	0.45	0.84	1.45	1.16	0.93
24$^{\Psi}$	2014	5	17	3.40	2.23	2.71	3.00	2.63	2.24	12.82	2.56	3.11	3.45	3.02	2.58	14.72	1.17	0.64	0.29	1.98	1.94	1.16
25$^{\Psi}$	2018	1	1	1.00	1.99					1.99	1.57					1.57	0.64					0.64

Note: *Three-legged, $^{\Psi}$OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

Table E-7(A). EB analysis for FI crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Intersection name	Latitude	Longitude	Built year	Before period: # of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor: Y1	Y2	Y3	Y4	Y5	Total	Total exp. # of crashes	Exp. # of crashes per year
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	GA	GA 81 / Snapping Shoals Rd / Jackson Lake Rd	33.462826	-83.968645	2016	5	23	4.60	1.18	1.10	1.40	1.36	2.75	7.78	17.69	3.54
6	IA	29th Ave / 35th St	42.050433	-91.574481	2016	5	6	1.20	0.57	0.58	0.70	1.02	0.94	3.82	5.23	1.05
12	MN	18th Ave / 48th St	44.071671	-92.488824	2018	5	5	1.00	1.24	1.20	1.71	0.79	1.03	5.97	5.25	1.05
13	MN	S Park Dr / Louisiana Ave S	44.7393	-93.36903	2016	5	1	0.20	1.05	0.77	0.82	0.83	1.19	4.66	2.13	0.43
14*	MO	US 54 Business / N Shore Dr	38.21423	-92.62436	2014	5	5	1.00	0.33	0.54	0.10	0.10	0.22	1.29	2.81	0.56
15	NC	Carver St / Broad St / Kenan Rd	36.040047	-78.908427	2016	5	9	1.80	2.94	3.05	2.11	3.27	3.19	14.57	9.70	1.94
16*	NC	Fairplains Rd / Reynolds Rd	36.19561	-81.14437	2017	5	0	0	0.10	0.06	0.11	0.10	0.12	0.49	0.39	0.08
17	VA	Ravensworth Rd / Jayhawk St / Fountain Head Dr	38.82629	-77.19992	2018	5	8	1.60	1.64	1.91	1.64	1.67	1.48	8.33	8.07	1.61
18	WA	Anderson Rd / Cedardale Rd	48.399471	-122.328164	2013	5	2	0.40	0.32	0.32	0.44	0.34	0.37	1.80	1.89	0.38
20	WA	Slater Rd / Pacific Hwy	48.817168	-122.544338	2014	5	5	1.00	0.54	0.75	0.59	0.69	1.19	3.77	4.56	0.91
21	WA	SR 546 / Northwood Rd	48.964108	-122.407553	2016	5	6	1.20	0.59	0.63	0.94	0.66	1.09	3.90	4.91	0.98
22	WA	E George Hopper Rd / S Walnut St	48.452	-122.33174	2015	5	2	0.40	0.78	0.61	0.65	1.09	1.08	4.21	2.73	0.55
23$^{\Psi}$	WA	Slater Rd / I-5 SB Ramps	48.81707	-122.5505	2014	5	3	0.60	0.73	0.73	0.56	0.73	0.73	3.48	3.18	0.64
24$^{\Psi}$	WA	Slater Rd / I-5 NB Ramps	48.817358	-122.546092	2014	5	2	0.40	0.49	0.49	0.38	0.51	0.51	2.39	2.18	0.44
25$^{\Psi}$	WA	Portal Way / I-5 NB Ramps	48.858362	-122.586126	2018	5	3	0.60	0.37	0.42	0.48	0.63	0.66	2.57	2.80	0.56

Note: *Three-legged, $^{\Psi}$OWSC (ramp).

Table E-7(B). EB analysis for FI crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	Built year	After period																Odds ratio (observed crashes/expected crashes)					
		# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Exp. # of crashes										
					Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total (observed crashes/expected crashes)
1	2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
1	2016	3	5	1.67	2.06	2.38	3.82			8.26	4.69	5.40	8.69			18.78	0.43	0.37	0.12			0.27
6	2016	3	2	0.67	1.54	1.16	1.15			3.85	2.11	1.60	1.57			5.27	0.47	0	0.64			0.38
12	2018	1	0	0	1.26					1.26	1.11					1.11	0					0
13	2016	3	0	0	0.72	0.71	0.96			2.39	0.33	0.32	0.44			1.10	0	0	0			0
14*	2014	5	0	0	0.98	0.64	0.21	0.77	0.25	2.85	2.13	1.40	0.45	1.68	0.54	6.21	0	0	0	0	0	0
15	2016	3	0	0	3.01	3.29	3.34			9.64	2.00	2.19	2.22			6.42	0	0	0			0
16*	2017	2	0	0	0.22	0.21				0.43	0.17	0.17				0.34	0	0				0
17	2018	1	0	0	1.51					1.51	1.46					1.46	0					0
18	2013	5	7	1.40	0.90	0.52	0.47	0.87	1.36	4.13	0.95	0.55	0.50	0.92	1.43	4.34	2.10	0	4.03	1.09	1.39	1.61
20	2014	5	2	0.40	1.13	0.88	1.62	1.86	1.46	6.95	1.36	1.07	1.96	2.25	1.76	8.40	0.73	0.93	0	0	0	0.24
21	2016	3	2	0.67	0.57	0.70	0.83			2.10	0.72	0.88	1.05			2.65	1.39	0	0.95			0.75
22	2015	4	2	0.50	0.57	1.04	1.19	0.93		3.74	0.37	0.68	0.77	0.60		2.43	0	0	0	3.32		0.82
23Ψ	2014	5	4	0.80	0.73	0.99	1.02	1.06	0.65	4.45	0.67	0.90	0.93	0.97	0.60	4.07	1.50	0	1.07	0	3.35	0.98
24Ψ	2014	5	2	0.40	0.53	0.72	0.75	0.79	0.52	3.31	0.48	0.66	0.69	0.72	0.47	3.02	0	0	1.45	1.39	0	0.66
25Ψ	2018	1	0	0	0.43					0.43	0.47					0.47	0					0

Note: *Three-legged, ΨOWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

Table E-8(A). EB analysis for PDO crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Intersection name	Latitude	Longitude	Built year	Before period										
						# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Total exp. # of crashes	Exp. # of crashes per year
									Y1	Y2	Y3	Y4	Y5	Total		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	GA	GA 81 / Snapping Shoals Rd / Jackson Lake Rd	33.462826	-83.968645	2016	5	33	6.60	2.48	2.92	2.06	2.47	2.42	12.34	27.79	5.56
6	IA	29th Ave / 35th St	42.050433	-91.574481	2016	5	19	3.80	0.78	0.94	1.19	1.67	1.89	6.47	15.51	3.10
12	MN	18th Ave / 48th St	44.071671	-92.488824	2018	5	7	1.40	1.37	1.14	1.09	0.86	0.60	5.07	6.36	1.27
13	MN	S Park Dr / Louisiana Ave S	44.7393	-93.36903	2016	5	1	0.20	0.88	0.65	0.97	0.84	0.81	4.16	2.19	0.44
14*	MO	US 54 Business / N Shore Dr	38.21423	-92.62436	2014	5	37	7.40	1.65	2.04	1.46	1.78	0.98	7.91	31.48	6.30
15	NC	Carver St / Broad St / Kenan Rd	36.040047	-78.908427	2016	5	27	5.40	2.54	2.63	2.12	3.24	3.63	14.16	25.07	5.01
16*	NC	Fairplains Rd / Reynolds Rd	36.19561	-81.14437	2017	5	0	0	0.15	0.13	0.23	0.13	0.19	0.82	0.57	0.11
17	VA	Ravensworth Rd / Jayhawk St / Fountain Head Dr	38.82629	-77.19992	2018	5	5	1.00	1.98	2.60	1.87	1.97	1.67	10.08	6.01	1.20
18	WA	Anderson Rd / Cedardale Rd	48.399471	-122.328164	2013	5	11	2.20	0.62	0.62	0.75	0.61	0.58	3.19	7.57	1.51
20	WA	Slater Rd / Pacific Hwy	48.817168	-122.544338	2014	5	9	1.80	0.96	1.18	0.97	0.98	1.00	5.07	7.70	1.54
21	WA	SR 546 / Northwood Rd	48.964108	-122.407553	2016	5	3	0.60	0.66	0.50	1.16	0.82	0.67	3.80	3.42	0.68
22	WA	E George Hopper Rd / S Walnut St	48.452	-122.33174	2015	5	0	0	1.20	0.99	0.93	0.93	1.07	5.11	1.68	0.34
23^{Ψ}	WA	Slater Rd / I-5 SB Ramps	48.81707	-122.5505	2014	5	15	3.00	1.96	1.96	1.45	1.66	1.96	8.98	13.11	2.62
24^{Ψ}	WA	Slater Rd / I-5 NB Ramps	48.817358	-122.546092	2014	5	10	2.00	1.68	1.68	1.25	1.44	1.70	7.75	9.22	1.84
25^{Ψ}	WA	Portal Way / I-5 NB Ramps	48.858362	-122.586126	2018	5	5	1.00	1.40	1.49	1.54	1.77	2.04	8.25	6.08	1.22

Table E-8(B). EB analysis for PDO crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	Built year	After period															Odds ratio (observed crashes/expected crashes)					
		# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Exp. # of crashes											
					Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total (observed crashes/expected crashes)
1	2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
1	2016	3	22	7.33	3.03	5.20			11.59	1.36	7.57	6.82	11.71			26.10	0.79	1.17	0.68			0.84
6	2016	3	11	3.67	1.86	1.87			5.44	1.32	4.08	4.46	4.49			13.03	0.98	1.12	0.45			0.84
12	2018	1	4	4.00					0.86	0.84	1.07					1.07	3.72					3.72
13	2016	3	7	2.33	1.06	0.68			2.19	0.54	0.24	0.56	0.36			1.15	12.75	1.80	8.36			6.08
14*	2014	5	8	1.60	1.83	2.24	0.88	2.36	9.60	1.45	9.12	7.29	8.91	3.49	9.39	38.21	0	0.14	0.22	0.86	0.21	0.21
15	2016	3	14	4.67	2.46	2.59			7.57	0.89	4.47	4.35	4.58			13.40	0.90	1.15	1.09			1.04
16*	2017	2	2	1.00	0.20				0.42	1.33	0.15	0.14				0.29	13.17	0				6.96
17	2018	1	1	1.00					2.29	1.14	1.37					1.37	0.73					0.73
18	2013	5	36	7.20	0.78	0.88	0.94	1.04	4.56	1.44	2.19	1.85	2.10	2.23	2.46	10.83	1.83	3.78	4.76	1.79	4.46	3.32
20	2014	5	13	2.60	1.49	1.57	1.34	1.49	7.38	1.46	2.25	2.26	2.38	2.04	2.27	11.21	0.89	2.21	0.42	0.49	1.76	1.16
21	2016	3	3	1.00	1.62	1.75			4.88	1.99	1.36	1.46	1.57			4.39	0.74	0	1.27			0.68
22	2015	4	5	1.25	1.09	0.93	1.03		4.09	1.02	0.34	0.36	0.31	0.34		1.34	2.93	2.80	6.55	2.96		3.73
23Ψ	2014	5	15	3.00	2.25	2.45	1.97	1.86	10.47	1.08	2.84	3.28	3.57	2.88	2.71	15.27	0.70	0.61	0.84	2.09	0.74	0.98
24Ψ	2014	5	15	3.00	1.97	2.23	1.80	1.73	9.45	1.10	2.03	2.35	2.66	2.15	2.06	11.24	1.48	0.85	0	2.33	2.42	1.33
25Ψ	2018	1	1	1.00					1.56	0.94	1.15					1.15	0.87					0.87

Note: OR = 0 indicates observed # of crashes in the after period is zero.

Table E-9(A). EB analysis for total crashes – AWSC intersections converted to mini-roundabouts.

Site ID	State	Intersection name	Latitude	Longitude	Built year	Before period: # of years	Before period: Obs. # of crashes	Before period: Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor: Y1	Y2	Y3	Y4	Y5	Total	Total exp. # of crashes	Exp. # of crashes per year
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	33.38354	-83.90331	2017	5	8	1.60	1.63	2.23	2.23	2.34	2.16	10.59	8.61	1.72
3	GA	GA36 / GA212	33.429632	-83.847068	2015	5	18	3.60	4.32	3.72	2.42	3.34	4.60	18.41	18.06	3.61
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	34.091894	-83.615688	2013	5	18	3.60	3.51	3.51	3.42	3.49	2.95	16.89	17.82	3.56
5	GA	GA 16 / GA 54	33.329808	-84.644824	2016	5	42	8.40	5.44	4.78	6.69	7.03	7.34	31.28	40.99	8.20
7	MI	Ann Arbor-Saline Rd / Textile Rd	42.19859	-83.79691	2016	5	3	0.60	3.80	2.78	3.20	3.31	3.42	16.51	5.61	1.12
8	MI	Textile Rd / Hitchingham Rd	42.201706	-83.620946	2015	5	8	1.60	2.28	2.93	2.23	3.43	3.45	14.32	9.37	1.87
9	MI	Textile Rd / Stony Creek Rd	42.20173	-83.623122	2015	5	9	1.80	2.26	2.91	2.30	3.11	3.12	13.70	10.05	2.01
10	MI	Moon Rd / Bemis Rd	42.170612	-83.738319	2018	5	12	2.40	2.69	2.70	2.78	2.83	3.00	14.00	12.44	2.49
11	MN	Vierling Dr E / Rd 79	44.783334	-93.520148	2014	5	18	3.60	2.13	2.13	1.68	1.59	2.02	9.56	16.11	3.22
19	WA	Everson Goshen Rd / E Smith Rd	48.833025	-122.37673	2015	5	23	4.60	1.72	1.05	0.86	1.49	1.51	6.63	18.16	3.63

Table E-9(B). EB analysis for total crashes – AWSC intersections converted to mini-roundabouts.

Site ID	Built year	After period																Odds ratio (observed crashes/expected crashes)					
		# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Exp. # of crashes											
					Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total (observed crashes/expected crashes)
1	2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
2	2017	2	10	5.00	1.75	2.72				4.48	1.42	2.21				3.64	6.32	0.45				2.75
3	2015	4	69	17.25	4.15	4.90	4.33	6.13		19.51	4.08	4.80	4.25	6.01		19.15	5.89	2.71	2.12	3.82		3.60
4	2013	5	56	11.20	4.18	4.86	4.22	5.20	4.41	22.88	4.41	5.13	4.46	5.49	4.65	24.13	4.31	1.37	2.47	1.82	1.94	2.32
5	2016	3	85	28.33	7.21	7.01	9.24			23.47	9.45	9.19	12.11			30.76	3.70	3.48	1.49			2.76
7	2016	3	4	1.33	3.77	3.94	4.23			11.94	1.28	1.34	1.44			4.05	1.56	0	1.39			0.99
8	2015	4	13	3.25	2.87	3.05	3.09	3.23		12.24	1.88	2.00	2.02	2.11		8.01	1.60	1.50	1.98	1.42		1.62
9	2015	4	48	12.00	2.56	2.72	2.76	2.88		10.91	1.88	2.00	2.02	2.11		8.01	6.39	10.01	1.98	5.69		5.99
10	2018	1	12	12.00	3.17					3.17	2.82					2.82	4.26					4.26
11	2014	5	53	10.60	2.01	1.69	1.97	2.00	2.33	10.02	3.40	2.86	3.32	3.38	3.93	16.88	1.77	4.55	3.01	4.15	2.54	3.14
19	2015	4	57	14.25	1.37	1.37	1.86	1.53		6.13	3.75	3.76	5.08	4.19		16.79	4.27	5.06	2.16	2.62		3.40

Note: OR = 0 indicates observed # of crashes in the after period is zero.

Table E-10(A). EB analysis for FI crashes – AWSC intersections converted to mini-roundabouts.

Site ID	State	Intersection name	Latitude	Longitude	Built year	Before period											
						# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Total exp. # of crashes	Exp. # of crashes per year
									Y1	Y2	Y3	Y4	Y5	Total		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	33.38354	-83.90331	2017	5	2	0.40	0.44	0.55	0.55	0.57	0.65	2.75	2.43	0.49
3	GA	GA36 / GA212	33.429632	-83.847068	2015	5	6	1.20	1.43	0.74	0.68	0.85	1.25	4.95	5.55	1.11
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	34.091894	-83.615688	2013	5	6	1.20	0.97	0.97	1.12	0.64	0.84	4.55	5.35	1.07
5	GA	GA 16 / GA 54	33.329808	-84.644824	2016	5	8	1.60	1.10	1.42	1.79	1.90	2.01	8.22	8.07	1.61
7	MI	Ann Arbor-Saline Rd / Textile Rd	42.19859	-83.79691	2016	5	0	0	0.65	0.57	0.35	0.35	0.36	2.29	1.16	0.23
8	MI	Textile Rd / Hitchingham Rd	42.201706	-83.620946	2015	5	2	0.40	0.33	0.64	0.50	0.58	0.58	2.63	2.30	0.46
9	MI	Textile Rd / Stony Creek Rd	42.20173	-83.623122	2015	5	2	0.40	0.32	0.63	0.56	0.40	0.40	2.30	2.15	0.43
10	MI	Moon Rd / Bemis Rd	42.170612	-83.738319	2018	5	3	0.60	0.48	0.48	0.50	0.42	0.68	2.56	2.79	0.56
11	MN	Vierling Dr E / Rd 79	44.783334	-93.520148	2014	5	5	1.00	0.58	0.58	0.43	0.54	0.56	2.69	3.51	0.70
19	WA	Everson Goshen Rd / E Smith Rd	48.833025	-122.37673	2015	5	7	1.40	0.39	0.59	0.30	0.38	0.38	2.05	5.05	1.01

Table E-10(B). EB analysis for FI crashes – AWSC intersections converted to mini-roundabouts.

Site ID	Built year	After period															Odds ratio (observed crashes/expected crashes)					
		# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Exp. # of crashes											
					Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total (observed crashes/expected crashes)
1	2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
2	2017	2	3	1.50	0.33	0.53				0.86	0.30	0.46				0.76	10.16	0	0			3.95
3	2015	4	17	4.25	1.34	1.17	0.97	1.30		4.78	1.50	1.31	1.09	1.46		5.36	5.99	2.29	0.92	2.74		3.17
4	2013	5	11	2.20	0.96	1.17	1.24	1.18	0.90	5.45	1.13	1.38	1.46	1.39	1.05	6.42	2.65	1.45	1.37	1.44	1.90	1.71
5	2016	3	9	3.00	1.77	1.56	1.92			5.25	1.74	1.53	1.89			5.16	1.15	2.62	1.59			1.75
7	2016	3	2	0.67	0.48	0.38	0.74			1.60	0.25	0.19	0.37			0.81	0	0	5.34			2.46
8	2015	4	1	0.25	0.43	0.70	0.47	0.81		2.41	0.38	0.61	0.41	0.71		2.11	2.64	0	0	0		0.47
9	2015	4	3	0.75	0.28	0.45	0.31	0.52		1.56	0.26	0.42	0.29	0.49		1.46	0	2.38	3.50	2.04		2.06
10	2018	1	1	1.00	0.79					0.79	0.86					0.86	1.17					1.17
11	2014	5	6	1.20	0.56	0.42	0.63	0.44	0.64	2.69	0.73	0.55	0.82	0.58	0.84	3.51	1.37	0	2.43	1.73	2.38	1.71
19	2015	4	9	2.25	0.36	0.43	0.54	0.56		1.89	0.88	1.07	1.32	1.39		4.66	1.14	2.81	2.27	1.44		1.93

Note: OR = 0 indicates observed # of crashes in the after period is zero.

Table E-11(A). EB analysis for PDO crashes – AWSC intersections converted to mini-roundabouts.

Site ID	State	Intersection name	Latitude	Longitude	Built year	Before period										
						# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Total exp. # of crashes	Exp. # of crashes per year
									Y1	Y2	Y3	Y4	Y5	Total		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	33.38354	-83.90331	2017	5	6	1.20	1.65	1.70	1.70	1.79	2.14	8.98	6.95	1.39
3	GA	GA36 / GA212	33.429632	-83.847068	2015	5	12	2.40	2.87	2.91	2.39	2.50	3.31	13.98	12.46	2.49
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	34.091894	-83.615688	2013	5	12	2.40	2.51	2.51	2.28	2.84	2.91	13.06	12.26	2.45
5	GA	GA 16 / GA 54	33.329808	-84.644824	2016	5	34	6.80	4.22	4.59	4.84	5.05	5.25	23.96	32.50	6.50
7	MI	Ann Arbor-Saline Rd / Textile Rd	42.19859	-83.79691	2016	5	3	0.60	3.02	2.10	2.82	2.92	3.02	13.88	5.73	1.15
8	MI	Textile Rd / Hitchingham Rd	42.201706	-83.620946	2015	5	6	1.20	1.92	2.24	1.66	2.81	2.82	11.45	7.58	1.52
9	MI	Textile Rd / Stony Creek Rd	42.20173	-83.623122	2015	5	7	1.40	1.92	2.24	1.69	2.66	2.67	11.17	8.23	1.65
10	MI	Moon Rd / Bemis Rd	42.170612	-83.738319	2018	5	9	1.80	2.19	2.20	2.26	2.38	2.36	11.38	9.69	1.94
11	MN	Vierling Dr E / Rd 79	44.783334	-93.520148	2014	5	13	2.60	1.59	1.59	1.31	1.05	1.50	7.02	11.88	2.38
19	WA	Everson Goshen Rd / E Smith Rd	48.833025	-122.37673	2015	5	16	3.20	1.31	0.39	0.54	1.09	1.10	4.42	10.37	2.07

Table E-11(B). EB analysis for PDO crashes – AWSC intersections converted to mini-roundabouts.

Site ID	Built year	After period															Odds ratio (observed crashes/expected crashes)					
		# of years	Obs. # of crashes	Obs. # of crashes per year	Pred. # of crashes using SPF and calibration factor						Exp. # of crashes											
					Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total	Y1	Y2	Y3	Y4	Y5	Total (observed crashes/expected crashes)
1	2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
2	2017	2	7	3.50	1.56	1.62				3.18	1.21	1.25				2.46	4.96	0.80				2.84
3	2015	4	52	13.00	3.94	2.82	3.55	3.45		13.76	3.51	2.51	3.16	3.08		12.26	4.27	3.98	2.53	6.18		4.24
4	2013	5	45	9.00	3.28	3.71	4.20	3.07	3.78	18.03	3.08	3.48	3.94	2.88	3.55	16.93	5.20	1.44	2.28	2.78	1.97	2.66
5	2016	3	76	25.33	4.08	5.74	5.25			15.07	5.54	7.79	7.11			20.44	5.96	3.60	2.11			3.72
7	2016	3	2	0.67	3.24	3.55	3.43			10.22	1.34	1.47	1.42			4.22	1.50	0	0			0.47
8	2015	4	12	3.00	2.41	2.39	2.59	2.47		9.87	1.60	1.58	1.71	1.63		6.53	1.25	1.90	2.33	1.84		1.84
9	2015	4	45	11.25	2.27	2.25	2.44	2.32		9.28	1.67	1.66	1.80	1.71		6.83	7.18	11.47	1.67	6.43		6.59
10	2018	1	11	11.00	2.44					2.44	2.07					2.07	5.30					5.30
11	2014	5	47	9.40	1.49	1.33	1.35	1.62	1.67	7.47	2.52	2.25	2.29	2.75	2.84	12.64	1.98	5.79	3.50	4.73	2.82	3.72
19	2015	4	48	12.00	1.00	0.93	1.30	0.95		4.17	2.35	2.17	3.04	2.23		9.79	6.39	7.37	2.63	4.03		4.90

Note: OR = 0 indicates observed # of crashes in the after period is zero.

APPENDIX F: CORRELATION ANALYSIS

Table F-1. Pearson correlation analysis based on crashes per year (after period) – TWSC/OWSC converted to mini-roundabouts.

Variable	Crashes per year (after period)		
	Total crashes	FI crashes	PDO crashes
Total crashes per year before period	0.553*	-	-
Total crashes per year after period	1	-	-
FI crashes per year before period	-	0.501	-
FI crashes per year after period	-	1	-
PDO crashes per year before period	-	-	0.533*
PDO crashes per year after period	-	-	1
Major street AADT (before period)	-0.162	-0.213	-0.140
Cross-street AADT (before period)	-0.074	-0.202	-0.037
Cross-street share (before period)	0.131	0.019	0.152
Total AADT (major + cross-street) (before period)	-0.150	-0.238	-0.118
Major street AADT (after period)	-0.075	-0.096	-0.065
Cross-street AADT (after period)	-0.012	-0.125	0.017
Cross-street share after period	0.098	-0.010	0.120
Total AADT (major + cross-street) (after period)	-0.063	-0.128	-0.043
Speed limit major street	0.228	0.347	0.184
Speed limit cross -street	0.265	0.310	0.237
Speed limit difference between major and cross-street	0.232	0.452	0.162
Inscribed circle diameter	0.221	0.353	0.174
Center island diameter	-0.084	0.058	-0.115
Entry width (max.)	-0.040	0.113	-0.076
Entry width (min.)	0.116	0.134	0.104
Entry width (avg.)	0.015	0.140	-0.018
Exit width (max.)	0.006	0.056	-0.006
Exit width (min.)	0.099	0.078	0.098
Exit width (avg.)	0.019	0.020	0.018
Circulating width (max.)	-0.193	-0.203	-0.179
Circulating width (min.)	-0.072	0.026	-0.092
Circulating width (avg.)	-0.085	-0.079	-0.082
Distance between entry to the next leg (max.)	-0.124	-0.010	-0.146
Distance between entry to the next leg (min.)	0.054	0.087	0.042
Distance between entry to the next leg (avg.)	-0.089	0.008	-0.108
Weaving length (max.)	-0.057	0.077	-0.088
Weaving length (min.)	-0.233	-0.176	-0.234
Weaving length (avg.)	-0.124	0.002	-0.149
Entry angle (max.)	0.480	0.494	0.448
Entry angle (min.)	-0.123	-0.186	-0.099
Entry angle (avg.)	0.173	0.142	0.171
Angle-to-the-next-leg (max.)	-0.053	-0.028	-0.057
Angle-to-the-next-leg (min.)	-0.184	-0.285	-0.147
Angle-to-the-next-leg (avg.)	-0.315	-0.395	-0.276

Note: * indicates statistical significance at a 90% confidence level. Highlighted cell indicates Pearson correlation (r) greater/less or equal to ±0.4. Max., min., and avg. are the maximum, minimum and average values considering all approaches.

Table F-2. Pearson correlation analysis based on crashes per year (after period) – AWSC converted to mini-roundabouts.

Variable	Crashes per year (after period)		
	Total crashes	FI crashes	PDO crashes
Total crashes per year before period	0.923*	-	-
Total crashes per year after period	1	-	-
FI crashes per year before period	-	0.645*	-
FI crashes per year after period	-	1	-
PDO crashes per year before period	-	-	0.919*
PDO crashes per year after period	-	-	1
Major street AADT (before period)	0.395	0.075	0.429
Cross-street AADT (before period)	.664*	0.158	.716*
Cross-street share (before period)	0.459	0.094	0.497
Total AADT (major + cross-street) (before period)	0.607	0.134	.656*
Major street AADT (after period)	0.479	0.399	0.466
Cross-street AADT (after period)	0.610	0.205	.647*
Cross-street share after period	0.237	-0.088	0.281
Total AADT (major + cross-street) (after period)	0.620	0.364	0.630
Speed limit major street	0.342	0.508	0.293
Speed limit cross -street	0.391	0.441	0.359
Speed limit difference between major and cross-street	-0.251	-0.210	-0.243
Inscribed circle diameter	-0.228	-0.159	-0.227
Center island diameter	-0.059	-0.029	-0.061
Entry width (max.)	-0.532	-.736*	-0.464
Entry width (min.)	-0.301	-0.510	-0.246
Entry width (avg.)	-0.439	-.643*	-0.377
Exit width (max.)	0.070	0.134	0.054
Exit width (min.)	-0.454	-.734*	-0.378
Exit width (avg.)	-0.071	-0.098	-0.062
Circulating width (max.)	-0.127	0.059	-0.153
Circulating width (min.)	-0.027	0.155	-0.058
Circulating width (avg.)	-0.074	0.136	-0.107
Distance between entry to the next leg (max.)	0.378	0.406	0.352
Distance between entry to the next leg (min.)	-.667*	-0.546	-.650*
Distance between entry to the next leg (avg.)	-0.009	0.093	-0.026
Weaving length (max.)	0.408	0.312	0.401
Weaving length (min.)	-.727*	-.677*	-.693*
Weaving length (avg.)	-0.350	-0.266	-0.344
Entry angle (max.)	.708*	0.431	.716*
Entry angle (min.)	-.679*	-.651*	-.644*
Entry angle (avg.)	0.385	0.129	0.408
Angle-to-the-next-leg (max.)	.709*	0.605	.687*
Angle-to-the-next-leg (min.)	-.732*	-0.491	-.733*
Angle-to-the-next-leg (avg.)	0.201	.714*	0.098

Note: * indicates statistical significance at a 90% confidence level. Highlighted cell indicates Pearson correlation (r) greater/less or equal to ±0.4. Max., min., and avg. are the maximum, minimum and average values considering all approaches.