RESEARCH & DEVELOPMENT

Mini-Roundabout CMF Development

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MINI-ROUNDABOUT CMF DEVELOPMENT

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By

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EXECUTIVE SUMMARY

Over the past decade, the concept of mini-roundabouts has gained popularity in many countries. They are a type of intersection rather than merely a traffic calming measure, and are best 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 North Carolina and the United States. The objectives of the proposed research project are: 1) to identify mini-roundabout installations in the United States, 2) to collect before and after crash data at the existing mini-roundabout locations, 3) to conduct a before and after study for determining safety benefits of mini-roundabouts, 4) to compute CMFs for mini-roundabouts based on before and after crash data, 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..

To accomplish these objectives, this research identified 25 mini-roundabout installations in the United States. The identified mini-roundabouts 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. Additionally, 649 reference intersections with crash data and traffic volume data were gathered and used for computing the calibration factors and developing jurisdiction-specific safety performance functions (SPFs).

The safety benefits of a mini-roundabout were assessed on two-levels; naïve before and after analysis and the Empirical Bayes (EB) before and after analysis. In naïve before and after analysis, crashes per year in the before period are compared to crashes per year in the after period. The 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 change in the crash rate in the after

period was compared with the crash rate in the before period. The EB before and after analysis estimates the number of crashes that would have occurred at a mini-roundabout in the after period had it not been implemented and addresses the regression-to-the-mean bias. 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)/one-way stop-controlled (OWSC) and all-way stop-controlled (AWSC) intersections. Table ES-1 summarizes the naïve before and after analysis and EB analysis results by the number of total crashes, FI crashes, and PDO crashes.

The results from the naïve before and after analysis indicated a decrease in the number of total crashes per year at seven mini-roundabouts and a decrease in the crash rate at eight mini-roundabouts, out of the fourteen selected TWSC/OWSC intersections converted to mini-roundabouts. One intersection had zero crashes in the before period. The results from the naïve before and after analysis indicated an increase in the number of total crashes per year and crash rate at all the ten selected AWSC intersections converted to mini-roundabouts. Differences were observed when analyzed based on FI crashes and PDO crashes separately.

Table ES-1. Before and after naïve and EB method analysis summary - # of intersections with odds ratio less than 1, and greater or equal to 1.

Prior control type	Crash severity type	Naïve analysis				EB analysis	
		Crashes per year		Crash rate (crashes per year/traffic volume)			
		# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1	# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1	# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1
TWSC/OWSC	Total	7	7	8	6	8	7
	FI	10	4	11	3	12	3
	PDO	3	10	6	7	6	9
AWSC	Total	0	10	0	10	1	9
	FI	1	8	1	8	1	9
	PDO	0	10	1	9	1	9

Using the EB method, crashes in the before period were predicted as a function of traffic volume (major street and cross-street). The SPFs available for the TWSC/OWSC control types in AASHTO (2010) were calibrated for the considered time period in each state. Jurisdiction-specific SPFs were developed for AWSC and OWSC (ramp) control types. The odds ratio (observed number of crashes to the expected number of crashes) for each selected mini-roundabout was computed using the EB method. An odds ratio of less than 1 indicates that the installation of the mini-roundabout is effective. However, an odds ratio of greater than or equal to 1 indicates that the installation of the mini-roundabout is not effective.

In the case of total 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 0.85 at the remaining seven 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 three TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.80 at the remaining twelve TWSC/OWSC intersections converted to mini-roundabouts. Further, in the case of PDO crashes, the odds ratio was observed to be equal to or greater than 1 at nine TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.95 at the remaining six TWSC/OWSC intersections converted to mini-roundabouts. Considering total crashes, FI crashes, and PDO crashes, the odds ratio was equal to or greater than 1 at three out of the fifteen TWSC/OWSC intersections converted to mini-roundabouts.

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 0.65 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. It was observed to be less than 0.45 at one AWSC intersection converted to a mini-roundabout. Further, 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. It was observed to be less than 0.30 at one AWSC intersection converted a mini-roundabout. Considering total crashes and PDO crashes, the odds ratio was less than 1 for one AWSC intersection converted to a mini-roundabout. However, it was greater than 1 for FI crashes.

In summary, the results from the EB before and after analysis indicate a decrease in the number of total crashes and FI crashes when a TWSC/OWSC intersection is converted to a mini-roundabout. However, an increase PDO crashes was observed when a TWSC/OWSC intersection is converted to a mini-roundabout. An increase in the number of total crashes, FI crashes, and PDO crashes is generally observed when an AWSC intersection is converted to a mini-roundabout.

Table ES-2 shows the recommended CMFs for converting a TWSC/OWSC intersection, and an AWSC intersection to a mini-roundabout.

Table ES-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	*0.83*	0.08	± 1.96	0.67	0.98	Significant at α=0.05
FI	*0.41*	0.09	± 1.96	0.23	0.59	Significant at α=0.05
PDO	1.09	0.12	± 1.96	0.86	1.32	Not significant
AWSC intersection						
Total	*3.25*	0.27	± 1.96	2.72	3.78	Significant at α=0.05
FI	*1.74*	0.26	± 1.96	1.23	2.25	Significant at α=0.05
PDO	*3.83*	0.31	± 1.96	3.22	4.44	Significant at α=0.05

No specific trend was observed between the odds ratio and traffic volume (major street, cross-street, and cross-street volume share) for all the considered prior control types. Also, no specific trend was observed between the odds ratio and the speed limit. However, mini-roundabouts installed at intersections with 45 mph (~72.42 kmph) or higher as the speed limit seem to be effective in reducing crashes at TWSC/OWSC intersections when converted. Further, there exists a positive relationship between the after period crashes at mini-roundabouts with before period crash history, cross-street traffic volume, and speed limit at the major street and cross-street. It indicates an increase in crashes per year with an increase in the aforementioned variables. Also, the relationship between the after period crashes at mini-roundabouts with entry angle (minimum of all approaches), weaving length (minimum of all approaches), and angle to the next leg (minimum of all approaches) showed a negative trend. It indicates an increase in crashes per year with a decrease in the entry angle, weaving length, and angle to the next leg. In summary, some of the mini-roundabout characteristics may have influenced crashes that occurred after the installation. The Pearson correlation analysis indicates that variables such as crashes in the before period crash history, cross-street traffic volume, speed limit at major street and cross-street, and intersection skewness have a statistically significant influence on after period crashes at a 90% confidence level.

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CHAPTER 1 INTRODUCTION

Mini-roundabouts are common in the United Kingdom and many European countries. They are featured designs for slowing traffic, improving intersection safety, and reducing delay at minor approaches (Robinson et al., 2000). They are a type of roundabout characterized by small diameter and traversable islands (central island and splitter islands). Mini-roundabouts offer most of the benefits of regular roundabouts, with the added benefit of a smaller footprint. Mini-roundabouts are a type of intersection rather than merely a traffic calming measure, although they may produce some traffic calming effect. They are best suited to environments where speeds are already low and environmental constraints would preclude the use of a larger roundabout with a raised central island.

Mini-roundabouts are common in the United Kingdom and France and are emerging in the United States, Germany, and other countries. In the United Kingdom, mini-roundabouts have been successfully implemented to reduce crash rates by 30% when compared to signalized intersections (Department for Transport, 2006). Also, they result in less delay for critical movements, with reduced fuel consumption, relatively lower greenhouse gas emissions, and with less or no room for aesthetic beautification.

A mini-roundabout may not be a proper fit for an intersection with more than four legs. Generally, roundabouts with a small diameter (45 feet [~13.72 meters] to 90 feet [~27.43 meters] of inscribed circle) and fully traversable island are considered as mini-roundabouts (Rodegerdts et al. 2010). The central traversable island may range from 16 feet (~4.88 meters) to 45 feet (~13.72 meters) (Zhang et al., Year Unknown). This innovative intersection design is best suited for low speed (35 mph [~56 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.

These days mini-roundabouts are emerging as the most common design near residential and commercial entrances in urban and suburban areas. In the United States, they can be found in California, Georgia, Iowa, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New York, North Carolina, Tennessee, Virginia, Washington State, and Wisconsin.

A mini-roundabout design considers four types of users: motorists, pedestrians, bicyclists, and emergency vehicles. Hence, the structure accommodates crosswalks around the perimeter and 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 are needed for all the user types, considering older drivers as well.

In general, roundabouts are considered safer than four-legged signalized intersections (Badgley et al., 2018). 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). However, there are still risks of less severe sideswipe crashes at roundabouts.

1.1 Need for the Research

At the time of this research, there are two locations in North Carolina with a mini-roundabout on non-neighborhood roads. It is envisioned that the installation of mini-roundabouts could become more common in North Carolina as engineers/agencies are identifying more sites that would benefit from the installation of a mini-roundabout, especially in locations with constraints that would prevent the construction of a regular or a normal-sized roundabout. The cost of a mini-roundabout is about 1/3rd of a full-sized roundabout and has fewer right-of-way impacts. The primary concern arising from installing a mini-roundabout is the lack of documented evidence pertaining to safety benefits associated with them compared to full-sized roundabouts. This needs to be determined before their large-scale implementation.

Crash modification factors (CMFs) were developed for various designs of roundabouts (single-lane roundabout, multilane roundabout, etc.) and are reported in the CMF Clearinghouse. However, safety impacts on converting regular intersections to mini-roundabouts are unknown.

NCDOT is planning to install mini-roundabouts at locations where the construction of normal-sized roundabouts is not feasible. NCDOT is also looking at installing mini-roundabouts in rural areas and at high-speed intersections (posted limit is 35 mph [~56 kmph] or higher; collector road or higher functional class). Before installing mini-roundabouts, there is a need to develop CMFs for them that would help engineers 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.

1.2 Research Objectives

The objectives of the proposed research project are:

1) to identify a significant sample of mini-roundabout installations in the United States,
2) to collect before and after crash data at selected mini-roundabout locations,
3) to conduct a before and after study for determining safety benefits of mini-roundabouts,
4) to compute CMFs for mini-roundabouts based on before and after crash data, 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.

1.3 Organization of the Report

The remainder of this report is comprised of six chapters. A review of existing literature on roundabouts (in particular, mini-roundabouts) and their safety benefits is discussed in Chapter 2. The mini-roundabout identification, inventory, crash and traffic volume data collection, and data processing details are discussed in Chapter 3. The descriptive analysis of selected mini-roundabouts is discussed in Chapter 4. The computation of CMFs for mini-roundabouts based on the before-after study are discussed in Chapter 5. The analysis on the influence of traffic, network, and off-network characteristics on safety at mini-roundabouts is discussed in Chapter 6. The conclusions from this research study and scope for future research are discussed in Chapter 7.

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, 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 at a single-lane roundabout compared to sixteen crossing conflict points at 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 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, vulnerable road user's safety assessment at mini-roundabouts, and an overview of related safety evaluation methods and models. 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 Empirical Bayes (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).

In Maryland, 38 roundabouts with 283 crash reports were examined to propose countermeasures based on field observations (Mandavilli et al., 2009). Most common types of injury crashes included single-vehicle run-off, rear-end, and sideswipe crashes. Based on the crash reports and field observations, most of the crashes occurred at the entrances to the roundabouts. High approach speed was noted as an important driver crash contributing factor. 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. A meta-regression analysis performed for roundabouts showed that safety benefits are more likely to occur at four-legged roundabouts than at three-legged roundabouts (Elvik, 2003). The number of crashes may also depend on the central island size of the roundabout (roundabouts with a small central island were found to be associated with a low injury crash rate) and driver compliance behavior at the yield control locations.

Montella (2010) identified contributing factors such as road users, vehicle, geometric characteristics, pavement markings and signs, road environment, etc. for urban roundabout crashes in Italy. They 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 locations. Likewise, improper/lack of yield signs and pedestrian crossing 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 three years before-after period crash data and analyzed using EB method. Before control types included no control/yield control (at 2 roundabouts), two-way stop signs (at 12 roundabouts), all-way stop signs (at 5 roundabouts) and signal (at 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. Their study found a 35.98 % reduction in total crashes at single-lane roundabouts, whereas a 6.23% increase in total crashes was observed at multi-lane roundabouts. A reduction in fatal and injury crashes was observed at both single-lane (18.20% reduction) and multi-lane roundabouts (63.28% reduction). Also, 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) for total crashes. A reduction in fatal and injury (FI) crashes was observed for all the 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, 2018). 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 Federal Highway Administration (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 (Figure 2-1). 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 (Figure 2-2). 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).

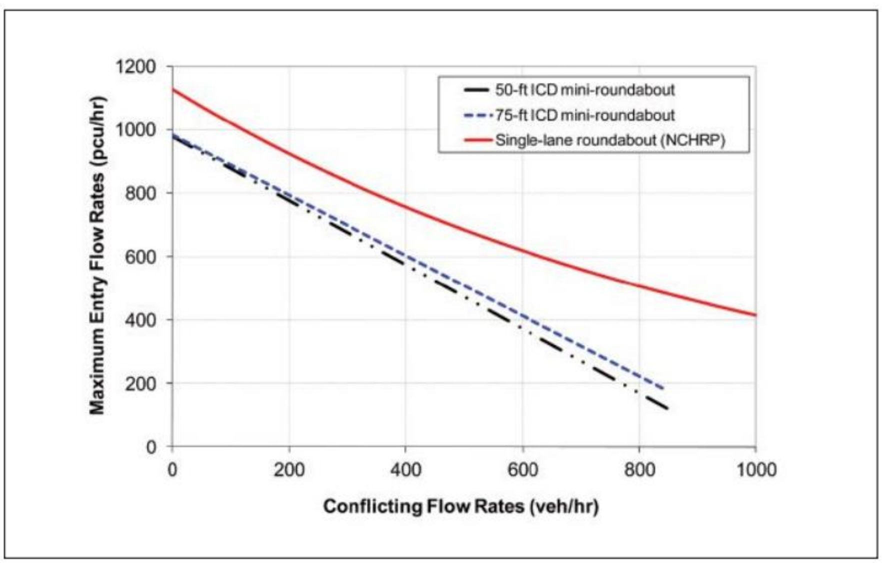


Figure 2-1. Entry capacity as a function of conflicting flow.
Note: 1 meter = 3.28 feet.

Source: Lochrane et al. (2014)

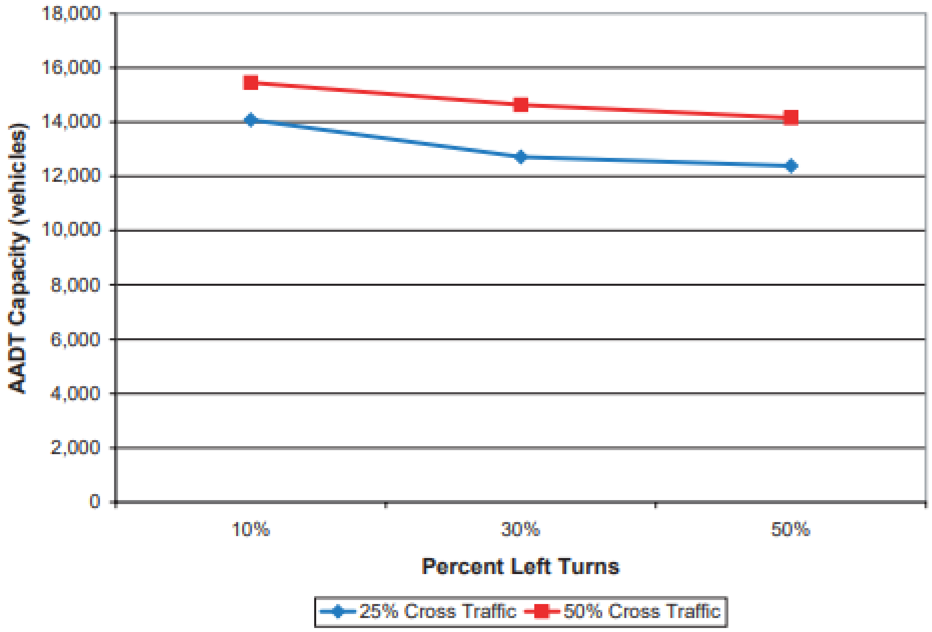


Figure 2-2. Planning-level maximum daily service volumes for mini-roundabouts.

Source: Rodegerdts et al. (2010) Exhibit 3-16

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).

2.3 Safety Assessment of Mini-Roundabout Design

Several researchers have assessed the safety benefits of the mini-roundabout design. Lalani et al. (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 et al. (1977) analyzed 88 small and mini-roundabouts converted from priority controlled junctions. They 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.

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 speed (from ~30 mph [48.2 kmph] to ~25.4 mph [40.9 kmph]). 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.

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. 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.

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. The selected mini-roundabouts were compared with two control sites, one with a give way controlled intersection and the other with a mini-roundabout intersection installed in 2008. They observed a marginal decrease in the average approach speed, from ~26.6 mph (43 kmph) to ~24.4 mph (39.3 kmph). They also observed a decrease in the proportion of vehicles exceeding the speed limit (~31.6 mph or 50 kmph) 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 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 et al., 1975; Green et al., 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 North Carolina and 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. 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 found 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 Safety Effectiveness Evaluation Methods

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 Highway Safety Manual (HSM) recommends before-after evaluation methods that are reproduced as shown in Table 2-2 (AASHTO, 2010).

2.5.1 Crash Frequency Modeling

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. Lord and Mannering (2010) provided a comprehensive review of the advantages and disadvantages of different models for crash frequency modeling (reproduced as Table 2-3).

Table 2-2. 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)

Table 2-3. Summary of existing models for analyzing crash-frequency data.

Model type	Advantages	Disadvantages
Poisson	Most basic model; easy to estimate.	Cannot handle over- and under-dispersion; negatively influenced by the low sample mean and small sample size bias.
Negative	Easy to estimate; can account for	Cannot handle under-dispersion;

Model type	Advantages	Disadvantages
binomial/Poisson gamma	overdispersion.	can be adversely influenced by the low sample mean and small sample size bias.
Poisson-lognormal	More flexible than the Poisson-gamma to handle over-dispersion.	Cannot handle under-dispersion; can be adversely influenced by the low sample mean and small sample size bias (less than the Poisson-gamma); cannot estimate a varying dispersion parameter.
Zero-inflated Poisson and negative binomial	Handles datasets that have a large number of zero-crash observations.	Can create theoretical inconsistencies; zero-inflated negative binomial can be adversely influenced by the low sample mean and small sample size bias.
Conway-Maxwell-Poisson	Can handle under- and over-dispersion or combination of both using a variable dispersion (scaling) parameter.	Could be negatively influenced by the low sample mean and small sample size bias; no multivariate extensions available to date.
Gamma	Can handle under-dispersed data.	Dual state model with one state having a long term mean equal to zero.
Generalized estimating equation models	Can handle temporal correlation.	May need to determine or evaluate the type of temporal correlation a priori; results sensitive to missing values.
Generalized additive models	More flexible than the traditional generalized estimating equation models; allows non-linear variable interactions.	Relatively complex to implement; may not be easily transferable to other datasets.
Random-effects models	Handles temporal and spatial correlation.	May not be easily transferable to other datasets.
Negative multinomial	Can account for overdispersion and serial correlation; panel count data.	Cannot handle under-dispersion; can be adversely influenced by the low sample mean and small sample size bias.
Random-parameters models	More flexible than the traditional fixed parameter models in accounting for unobserved heterogeneity.	Complex estimation process; may not be easily transferable to other datasets.
Bivariate/multivariate models	Can model different crash types simultaneously; more flexible functional form than the generalized estimating equation models (can use non-linear functions).	Complex estimation process; requires the formulation of a correlation matrix.
Finite mixture/Markov Switching	Can be used for analyzing sources of dispersion in the data.	Complex estimation process; may not be easily transferable to other datasets.
Duration models	By considering the time between crashes (as opposed to crash frequency directly); allows for a very in-depth analysis of data and duration effects.	Requires more detailed data than traditional crash frequency models; time-varying explanatory variables are difficult to handle.
Hierarchical/Multilevel models	Can handle temporal, spatial and other correlations among groups of observations.	May not be easily transferable to other datasets; correlation results can be difficult to interpret.
Neural Network, Bayesian Neural Network, and support	Nonparametric approach does not require an assumption about the distribution of data; flexible functional form; usually provides a	Complex estimation process; may not be transferable to other datasets; works as a blackbox; may not have

Model type	Advantages	Disadvantages
vector machine	better statistical fit than the traditional parametric models.	interpretable parameters.

Source: Lord and Mannering (2010)

2.5.2 Safety Performance Functions (SPFs)

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 (with specified base conditions) as a function of annual average daily traffic in (AADT) and, in the case of roadway segments, the segment length (L). Base conditions are specified for each SPF and may include conditions such as lane width, presence or absence of lighting, presence of turn lines, etc." (AASHTO, 2010).

The SPFs for roundabouts were not available in the HSM first edition (AASHTO, 2010). Recently, the National Cooperative Highway Research Program (NCHRP) Research Report 888 titled "Development of Roundabout Crash Prediction Models and Method" was published in 2018 (Ferguson et al., 2018). This report contains the SPFs for roundabouts developed using data for 355 roundabouts in the United States. Three categories of crash prediction models were presented in the report: (i) planning-level crash prediction models, (ii) intersection-level crash prediction models, and (iii) leg-level crash prediction models. The crash prediction model for rural and urban single lane roundabout from the NCHRP Research Report 888 is presented as equations (2.1) and (2.2) (Ferguson et al., 2018).

Crash prediction model for rural roundabouts:

$$N = exp^{a+STATE} \times AADT_{MS}^{b} \times AADT_{CS}^{C} \times \exp^{(d\times NL+e\times CIRCNL)} \quad (2.1)$$

where N = predicted average crash frequency (crashes/year);

STATE = an additive intercept term dependent on the geographic state a roundabout resides in;

$AADT_{MS}$ = total entering AADT on the major street;

$AADT_{CS}$ = total entering AADT on the cross-street;

NL = 1 if it is a 3-legged roundabout; 0 if it is a 4-legged roundabout; and

CIRCNL = 1 if it is a single-lane roundabout; 0 if more than 1 circulating lane.

Crash prediction model for urban single-lane roundabouts:

$$N = exp^{a+STATE} \times AADT_{MS}^{b} \times AADT_{CS}^{C} \times \exp^{(d\times NL)} \quad (2.2)$$

where N = predicted average crash frequency (crashes/year);

STATE = an additive intercept term dependent on the geographic state a roundabout resides in;

$AADT_{MS}$ = total entering AADT on the major street;

$AADT_{CS}$ = total entering AADT on the cross-street; and,

NL = 1 if it is a 3-legged roundabout; 0 if it is a 4-legged roundabout.

2.5.3 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 CMFs of stop-controlled and signalized intersection converted to a single-lane roundabout are summarized in Table 2-4.

Table 2-4. 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 2-lane roundabout.

Gross et al. (2010) researched on study designs for CMF development with their application, strengths, and weaknesses. They are reproduced and summarized in Table 2-5.

Table 2-5. Summary of study designs for developing CMFs.

Study design	General applicability	Strengths	Weaknesses
Before-after with a comparison group	Treatment is sufficiently similar among treatment sites. Before and after data are available for both treated and untreated sites. Untreated sites are used to account for non-treatment related crash trends.	Simple. Accounts for non-treatment related time trends and changes in traffic volume.	Difficult to account for regression-to-the-mean bias.
Before-after with Empirical Bayes (EB) analysis	Treatment is sufficiently similar among treatment sites. Before and after data are available for both treated sites and an untreated reference group. A separate comparison group may be required where the treatment has an effect on the reference group.	Employs SPFs to account for regression-to-the-mean bias, and traffic volume changes over time. Non-treatment related time trends.	Relatively complex. No prior knowledge of treatment. Cannot consider spatial correlation. Cannot specify complex model forms.
Full Bayes	Useful for before-after or cross-section studies when complex model forms are required. There is a need to consider spatial correlation among sites. Previous model estimates or CMF estimates are to be introduced in the modeling.	Reliable results with small sample sizes. Can include prior knowledge, spatial correlation, and complex model forms in the evaluation process.	Implementation requires a high degree of training.
Cross-sectional	Useful when limited before-after data are available. Requires sufficient sites that are similar except for the treatment of interest.	Possible to develop CMF functions. Allows estimation of CMFs when conversions are rare. Useful for predicting crashes.	CMFs may be inaccurate for a number of reasons, such as an inappropriate functional form, omitted variable bias, or due to correlation among variables.
Case-control	Assess whether exposure to a potential treatment is disproportionately distributed between sites with and without the target crash. Indicates the likelihood of an actual treatment through the odds	Useful for studying rare events because the number of cases and controls is predetermined. Can investigate multiple treatments per sample.	Can only investigate one outcome per sample. Does not differentiate between locations with one crash or multiple crashes. Cannot demonstrate

Study design	General applicability	Strengths	Weaknesses
	ratio.		causality.
Cohort	Used to estimate relative risk, which indicates the expected percent change in the probability of an outcome given a unit change in the treatment.	Useful for studying rare treatments because the sample is selected based on treatment status. Can demonstrate causality.	Only analyzes the time to the first crash. Large samples are often required.
Meta-analysis	Combines knowledge on CMFs from previous studies while considering the study quality in a systematic and quantitative way.	Can be used to develop CMFs when data are not available for recent installations and it is not feasible to install the strategy and collect data. Can combine knowledge from several jurisdictions and studies.	Requires the identification of previous studies for a particular strategy. Requires a formal statistical process. All studies included should be similar in terms of data used, outcome measure, and study methodology.
Expert panel	Expert panels are assembled to critically evaluate the findings of published and unpublished research. A CMF recommendation is made based on agreement among panel members.	Can be used to develop CMFs when data are not available for recent installations and it is not feasible to install the strategy and collect data. Can combine knowledge from several jurisdictions and studies. Does not require a formal statistical process.	Traditional expert panels do not systematically derive precision estimates of a CMF. Possible complications may arise from interactions and group dynamics. Possible forecasting bias.
Surrogate measures	Surrogate measures may be used to derive a CMF where crash data are not available or insufficient (e.g., there is limited after period data or the treatment is rarely implemented).	Can be used to develop CMFs in the absence of crash-based data.	Not a crash-based evaluation. The approach to establishing relationships between surrogates and crashes is relatively undeveloped.

Source: Gross et al. (2010)

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).

CMFs were developed for various roundabout designs (single-lane roundabout, multilane roundabout, etc.) and are reported in the CMF Clearinghouse database. However, safety effects on converting a conventional intersection to a mini-roundabout in North Carolina and the United States are not well documented. Their applicability in rural areas and at high-speed intersections (posted limit is 35 mph [~56 kmph] or higher; collector road or higher functional class) are also not well documented.

CHAPTER 3 DATA COLLECTION AND PROCESSING

The data collected and processed for conducting this research are discussed in this chapter.

3.1 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 in 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. This led to the identification of over 100 mini-roundabouts (70 fully traversable, 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.

3.2 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 (~56.32 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). Crash data, traffic volume data, and built year details of the selected mini-roundabouts were captured.

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 3-1. An example of a mini-roundabout is shown in Figure 3-2.

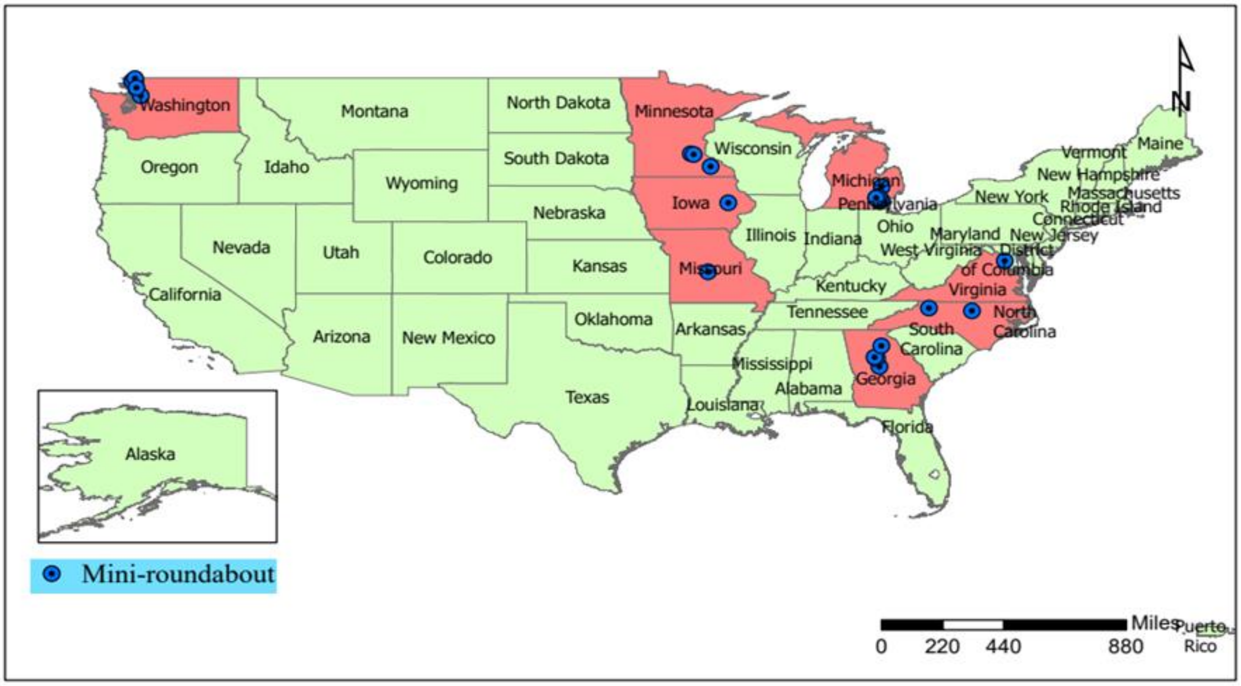


Figure 3-1. Selected mini-roundabouts.

3.3 Mini-Roundabout Inventory Data Collection

A database was prepared consisting of details such as prior control type (one-way stop-controlled [OWSC], TWSC, AWSC, and signal), built year, construction period, speed limit, geometric details, area type, land use, and other additional specific design features. Figure 3-3 shows the geometric characteristics captured for this research. Table 3-1 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.

Figure 3-2. Mini-roundabout example (Hickory Ridge Rd, Harrisburg, NC).

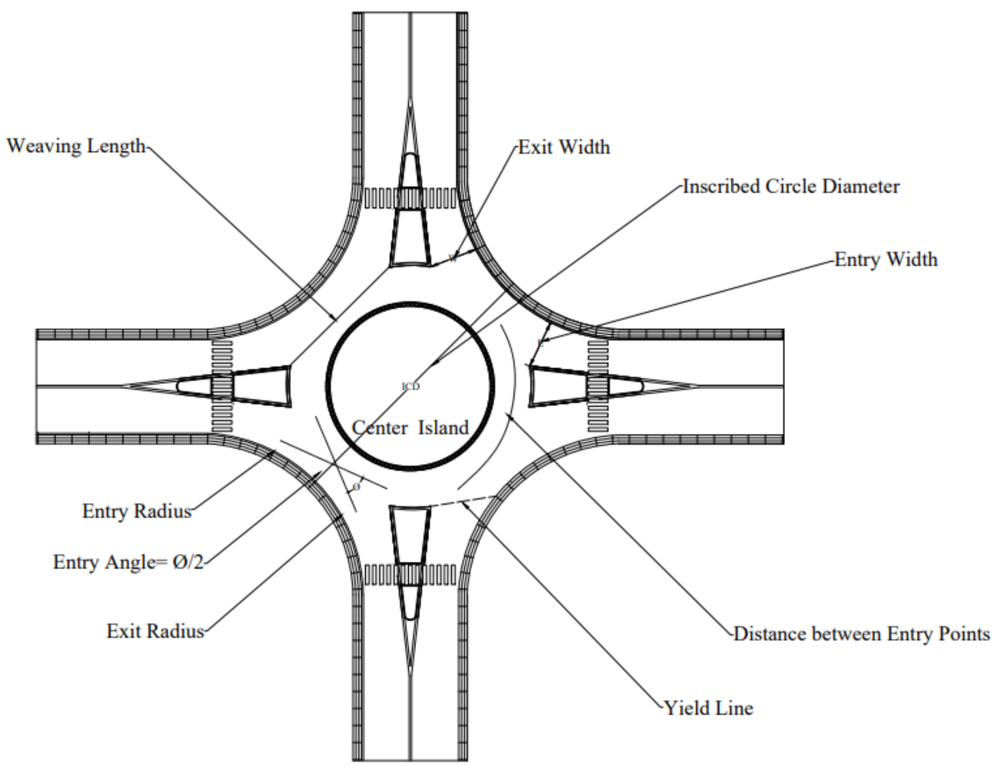


Figure 3-3. Geometric details captured.

Table 3-1. 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 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 intersections, 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 693 reference intersections in the selected states were identified based on the prior control type. Of these, 649 intersections with available crash and traffic volume data were used for the analysis. Table 3-2 shows a summary of reference intersections identified in each state based on the prior control type.

Table 3-2. 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	-	55	43	98
Total	444	55	194	693

*Three-legged

3.5 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 A-1 in Appendix A 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, and 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 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 3-4).

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 3-5 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.

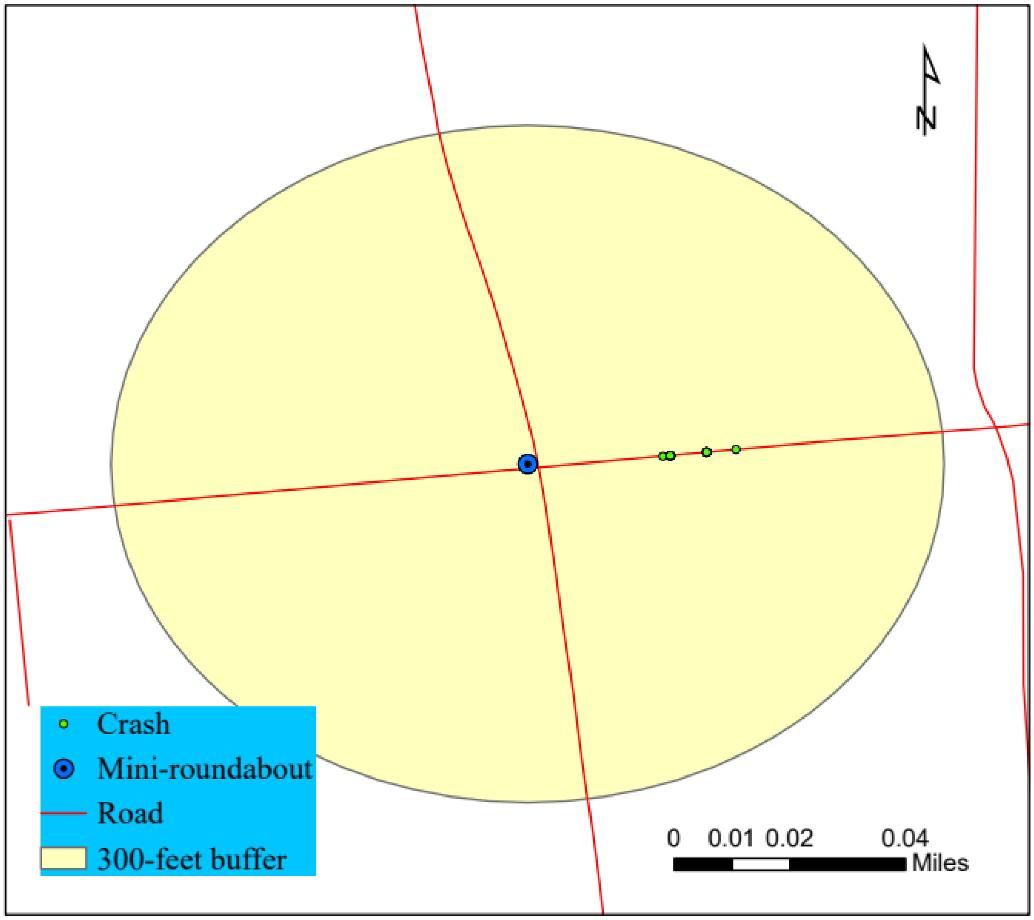
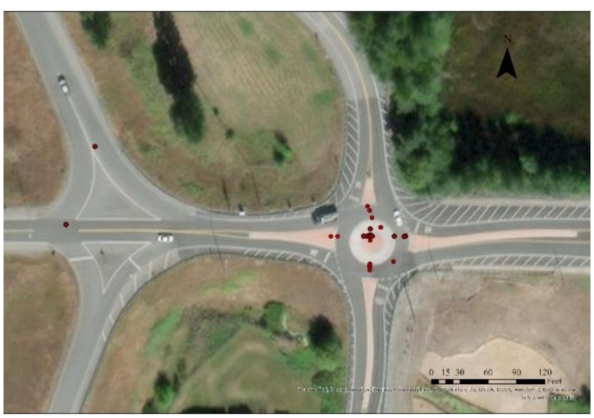
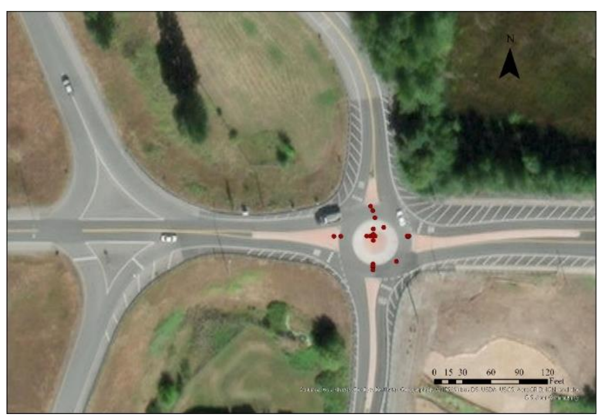


Figure 3-4. Extracting crash data using 300-feet (~91.44 meters) buffer.



(a) Crashes within the vicinity



(b) Crashes considered for analysis

Figure 3-5. Identifying crashes related to the subject intersection.

3.6 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 3-6.

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.

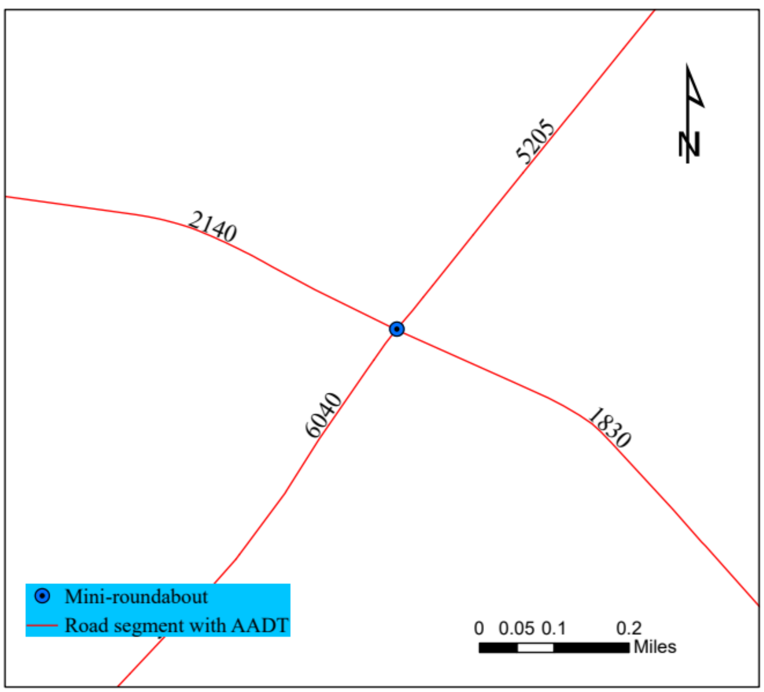


Figure 3-6. Extracting traffic volume.

Table A-2 in Appendix A shows a list of sources used to capture traffic volumes.

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 road and land use characteristics, and Table 4-2 summarizes the geometric characteristics of the selected mini-roundabouts.

Table 4-3 summarizes the average crash frequency 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. 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. 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 4-2. 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 25th and 75th 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 4-3. Crashes per year data summary– intersections converted to mini-roundabout.

Intersection	Period	Minimum	Median	Mean	Maximum	Std. dev.
Total crashes						
TWSC/OWSC (n = 15)	Before	0.00	2.60	3.49	11.20	3.18
	After	1.00	3.00	3.41	9.00	2.52
AWSC (n = 10)	Before	0.60	3.00	3.18	8.40	2.21
	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 (n = 15)	Before	0.00	1.00	1.07	4.60	1.10
	After	0.00	0.40	0.43	1.67	0.53
AWSC (n = 10)	Before	0.00	0.80	0.82	1.60	0.53
	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 (n = 15)	Before	0.00	1.80	2.43	7.40	2.38
	After	1.00	2.60	2.98	7.33	2.11
AWSC (n = 10)	Before	0.60	2.10	2.36	6.80	1.75
	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 CMF DEVELOPMENT

Crash modification factors (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). This chapter illustrates the mini-roundabout CMF development based on the prior control type using before and after analysis.

5.1 Naïve Before and After Analysis

This is the simplest method for a before and 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 change in the number of crashes per year in the after period from the before period indicates the safety effectiveness of mini-roundabouts.

This method 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 and 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. 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.

Table 5-1 shows the naïve before and after analysis results for TWSC/OWSC intersections converted to mini-roundabouts. The ratio of after to before period total crashes per year 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, the ratio of after to before period total crashes per year 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.

The ratio of after to before period total crash rate was less than 1 at eight TWSC/OWSC intersections converted to mini-roundabouts, indicating a decrease in total crash rate in the after period. However, the ratio of after to before period total crash rate was greater than 1 at six TWSC/OWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crash rate.

Table 5-1. Naïve before and after comparison of total crashes per year and crash rate - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Built year	Before period				After period			After crashes / Before crashes	After crash rate / Before crash rate	% change in traffic volume
			Control type	# of years	Crashes per year	Crash rate for 10,000 AADT	# of years	Crashes per year	Crash rate for 10,000 AADT			
1	Georgia	2016	TWSC	5	11.20	17.85	3	9.00	11.23	0.80	0.63	27.71
6	Iowa	2016	TWSC	5	5.00	5.17	3	4.33	3.41	0.87	0.66	31.14
12	Minnesota	2018	TWSC	5	2.40	1.91	1	4.00	3.09	1.67	1.61	3.30
13	Minnesota	2016	TWSC	5	0.40	0.41	3	2.33	2.06	5.83	5.02	16.09
14*	Missouri	2014	OWSC	5	8.40	8.60	5	1.60	1.46	0.19	0.17	12.02
15	North Carolina	2016	TWSC	5	7.20	4.15	3	4.67	2.94	0.65	0.71	-8.75
16*	North Carolina	2017	OWSC	5	0.00	0.00	2	1.00	4.05	-	-	4.84
17	Virginia	2018	TWSC	5	2.60	1.56	1	1.00	0.62	0.38	0.40	-3.40
18	Washington	2013	TWSC	5	2.60	3.71	5	8.60	8.80	3.31	2.37	39.51
20	Washington	2014	TWSC	5	2.80	2.63	5	3.00	1.91	1.07	0.73	46.97
21	Washington	2016	TWSC	5	1.80	1.94	3	1.67	1.72	0.93	0.88	4.65
22	Washington	2015	TWSC	5	0.40	0.38	4	1.75	1.61	4.38	4.25	2.91
23	Washington	2014	OWSC (ramp)	5	3.60	1.67	5	3.80	1.75	1.06	1.05	0.40
24	Washington	2014	OWSC (ramp)	5	2.40	1.60	5	3.40	2.08	1.42	1.30	9.13
25	Washington	2018	OWSC (ramp)	5	1.60	1.24	1	1.00	0.69	0.63	0.56	11.72

*Three-legged

Table 5-2 shows the naïve before and after analysis for AWSC intersections converted to mini-roundabouts. The ratio of after to before period total crashes per year and the crash rate was greater than 1 at all ten AWSC intersections converted to mini-roundabouts, indicating an increase in the after period total crashes.

The naïve before and after comparison of FI crashes and PDO crashes are shown in tables B-1 to B-4 in Appendix B.

Table 5-2. Naïve before and after comparison of total crashes per year and crash rate – AWSC converted to mini-roundabouts.

Site ID	State	Built year	Before period				After period			After crashes / Before crashes	After crash rate / Before crash rate	% change in traffic volume
			Control type	# of years	Crashes per year	Crash rate for 10,000 AADT	# of years	Crashes per year	Crash rate for 10,000 AADT			
2	Georgia	2017	AWSC	5	1.60	2.20	2	5.00	6.86	3.13	3.12	0.04
3	Georgia	2015	AWSC	5	3.60	3.13	4	17.25	11.65	4.79	3.72	28.65
4	Georgia	2013	AWSC	5	3.60	3.37	5	11.20	6.80	3.11	2.02	54.09
5	Georgia	2016	AWSC	5	8.40	4.15	3	28.33	11.83	3.37	2.85	18.42
7	Michigan	2016	AWSC	5	0.60	0.44	3	1.33	0.86	2.22	1.95	13.80
8	Michigan	2015	AWSC	5	1.60	1.26	4	3.25	2.34	2.03	1.86	9.36
9	Michigan	2015	AWSC	5	1.80	1.56	4	12.00	11.22	6.67	7.19	-7.31
10	Michigan	2018	AWSC	5	2.40	1.82	1	12.00	8.80	5.00	4.84	3.39
11	Minnesota	2014	AWSC	5	3.60	2.46	5	10.60	7.46	2.94	3.03	-2.95
19	Washington	2015	AWSC	5	4.60	4.07	4	14.25	13.19	3.10	3.24	-4.43

5.2 Empirical Bayes (EB) Before and After Analysis

The EB method is a widely used method for evaluating the countermeasures or any improvements at a given location. 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). The EB method as illustrated in the HSM (AASHTO, 2010) for safety evaluation is briefly summarized next.

The observed number of crashes and traffic volume availability in the before and after period are the prerequisite for before and 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 SPFs.

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 B-5 in Appendix B). 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.

As SPFs for estimating the predicted number of multiple-vehicle crashes or single-vehicle crashes at an AWSC intersection or OWSC (ramp) intersection are not available in the HSM, separate jurisdiction-specific SPFs were developed for estimating the predicted number of crashes at an AWSC and OWSC (ramp) intersection.

The predicted number of crashes from the SPF were then adjusted for site-specific observed crash history using a weighting factor. Equation 5.1 shows the general form of a SPF used for predicting the number of crashes at an intersection. Table B-6 in Appendix B shows the regression coefficients for different control types available in the HSM. Likewise, Table B-7 in Appendix B shows the regression coefficients for different control types developed in this research.

$$N_{SPF} = exp[a + b \times \ln(AADT_{MS}) + c \times \ln(\mathrm{AADT}_{CS})] \quad (5.1)$$

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, d = regression coefficients.

5.2.1 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 5.2.

The calibration factors were computed for total crashes, FI crashes, and PDO crashes. Table B-8 in Appendix B summarizes reference intersections and related details used for HSM SPFs calibration. Tables B-9 to B-11 in Appendix B show the year-wise calibration factors for the considered states based on the prior control type.

$$C_i = \frac{\sum_{All\ sites} Observed\ crashes}{\sum_{All\ sites} Predicted\ crashes} \quad (5.2)$$

5.2.2 SPF Development for AWSC and OWSC (Ramp) Intersections

SPFs for the four-legged AWSC and OWSC (ramp) intersections were not available in the HSM (AASHTO, 2010). Hence, jurisdiction-specific SPFs were developed for total crashes, FI crashes, and PDO crashes based on the prior control type. The reference intersections based on control type and geometry (four-legged, two-way two-lane roads) 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 satellite images and street-views on Google Earth and Google maps.

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 year period was considered as the dependent variable, and average traffic volumes for the major street and cross-street (three-year period) were taken as the independent variables.

Statistical models using negative binomial regression and log link function were used to develop SPFs using IBM SPSS software. Overdispersion parameter "k" and regression coefficients were estimated. The goodness of fit measures were used to check statistical validity of the model. Equation 5.3 shows the general form of a SPF developed for predicting the number of crashes at an intersection. Table B-7 in Appendix B shows the SPF regression coefficients for different control types used in this research.

$$N_{SPF} = [\exp\{[a + b \times \ln(AADT_{MS}) + c \times \ln(\text{AADT}_{CS})\}]/3 \quad (5.3)$$

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, d = regression coefficients.

5.2.3 CMF Development 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, and Virginia. Since crash data from Washington State was used in the development of SPFs available in the HSM for a TWSC/OWSC intersection, default calibration factor of 1 was considered in predicting the number of crashes at a TWSC/OWSC intersection in Washington State (WSDOT, 2020).

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) no intersection skew angle, b) no exclusive left-turn lanes at the intersection, c) no 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.

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 5.4. The weight 'w_i' was computed for each individual intersection using the overdispersion parameter 'k' and before period predicted number of crashes (Equation 5.5). Finally, the expected number of crashes in the before period for each intersection was computed using Equation 5.4.

$$N_{Expected,B} = w_{i,B} \times N_{Predicted,B} + (1-w_i) \times N_{Observed,B} \qquad (5.4)$$

$$\text{where } w_{i,B} = \frac{1}{1+k \sum_{Before\ years} N_{Predicted}} \qquad (5.5)$$

$N_{Expected,B}$ = 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 5.6. 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 5.7. 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 5.8. 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 5.9-5.11). Finally, the safety effectiveness of considered mini-roundabouts was computed using Equation 5.12. The standard error (SE) of safety effectiveness was computed using equations 5.13-5.15.

$$r_i = \frac{\sum_{After\ years} N_{Predicted,A}}{\sum_{Before\ years} N_{Predicted,B}} \tag{5.6}$$

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.

$$N_{Expected,A} = N_{Expected,B} \times r_i \tag{5.7}$$

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

$$OR_i = \frac{N_{Observed,A}}{N_{Expected,A}} \tag{5.8}$$

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

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

$$\text{Safety Effectiveness}_i = 100 \times (1- OR_i) \tag{5.9}$$

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

$$OR' = \frac{\sum_{All\ sites} N_{Observed,A}}{\sum_{All\ sites} N_{Expected,A}} \tag{5.10}$$

where OR' = odds ratio of all intersections combined.

$$OR = \frac{OR'}{1 + \frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}} \quad (5.11)$$

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 equation (3) and (4).

$$\text{Safety Effectiveness} = 100 \times (1 - \text{OR}) \quad (5.12)$$

where Safety Effectiveness = overall unbiased safety effectiveness.

$$\text{Var(OR)} = \frac{(OR')^2\left[\frac{1}{N_{Observed,\ A}} + \frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]}{\left[1 + \frac{Var\left(\sum_{All\ sites} N_{Expected,A}\right)}{\left(\sum_{All\ sites} N_{Expected,A}\right)^2}\right]} \quad (5.13)$$

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

$$\text{SE(OR)} = \sqrt{Var(OR)} \quad (5.14)$$

where SE(OR) = Standard error.

$$\text{SE (Safety Effectiveness)} = 100 \times \text{SE(OR)} \quad (5.15)$$

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

Table 5-3 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 B-12(A) and B-12(B) in Appendix B. A similar approach was adopted for FI crashes and PDO crashes and the results are summarized in tables 5-4 and 5-5, 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 seven TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.85 at the remaining eight 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 three TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.80 at the remaining twelve TWSC/OWSC intersections converted to mini-roundabouts. A detailed year-wise odds ratio computation for FI crashes is shown in tables B-13(A) and B-13(B) in Appendix B.

In the case of PDO crashes, the odds ratio was observed to be equal to or greater than 1 at nine TWSC/OWSC intersections converted to mini-roundabouts. It was observed to be less than 0.95 at the remaining six TWSC/OWSC intersections converted to mini-roundabouts. A detailed year-wise odds ratio computation for PDO crashes is shown in tables B-14(A) and B-14(B) in Appendix B.

At three mini-roundabouts (site ID #s 18, 22 and 23), the odds ratio was equal to or greater than 1 for total crashes, FI crashes, and PDO crashes. Figure 5-1 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.

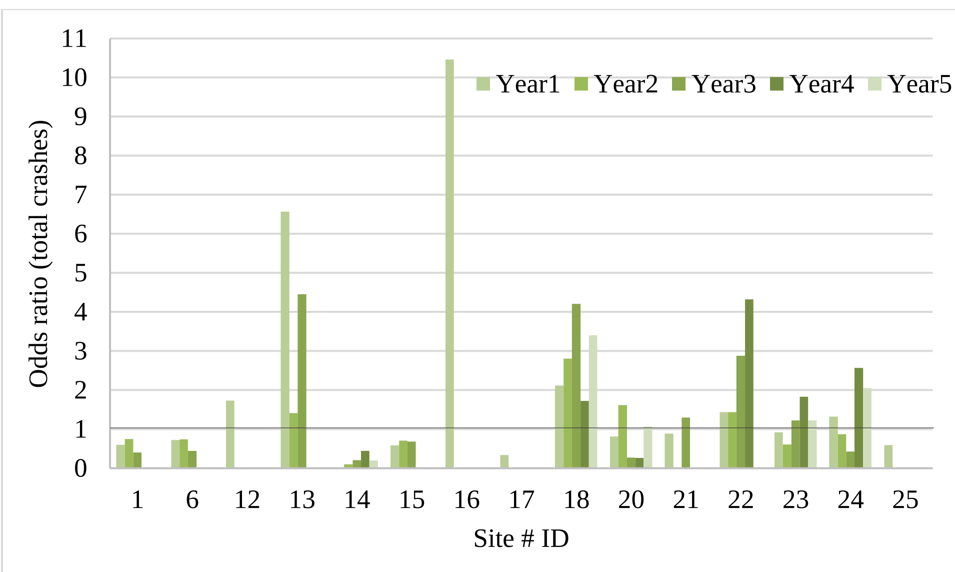


Figure 5-1. Odds ratio year-wise variation of total crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Table 5-3. EB analysis summary for total crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Before period				After period										OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF	Exp. # of crashes	# of years	Pred. # of crashes using SPF	Exp. # of crashes	Obs. # of crashes	Built year	Odds ratio (OR) Year 1	Year 2	Year 3	Year 4	Year 5	
1	Georgia	5	56	20.13	49.85	3	19.81	49.05	27.00	2016	0.60	0.75	0.40			0.55
6	Iowa	5	25	10.29	22.13	3	9.45	20.33	13.00	2016	0.73	0.74	0.45			0.64
12	Minnesota	5	12	10.95	11.80	1	2.14	2.31	4.00	2018	1.73					1.73
13	Minnesota	5	2	8.77	3.50	3	4.60	1.84	7.00	2016	6.57	1.42	4.46			3.81
14*	Missouri	5	42	9.35	36.60	5	12.61	49.36	8.00	2014	0.00	0.10	0.21	0.44	0.20	0.16
15	North Carolina	5	36	28.11	35.36	3	16.96	21.33	14.00	2016	0.58	0.70	0.68			0.66
16*	North Carolina	5	0	1.36	0.78	2	0.62	0.00	2.00	2017	10.47	0.00				5.60
17	Virginia	5	13	18.25	13.63	1	3.89	2.91	1.00	2018	0.34					0.34
18	Washington	5	13	4.66	10.09	5	6.88	14.89	43.00	2013	2.12	2.80	4.20	1.73	3.41	2.89
20	Washington	5	14	7.72	12.46	5	11.52	18.59	15.00	2014	0.81	1.62	0.27	0.27	1.07	0.81
21	Washington	5	9	20.91	10.98	3	13.06	6.86	5.00	2016	0.89	0.00	1.30			0.73
22	Washington	5	2	7.64	3.39	4	6.26	2.78	7.00	2015	1.44	1.44	2.88	4.32		2.52
23[Ψ]	Washington	5	18	11.06	16.28	5	11.10	16.34	19.00	2014	0.92	0.61	1.22	1.83	1.22	1.16
24[Ψ]	Washington	5	12	8.67	11.02	5	9.17	11.66	17.00	2014	1.32	0.87	0.43	2.56	2.06	1.46
25[Ψ]	Washington	5	8	8.00	8.00	1	1.69	1.69	1.00	2018	0.59					0.59

*Three-legged, [Ψ]OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

Table 5-4. EB analysis summary for FI Crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Before period				After period										OR (Obs. / Exp.)
											Odds ratio (OR)					
		# of years	Obs. # of crashes	Pred. # of crashes using SPF	Exp. # of crashes	# of years	Pred. # of crashes using SPF	Exp. # of crashes	Obs. # of crashes	Built year	Year 1	Year 2	Year 3	Year 4	Year 5	
1	Georgia	5	23	7.78	17.69	3	8.26	18.78	5.00	2016	0.43	0.37	0.12			0.27
6	Iowa	5	6	3.82	5.14	3	3.85	5.18	2.00	2016	0.48	0.00	0.65			0.39
12	Minnesota	5	5	5.97	5.29	1	1.26	1.12	0.00	2018	0.00					0.00
13	Minnesota	5	1	4.66	2.28	3	2.39	1.17	0.00	2016	0.00	0.00	0.00			0.00
14*	Missouri	5	5	1.29	2.81	5	2.85	6.21	0.00	2014	0.00	0.00	0.00	0.00	0.00	0.00
15	North Carolina	5	9	14.57	9.82	3	9.64	6.50	0.00	2016	0.00	0.00	0.00			0.00
16*	North Carolina	5	0	0.49	0.39	2	0.43	0.34	0.00	2017	0.00	0.00				0.00
17	Virginia	5	8	8.33	8.08	1	1.51	1.46	0.00	2018	0.00					0.00
18	Washington	5	2	1.59	1.75	5	2.48	2.73	7.00	2013	3.89	0.00	3.86	1.90	2.78	2.57
20	Washington	5	5	2.83	3.98	5	4.45	6.26	2.00	2014	0.81	0.80	0.00	0.00	0.00	0.32
21	Washington	5	6	9.01	6.95	3	5.63	4.34	2.00	2016	0.70	0.00	0.68			0.46
22	Washington	5	2	2.79	2.37	4	2.29	1.95	2.00	2015	0.00	0.00	0.00	4.10		1.03
23$^{\Psi}$	Washington	5	3	3.82	3.40	5	3.83	3.41	4.00	2014	1.47	0.00	1.47	0.00	2.92	1.17
24$^{\Psi}$	Washington	5	2	2.87	2.49	5	3.09	2.67	2.00	2014	0.00	0.00	1.88	1.84	0.00	0.75
25$^{\Psi}$	Washington	5	3	2.54	2.73	1	0.56	0.60	0.00	2018	0.00					0.00

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

Table 5-5. EB analysis summary for PDO crashes - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Before period				After period										OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF	Exp. # of crashes	# of years	Pred. # of crashes using SPF	Exp. # of crashes	Obs. # of crashes	Built year	Odds ratio (OR)					
											Year 1	Year 2	Year 3	Year 4	Year 5	
1	Georgia	5	33	12.34	27.79	3	11.59	26.10	22.00	2016	0.79	1.17	0.68			0.84
6	Iowa	5	19	6.47	15.51	3	5.44	13.03	11.00	2016	0.98	1.12	0.45			0.84
12	Minnesota	5	7	5.07	6.36	1	0.86	1.07	4.00	2018	3.72					3.72
13	Minnesota	5	1	4.16	2.19	3	2.19	1.15	7.00	2016	12.75	1.80	8.36			6.08
14*	Missouri	5	37	7.91	31.48	5	9.60	38.21	8.00	2014	0.00	0.14	0.22	0.86	0.21	0.21
15	North Carolina	5	27	14.16	25.07	3	7.57	13.40	14.00	2016	0.90	1.15	1.09			1.04
16*	North Carolina	5	0	0.82	0.57	2	0.42	0.29	2.00	2017	13.17	0.00				6.96
17	Virginia	5	5	10.08	6.01	1	2.29	1.37	1.00	2018	0.73					0.73
18	Washington	5	11	3.07	7.45	5	4.42	10.72	36.00	2013	1.95	3.85	4.85	1.92	4.07	3.36
20	Washington	5	9	4.95	7.64	5	7.19	11.11	13.00	2014	0.91	2.26	0.45	0.45	1.78	1.17
21	Washington	5	3	11.90	5.31	3	7.43	3.31	3.00	2016	0.92	0.00	1.79			0.91
22	Washington	5	0	4.89	1.65	4	4.00	1.35	5.00	2015	2.96	2.96	5.91	2.96		3.70
23[Ψ]	Washington	5	15	7.45	12.52	5	7.47	12.55	15.00	2014	0.80	0.80	1.20	2.38	0.79	1.19
24[Ψ]	Washington	5	10	6.05	8.52	5	6.37	8.96	15.00	2014	1.72	1.14	0.00	2.77	2.68	1.67
25[Ψ]	Washington	5	5	5.59	5.23	1	1.19	1.11	1.00	2018	0.90					0.90

*Three-legged, [Ψ]OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

The site ID #s 16, 13, and 18 have the highest odds ratio equal to 5.60, 3.81, and 2.89, 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.

5.2.4 CMF 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. SPF regression coefficients and overdispersion parameter were then used for EB before and after analysis. The results are shown in Table B-7 in Appendix B.

Tables 5-6 to 5-8 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 B-15 to B-17 in Appendix B.

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 0.65 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 0.45 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 0.30 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

5-2 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.

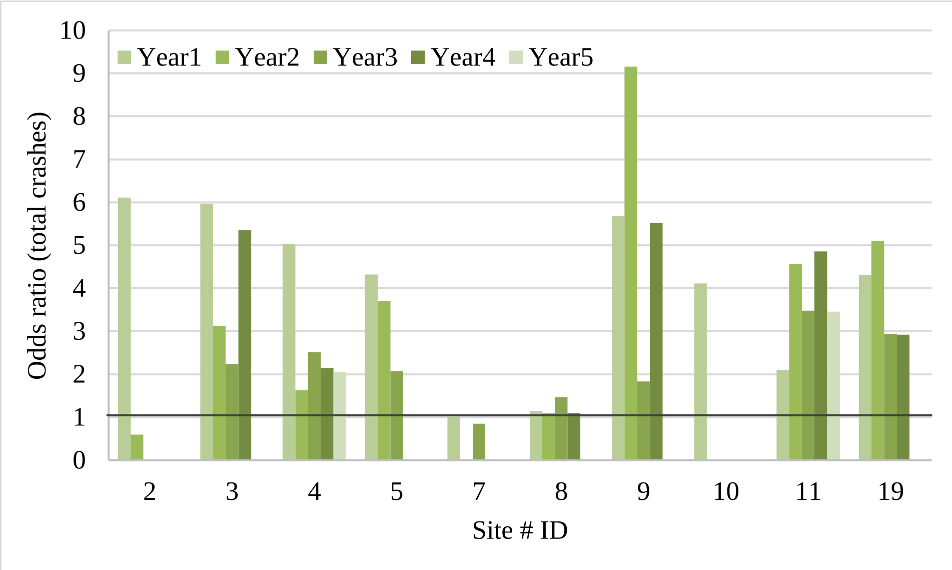


Figure 5-2. Odds ratio year-wise variation of total crashes - AWSC intersections converted to mini-roundabouts.

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 5-6. EB analysis summary for total crashes - AWSC intersections converted to mini-roundabouts.

Site ID	State	Before period				After period										OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF	Exp. # of crashes	# of years	Pred. # of crashes using SPF	Exp. # of crashes	Obs. # of crashes	Built year	Odds ratio (OR)					
											Year 1	Year 2	Year 3	Year 4	Year 5	
2	Georgia	5	8	8.74	8.35	2	3.30	3.16	10.00	2017	6.11	0.59				3.17
3	Georgia	5	18	14.24	16.65	4	14.11	16.50	69.00	2015	5.97	3.13	2.24	5.35		4.18
4	Georgia	5	18	13.34	16.25	5	17.64	21.48	56.00	2013	5.03	1.63	2.51	2.15	2.05	2.61
5	Georgia	5	42	23.35	37.24	3	15.95	25.44	85.00	2016	4.32	3.70	2.07			3.34
7	Michigan	5	3	13.45	9.25	3	9.47	6.51	4.00	2016	1.01	0.00	0.85			0.61
8	Michigan	5	8	14.50	11.77	4	13.33	10.82	13.00	2015	1.14	1.10	1.46	1.10		1.20
9	Michigan	5	9	12.85	11.34	4	9.80	8.65	48.00	2015	5.68	9.16	1.83	5.52		5.55
10	Michigan	5	12	15.84	14.14	1	3.27	2.92	12.00	2018	4.11					4.11
11	Minnesota	5	18	9.46	14.79	5	9.18	14.34	53.00	2014	2.10	4.57	3.48	4.86	3.46	3.70
19	Washington	5	23	5.84	19.86	4	4.39	14.95	57.00	2015	4.31	5.09	2.94	2.92		3.81

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

Table 5-7. EB analysis summary for FI crashes - AWSC intersections converted to mini-roundabouts.

Site ID	State	Before period				After period										OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF	Exp. # of crashes	# of years	Pred. # of crashes using SPF	Exp. # of crashes	Obs. # of crashes	Built year	Odds ratio (OR)					
											Year 1	Year 2	Year 3	Year 4	Year 5	
2	Georgia	5	2	3.25	3.19	2	1.20	1.18	3.00	2017	5.64	0.00				2.55
3	Georgia	5	6	5.84	5.85	4	5.87	5.89	17.00	2015	6.30	2.03	0.70	2.58		2.89
4	Georgia	5	6	5.42	5.46	5	6.97	7.02	11.00	2013	2.52	1.43	1.39	1.28	1.39	1.57
5	Georgia	5	8	10.12	9.86	3	6.91	6.73	9.00	2016	0.93	1.75	1.31			1.34
7	Michigan	5	0	2.10	1.35	3	1.57	1.01	2.00	2016	0.00	0.00	5.24			1.98
8	Michigan	5	2	2.55	2.33	4	2.54	2.32	1.00	2015	1.77	0.00	0.00	0.00		0.43
9	Michigan	5	2	2.11	2.07	4	1.61	1.58	3.00	2015	0.00	2.50	2.50	2.51		1.90
10	Michigan	5	3	2.96	2.98	1	0.62	0.62	1.00	2018	1.61					1.61
11	Minnesota	5	5	2.93	3.71	5	2.87	3.64	6.00	2014	1.38	0.00	2.74	1.37	2.72	1.65
19	Washington	5	7	5.75	6.60	4	4.66	5.36	9.00	2015	0.75	2.24	2.24	1.49		1.68

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

Table 5-8. EB analysis summary for PDO crashes - AWSC intersections converted to mini-roundabouts.

Site ID	State	Before period				After period										OR (Obs. / Exp.)
		# of years	Obs. # of crashes	Pred. # of crashes using SPF	Exp. # of crashes	# of years	Pred. # of crashes using SPF	Exp. # of crashes	Obs. # of crashes	Built year	Odds ratio (OR)					
											Year 1	Year 2	Year 3	Year 4	Year 5	
2	Georgia	5	6	7.01	6.68	2	2.68	2.55	7.00	2017	4.99	0.74				2.74
3	Georgia	5	12	11.29	11.60	4	11.30	11.61	52.00	2015	5.30	3.40	2.83	6.30		4.48
4	Georgia	5	12	10.57	11.18	5	14.54	15.38	45.00	2013	5.85	1.63	2.87	2.42	2.23	2.93
5	Georgia	5	34	18.73	27.39	3	12.94	18.92	76.00	2016	5.51	4.34	2.31			4.02
7	Michigan	5	3	10.63	10.18	3	7.37	7.06	2.00	2016	0.92	0.00	0.00			0.28
8	Michigan	5	6	10.86	10.57	4	9.64	9.37	12.00	2015	0.87	1.27	1.69	1.27		1.28
9	Michigan	5	7	9.82	9.66	4	7.44	7.32	45.00	2015	6.72	10.28	1.62	5.98		6.15
10	Michigan	5	9	11.51	11.35	1	2.37	2.34	11.00	2018	4.71					4.71
11	Minnesota	5	13	6.79	10.12	5	6.57	9.80	47.00	2014	2.56	6.67	4.08	6.62	4.06	4.80
19	Washington	5	16	2.72	7.31	4	2.03	5.47	48.00	2015	11.05	11.73	5.84	6.54		8.78

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

5.2.5 EB Before and After Analysis Summary

Tables 5-9 summarize results from the EB before and after analysis. A 17.24% decrease in total crashes, a 58.95% decrease in FI crashes, and an 8.67% increase in PDO crashes was observed when TWSC/OWSC intersections were converted to mini-roundabouts. The standard error was 7.99% in total crashes, 9.07% in FI crashes, and 11.70% 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 224.76% increase in total crashes, a 74.30% increase FI crashes, and a 282.71% increase in PDO crashes was observed when AWSC intersections were converted to mini-roundabouts. The standard error was 26.96% in total crashes, 26.08% in FI crashes, and 31.05% 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 5-9. 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	0.83	0.08	17.24	7.99	2.16	Significant at 95% confidence level
FI	0.41	0.09	58.95	9.07	6.51	Significant at 95% confidence level
PDO	1.09	0.12	-8.67	11.70	0.74	Not significant
10 AWSC intersections converted to mini-roundabouts						
Total	3.25	0.27	-224.76	26.96	8.34	Significant at 95% confidence level
FI	1.74	0.26	-74.30	26.08	2.85	Significant at 95% confidence level
PDO	3.83	0.31	-282.71	31.05	9.11	Significant at 95% confidence level

5.3 Before and After Analysis Summary – Naïve and EB Method Analysis

Table 5-10 shows the odds ratio summary of TWSC/OWSC, and AWSC intersections converted to mini-roundabouts. The odds ratio computed from the EB analysis for TWSC/OWSC intersections converted to mini-roundabouts based on the total crashes and FI crashes was lower than the odds ratio computed from the naïve analysis. However, the odds ratio for PDO crashes computed from the EB analysis was in between the odds ratio computed from the naïve analysis. The standard errors computed from the EB analysis are consistently less than standard error computed from the naïve analysis. 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.

The odds ratio computed from the EB analysis for AWSC intersections converted to mini-roundabouts based on the total crashes, FI crashes, and PDO crashes was in between the odds ratio computed from the naïve analysis. As noted in case of TWSC/OWSC intersections converted to mini-roundabouts, the standard errors computed for AWSC interactions from the EB analysis are also consistently less than the standard error computed from the naïve analysis.

Table 5-11 shows the number of intersections summary with odds ratio less than 1, and greater or equal to 1 using naïve and EB method analysis. Computing odds ratio for an individual intersection using the naïve analysis has limitation if the number of crashes (total/FI/PDO crashes) in the before period is zero. Therefore, the number of intersections form naïve analysis is 14 compared to EB analysis 15 when a TWSC/OWSC intersections converted to a mini-roundabouts.

Table 5-10. Naïve and EB method analysis summary - odds ratio.

Crash severity type	Naïve analysis		EB analysis
	OR based on crashes per year (standard error)	OR based on crash rate (crashes per year/traffic volume) (standard error)	Odds ratio (OR) (standard error)
15 TWSC/OWSC converted to mini-roundabouts			
Total	0.99 (0.10)	0.85 (0.09)	0.83 (0.08)
FI	0.53 (0.12)	0.44 (0.10)	0.41 (0.09)
PDO	1.15 (0.13)	0.99 (0.12)	1.09 (0.12)
10 AWSC intersections converted to mini-roundabouts			
Total	3.51 (0.34)	3.04 (0.34)	3.25 (0.27)
FI	1.96 (0.39)	1.67 (0.35)	1.74 (0.26)
PDO	4.06 (0.44)	3.53 (0.43)	3.83 (0.31)

Table 5-11. Naïve and EB method analysis summary - # of intersections with odds ratio less than 1, and greater or equal to 1.

Prior control type	Crash severity type	Naïve analysis				EB analysis	
		Crashes per year		Crash rate (crashes per year/traffic volume)			
		# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1	# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1	# of intersections with odds ratio < 1	# of intersections with odds ratio ≥ 1
TWSC/OWSC	Total	7	7	8	6	8	7
	FI	10	4	11	3	12	3
	PDO	3	10	6	7	6	9
AWSC	Total	0	10	0	10	1	9
	FI	1	8	1	8	1	9
	PDO	0	10	1	9	1	9

5.4 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. Table 5-12 shows the recommended CMFs for converting a TWSC/OWSC intersection and AWSC intersection to a mini-roundabout.

Table 5-12. Recommended CMFs for a mini-roundabout.

Crash severity type	CMF	Standard error	Confidence interval	Lower limit	Upper limit	Statistical significance
TWSC/OWSC intersection						
Total	*0.83*	0.08	± 1.96	0.67	0.98	Significant at α=0.05
FI	*0.41*	0.09	± 1.96	0.23	0.59	Significant at α=0.05
PDO	1.09	0.12	± 1.96	0.86	1.32	Not significant
AWSC intersection						
Total	*3.25*	0.27	± 1.96	2.72	3.78	Significant at α=0.05
FI	*1.74*	0.26	± 1.96	1.23	2.25	Significant at α=0.05
PDO	*3.83*	0.31	± 1.96	3.22	4.44	Significant at α=0.05

5.5 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 5-13. 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 5-13. Comparison of CMFs for mini-roundabouts and single-lane roundabouts.

Study title	Prior condition	# of sites	Setting	Crash severity type	CMF	Standard error	Source
Mini-roundabout CMF development	TWSC/OWSC	15	All	All	0.83	0.08	This research
				K, A, B & C	0.41	0.09	
				O	1.09	0.12	
	AWSC	10	All	All	3.25	0.27	
				K, A, B & C	1.74	0.26	
				O	3.83	0.31	
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 6 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 were 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.

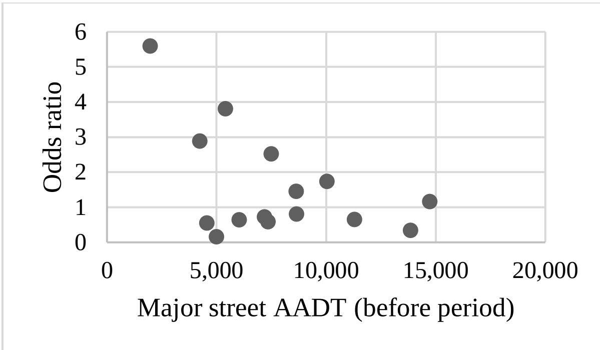
6.1 Examining the Effect of Traffic, On-Network and Off-Network Characteristics on the Safety Effectiveness

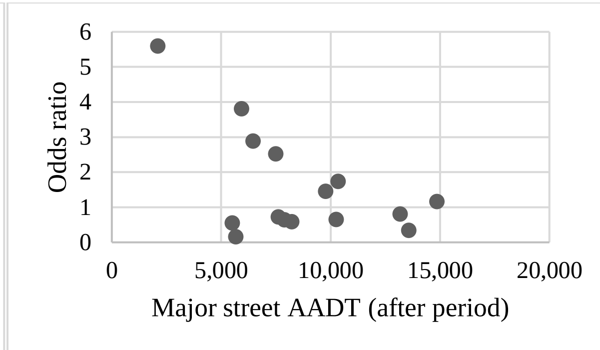
The results summarizing the effect of various characteristics on the safety effectiveness of mini-roundabouts are discussed next.

6.1.1 Effect of Traffic Volume on the Safety Effectiveness

The effect of traffic volume on the safety effectiveness was examined using scatter plots. Figure 6-1 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.

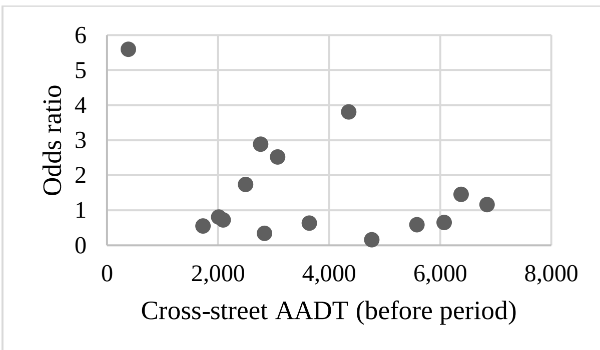
Figure 6-2 shows the scatter plots between the odds ratio and before and after period traffic volume (major-street volume, cross-street volume, and cross-street volume share) for AWSC intersections converted to mini-roundabouts. No specific trend between the odds ratio with major street and cross-street traffic volume was observed. Also, no specific trend between the odds ratio and cross-street volume share was observed.

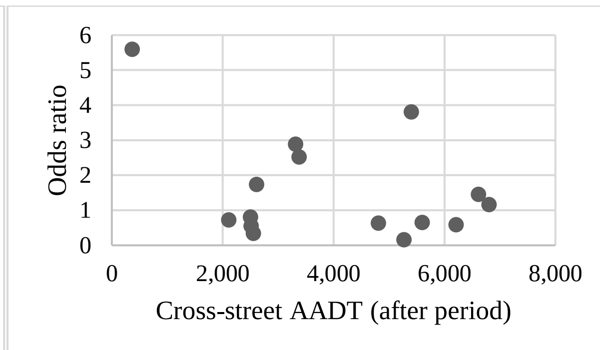




(a) Major street AADT (before period)

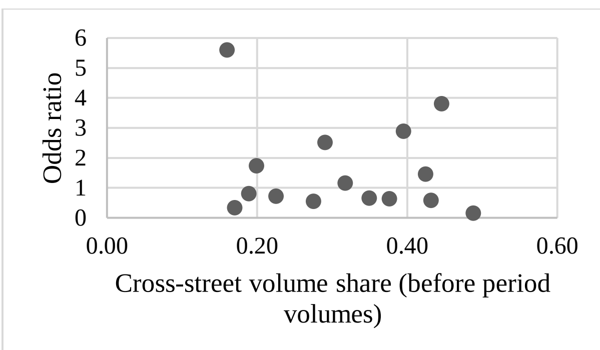
(b) Major street AADT (after period)

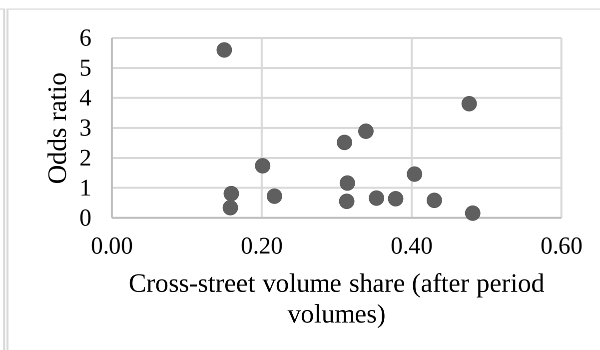




(c) Cross-street AADT (before period)

(d) Cross-street AADT (after period)

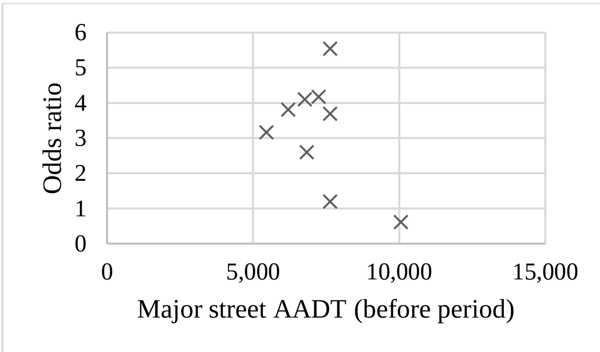




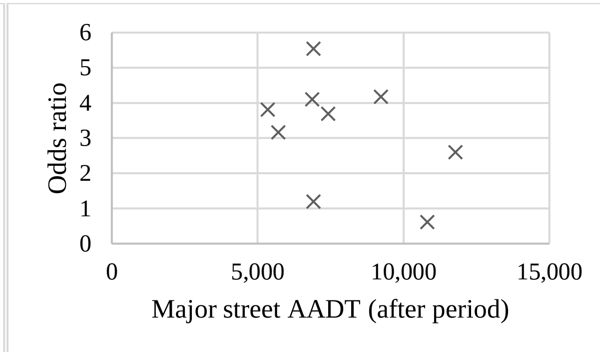
(e) Cross-street share (before period)

(f) Cross-street share (after period)

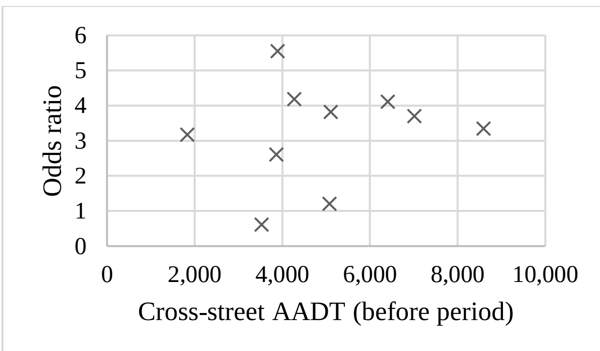
Figure 6-1. Scatterplot between odds ratio and AADT for TWSC/OWSC intersections converted to mini-roundabouts.



(a) Major street AADT (before period)

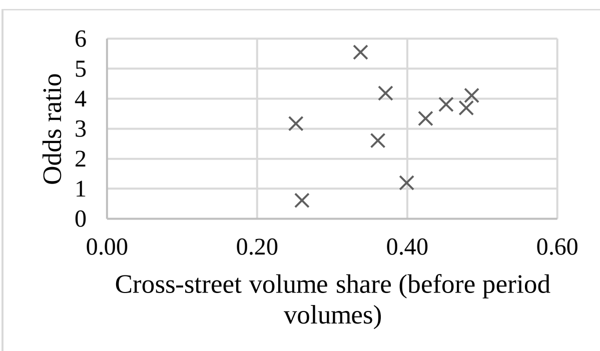


(b) Major street AADT (after period)

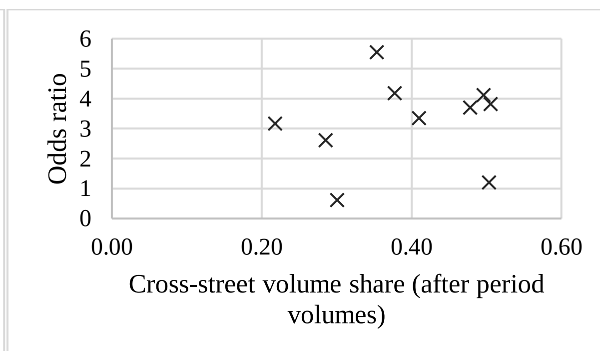


(c) Cross-street AADT (before period)

(d) Cross-street AADT (after period)



(e) Cross-street share (before period)



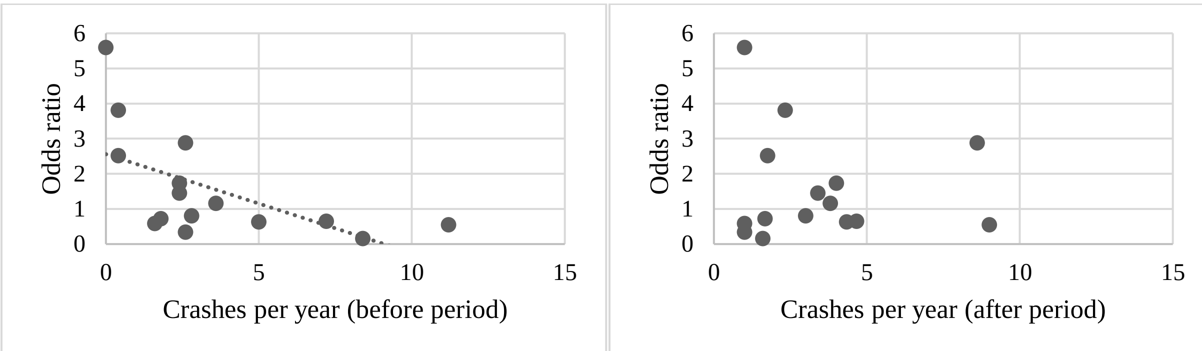
(f) Cross-street share (after period)

Figure 6-2. Scatterplot between odds ratio and AADT for AWSC intersections converted to mini-roundabouts.

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

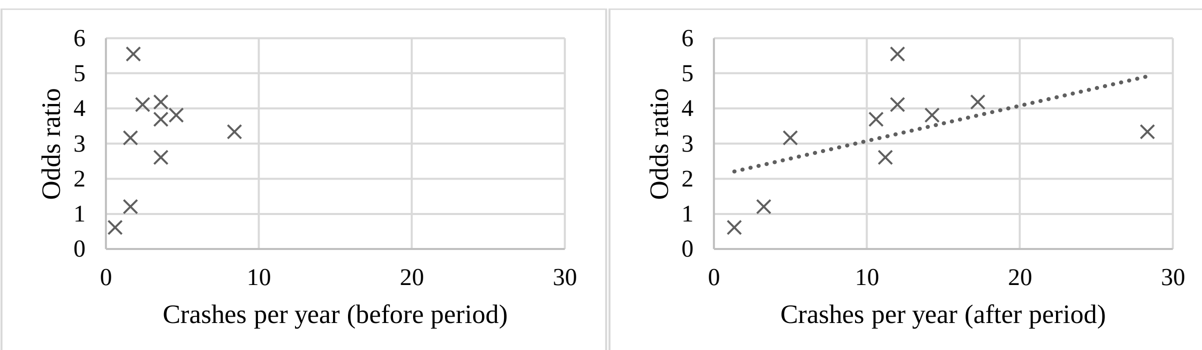
The effect of before period crash history on the safety effectiveness was examined using scatter plots. Figure 6-3 shows the scatter plots between the odds ratio and before period crashes per year for TWSC/OWSC intersections converted to mini-roundabouts. A negative trend was observed for the odds ratio 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 6-4 (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 6-3. Scatter plot between odds ratio and crashes for TWSC/OWSC intersections converted to mini-roundabouts.

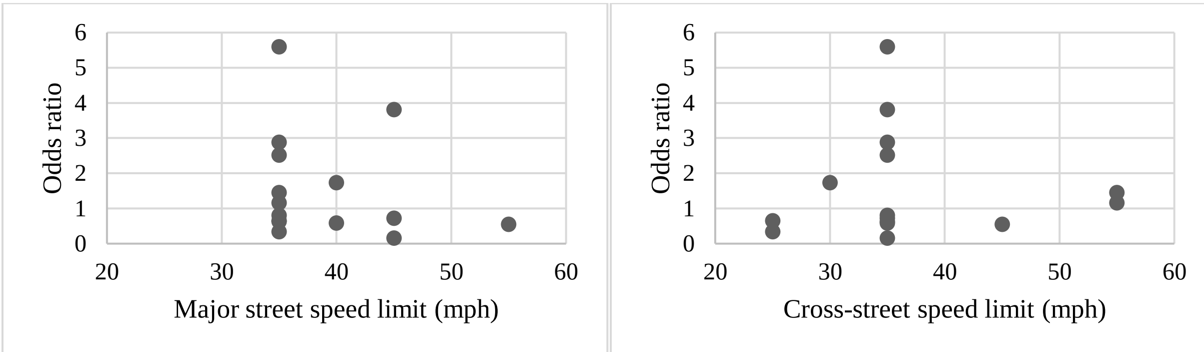


(a) Crashes per year (before period) (b) Crashes per year (after period)

Figure 6-4. Scatter plot between odds ratio and crashes for AWSC intersections converted to mini-roundabouts.

6.1.3 Effect of Speed Limit on the Safety Effectiveness

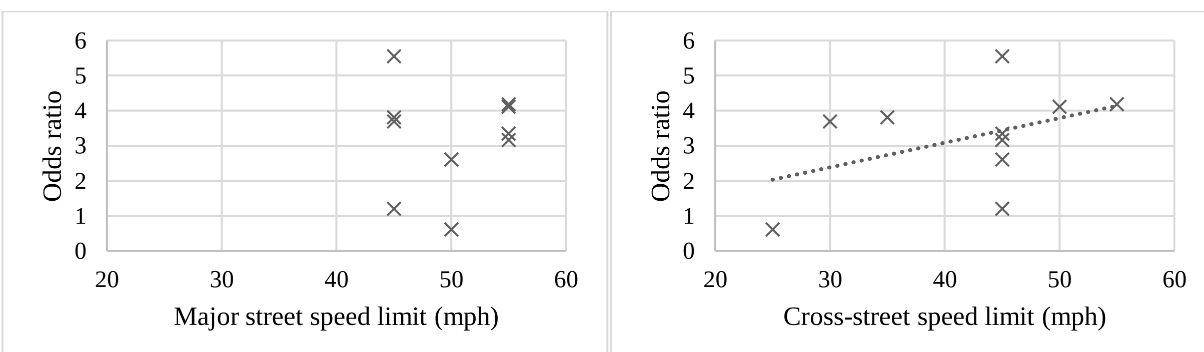
Figure 6-5 shows the effect of the speed limit on the odds ratio for TWSC/OWSC intersections converted to mini-roundabouts. No specific trend was observed between the odds ratio and major street and cross-street speed limits. However, an odds ratio of less than one was observed for all the speed limits at major streets, ranging from 35 to 55 mph.



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

Figure 6-5. Scatter plot between odds ratio and speed limit for TWSC/OWSC intersections converted to mini-roundabouts.

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

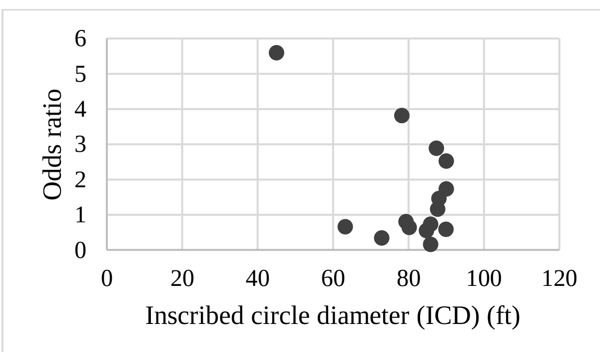
6.1.4 Effect of Area Type and Land use on the Safety Effectiveness

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 five out of eleven TWSC/OWSC intersections when converted to mini-roundabouts in urban/suburban areas (Figure E-1 in Appendix E). 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 (Figure E-2 in Appendix E).

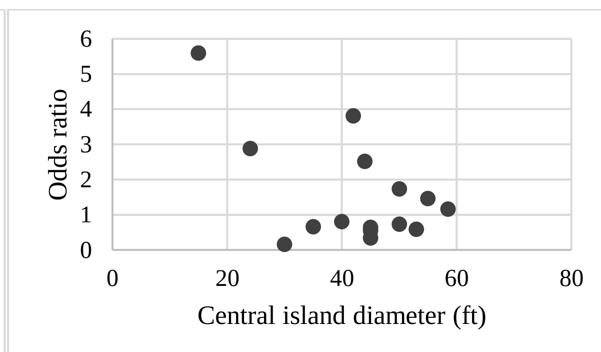
While looking into the land use types, the majority of the mini-roundabouts were installed in mixed land use areas. No specific trend between land use and odds ratio was observed for TWSC/OWSC and AWSC intersections converted to mini-roundabouts (Figure E-3 in Appendix E).

6.1.5 Effect of Geometric Characteristics on the Safety Effectiveness

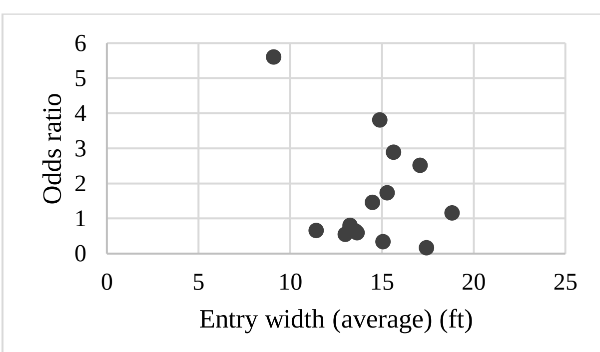
Figures 6-7 shows the effect of selected geometric characteristics on the safety effectiveness of TWSC/OWSC converted to mini-roundabouts.



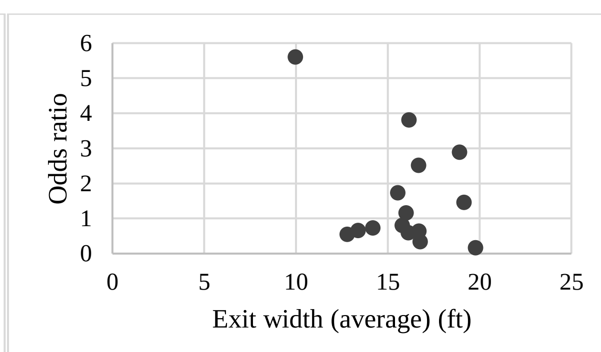
(a) Inscribed circle diameter



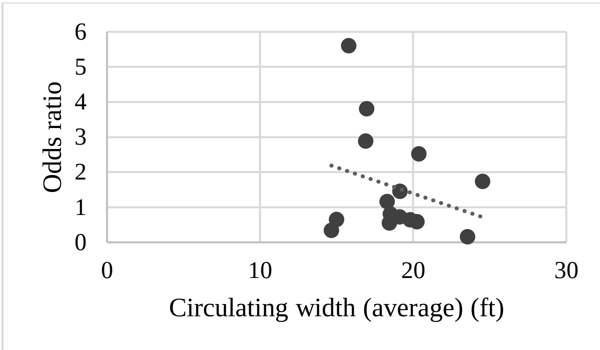
(b) Central island diameter



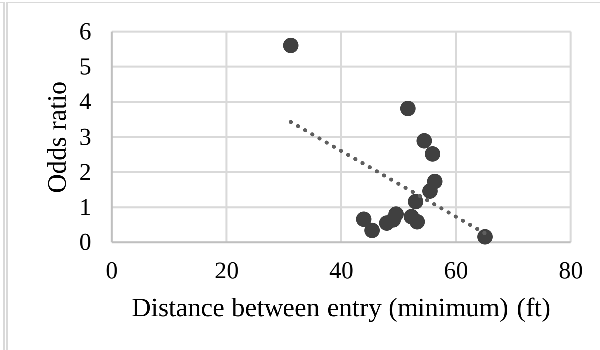
(c) Entry width (average)



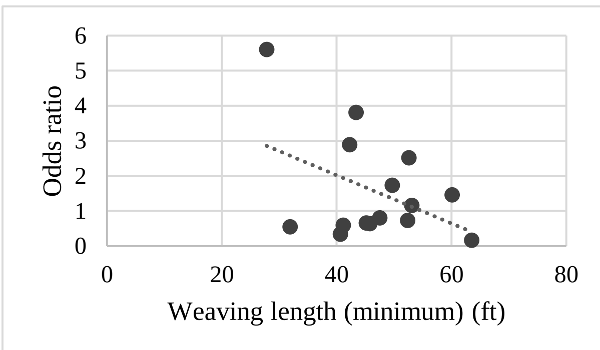
(d) Exit width (average)



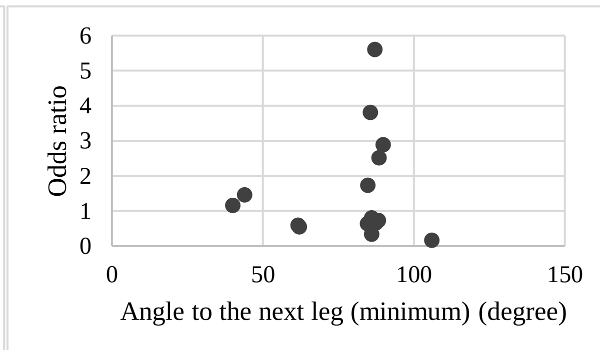
(e) Circulating width (average)



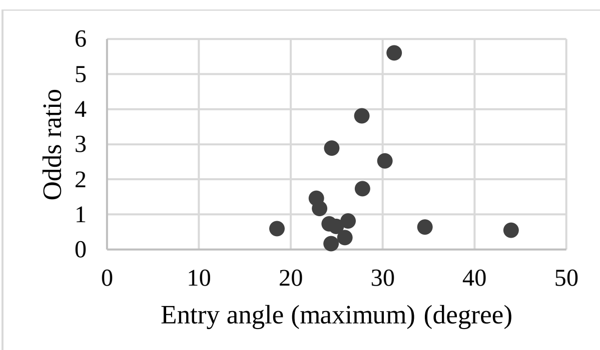
(f) Distance between entry to the next leg (minimum)



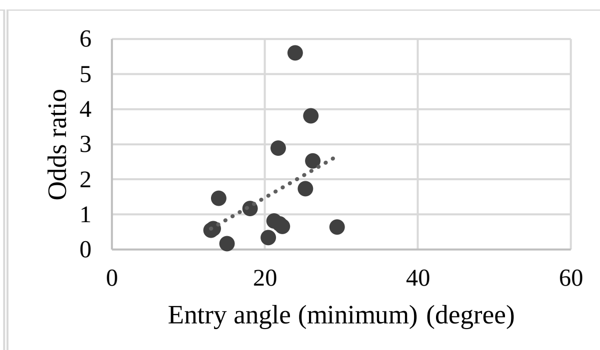
(g) Weaving length (minimum)



(h) Angle to the next leg (minimum)



(i) Entry angle (maximum)



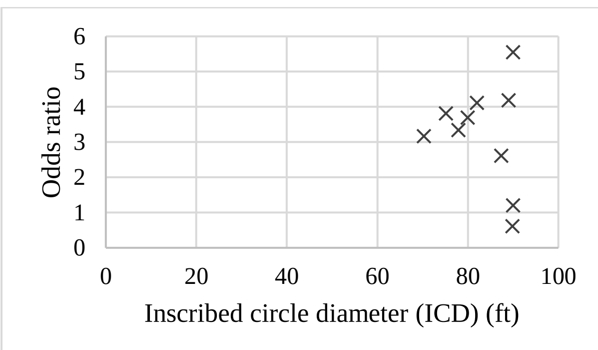
(j) Entry angle (minimum)

Figure 6-7. Scatter plot between odds ratio and selected geometric characteristics for TWSC/OWSC intersections converted to mini-roundabouts.

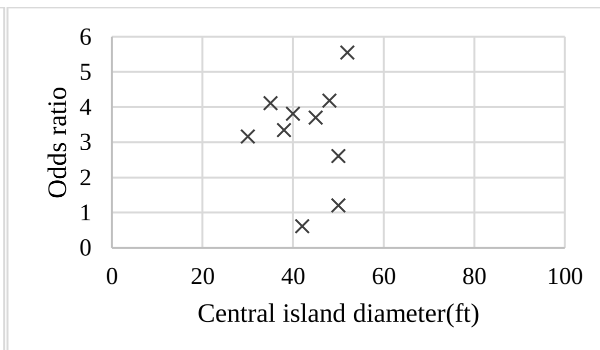
Note: 1 meter = 3.28 feet.

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 6-7). 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).

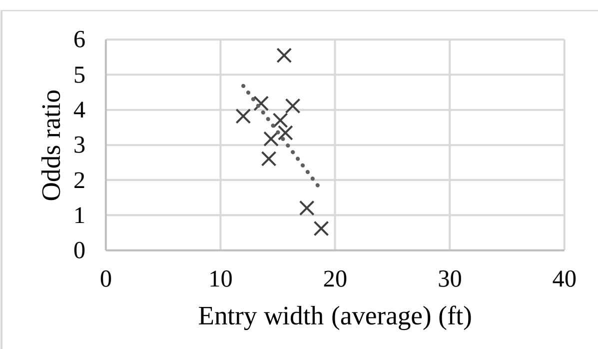
Likewise, entry width (average), circulating width (average), distance between entry to the next leg (minimum), weaving length (minimum), angle to the next leg (minimum), and entry angle (minimum) have an effect on the odds ratio in the case of AWSC intersections converted to mini-roundabouts (Figure 6-8 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 6-8 d & i).



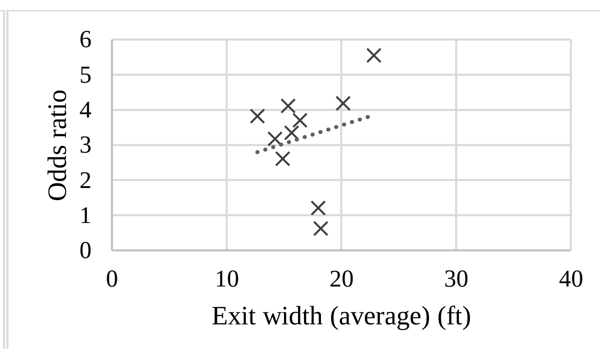
(a) Inscribed circle diameter



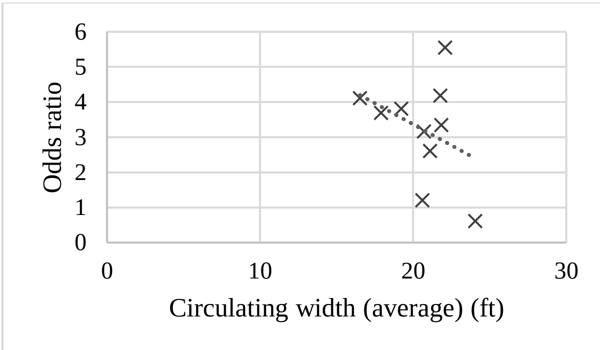
(b) Central island diameter



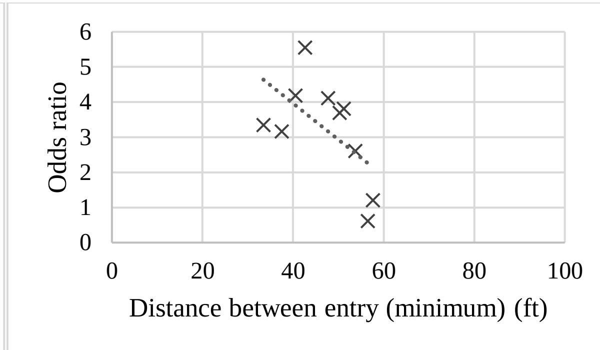
(c) Entry width (average)



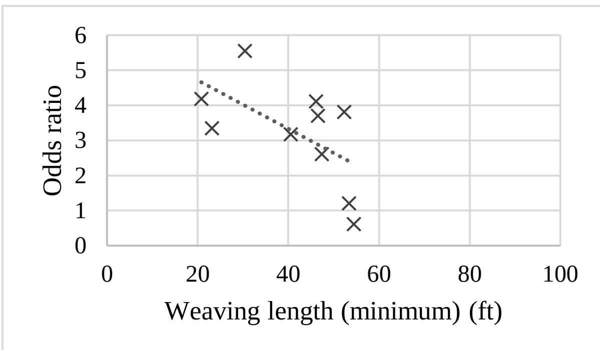
(d) Exit width (average)



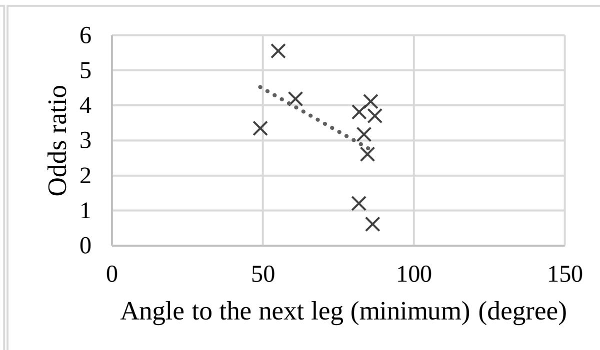
(e) Circulating width (average)



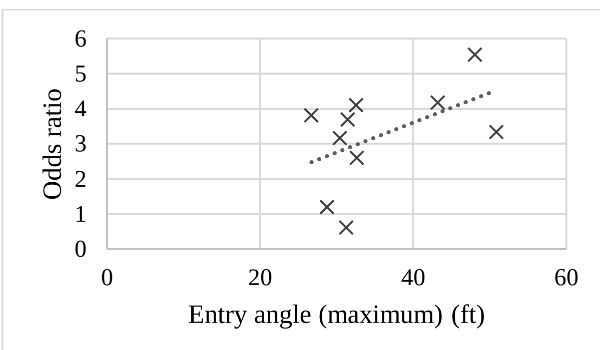
(f) Distance between entry to the next leg (minimum)



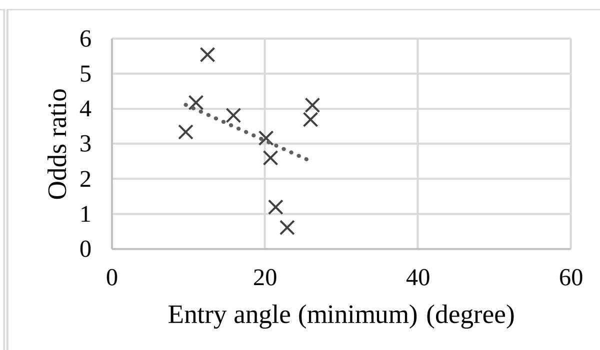
(g) Weaving length (minimum)



(h) Angle to the next leg (minimum)



(i) Entry angle (maximum)



(j) Entry angle (minimum)

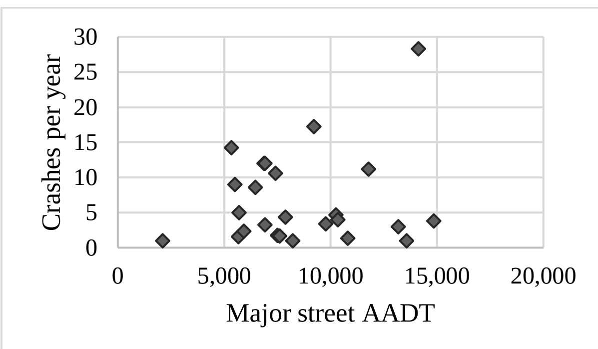
Figure 6-8. Scatter plot between odds ratio and selected geometric characteristics for AWSC intersections converted to mini-roundabouts.

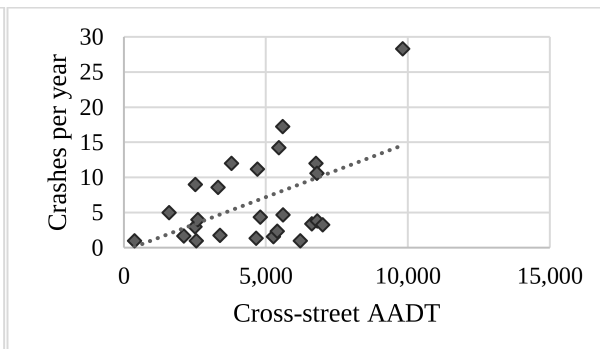
6.2 Examining the Effect of Traffic, On-Network and Off-Network Characteristics on After Period Crashes

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.

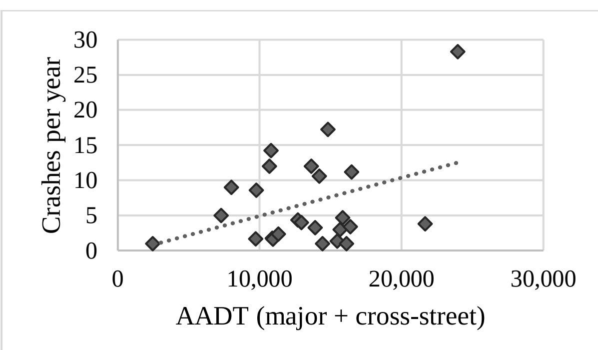
From the scatter plots, no specific trend was observed between after period crashes per year at mini-roundabouts and major street traffic volumes (Figure 6-9 a). However, cross-street traffic volume and total intersection traffic volume (major + cross-street AADT) show a positive trend with after period crashes per year (Figure 6-9 b & c). Also, cross-street volume share shows a positive trend with after period crashes per year (Figure 6-9 d).

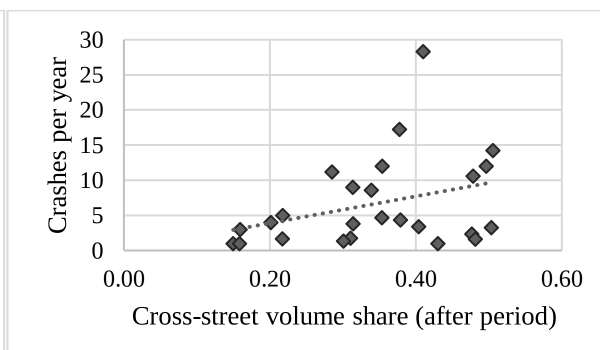
Likewise, scatter plot between after period crashes per year at mini-roundabouts and speed limit (major street and cross-street) shows a positive trend indicating number of crashes per year increases with an increase in the speed limit (Figure 6-10 a & b). The positive trend between after period crashes 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.





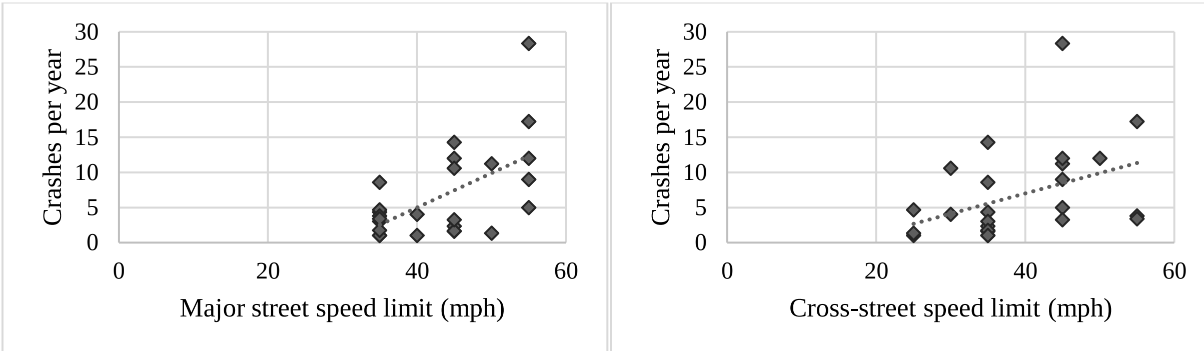
(a) Major street AADT (b) Cross-street AADT





(c) Total AADT (major + cross-street) (d) Cross-street volume share

Figure 6-9. Scatter plots between after period crashes and traffic volume for all mini-roundabouts.



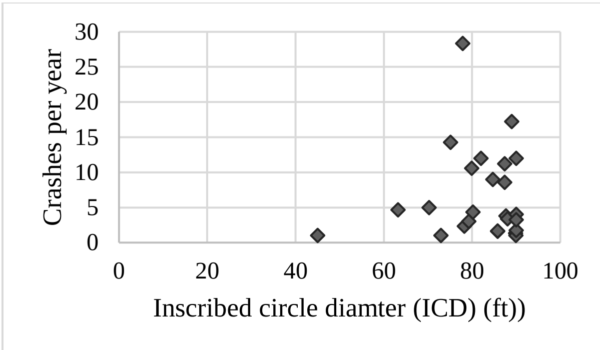
(a) Major street speed limit (b) Cross-street speed limit

Figure 6-10. Scatter plots between after period crashes and speed limit at major street and cross-street.

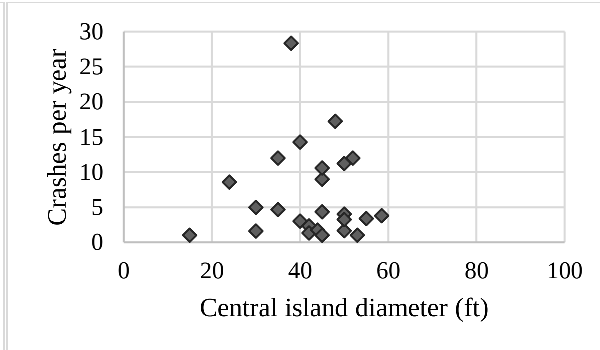
While looking into the geometric characteristics, inscribed circle diameter (ICD) and central island diameter show no trend with after period crashes per year (Figure 6-11 a & b). Likewise, entry width, exist width and circulating width (average of all approaches) show no trend with after period crashes per year (Figure 6-11 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 6-11 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 6-11 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 6-11 i).

Tables 6-1 to 6-4 summarize the variation of odds ratio based on traffic characteristics, on-network characteristics, and off-network characteristics by the prior control type. From Table 6-1 and 6-2, 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.

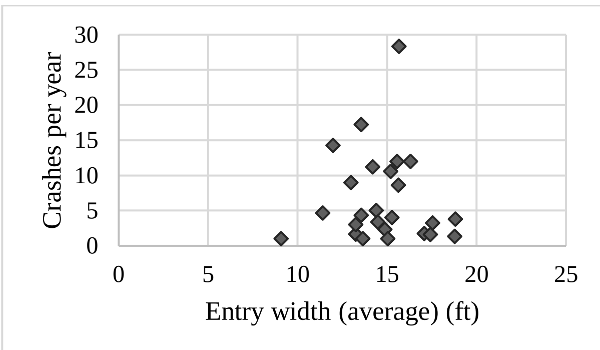
In the case of AWSC intersections converted to mini-roundabouts, high cross-street volume share, high speed limit at major street and cross-street, and exit width (average) have an increasing effect on the odds ratio. Also, weaving length (minimum), entry angle (minimum), and angle to the next leg (minimum) show negative trend, indicating an increase in the odds ratio with a decrease in aforementioned variables (Table 6-3 and 6-4).



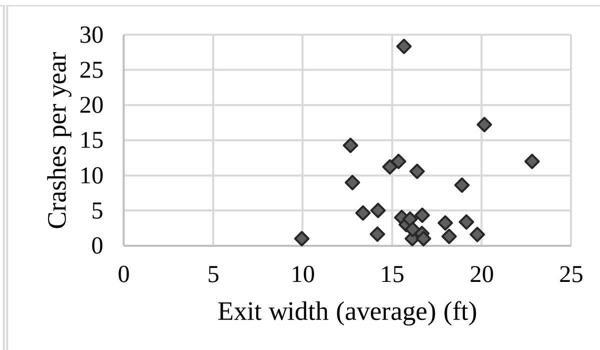
(a) Inscribed circle diameter



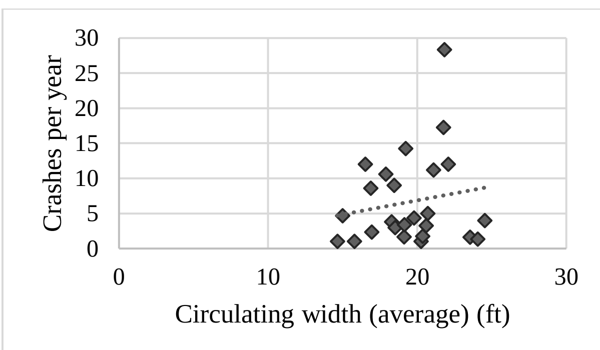
(b) Central island diameter



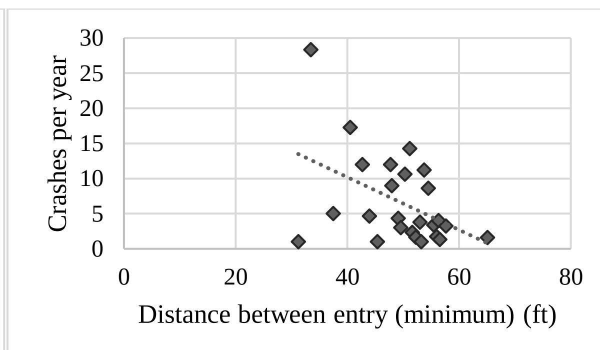
(c) Entry width (average)



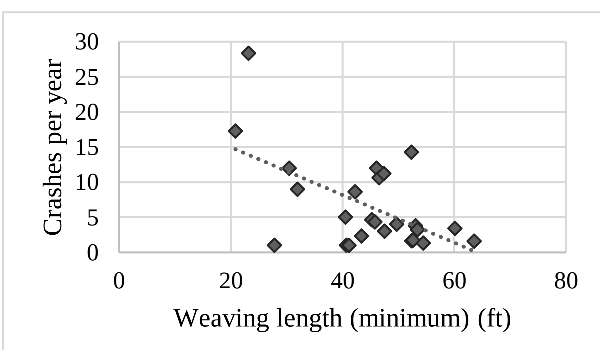
(d) Exit width (average)



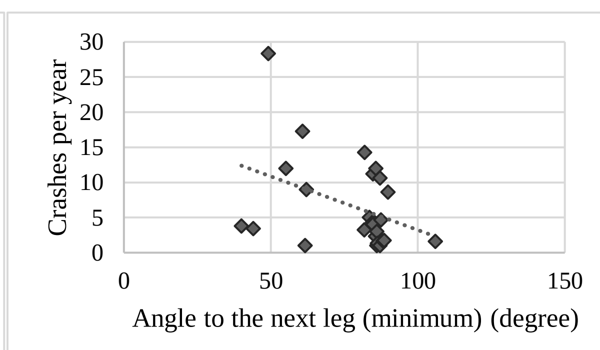
(e) Circulating width (average)



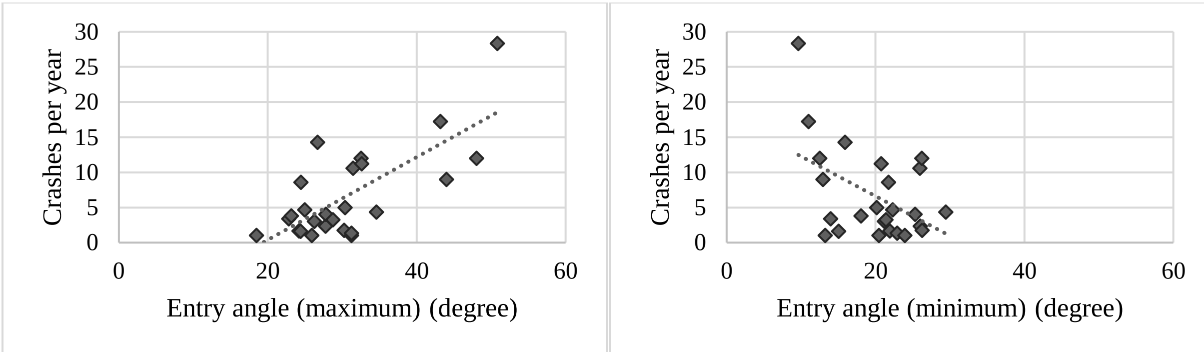
(f) Distance between entry to the next leg (minimum)



(g) Weaving length (minimum)



(h) Angle to the next leg (minimum)



(i) Entry angle (maximum) (j) Entry angle (minimum)

Figure 6-11. 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 6-1. 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[Ψ]	0.59	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
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
21	0.73	1.80	1.67	7,192	2,090	0.23	9,282	7,605	2,109	0.22	9,714	45	35
20	0.81	2.80	3.00	8,653	2,013	0.19	10,666	13,176	2,499	0.16	15,675	35	35
23[Ψ]	1.16	3.60	3.80	14,726	6,846	0.32	21,573	14,854	6,806	0.31	21,660	35	55
24[Ψ]	1.46	2.40	3.40	8,635	6,374	0.42	15,009	9,766	6,615	0.40	16,380	35	55
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	2.52	0.40	1.75	7,500	3,072	0.29	10,572	7,500	3,380	0.31	10,880	35	35
18	2.89	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	0.00	1.00	1,970	386	0.16	2,356	2,100	370	0.15	2,470	35	35

Low — High

Note: *Three-legged, [Ψ]OWSC (ramp).

Table 6-2. 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	85.82	30	18.71	16.01	17.42	21.71	17.86	19.77	23.56	77.67	63.52	68.46	24	15	19	137	106	120
17	0.34	72.93	45	16.08	13.83	15.05	18.53	13.85	16.77	14.65	49.10	40.67	46.71	26	20	24	93	86	89
1	0.55	84.74	45	13.40	12.30	12.99	13.40	12.20	12.79	18.45	51.28	31.90	43.26	44	13	26	108	62	82
25[Ψ]	0.59	89.97	53	14.65	13.07	13.65	17.12	15.33	16.13	20.25	64.23	41.13	53.88	19	13	16	110	62	89
6	0.64	80.20	45	14.28	12.90	13.55	19.18	15.32	16.69	19.80	54.46	45.78	50.83	35	29	32	93	85	91
15	0.66	63.21	35	12.03	10.94	11.42	14.20	11.95	13.38	14.99	50.66	45.18	47.26	25	22	24	95	87	91
21	0.73	85.82	50	13.81	12.43	13.25	14.67	13.67	14.18	19.11	56.50	52.35	55.08	24	22	23	91	88	90
20	0.81	79.30	40	14.64	11.77	13.26	21.79	12.34	15.79	18.51	51.78	47.50	49.50	26	21	24	88	86	87
23[Ψ]	1.16	87.69	59	21.22	15.01	18.83	18.69	13.70	16.00	18.29	121.56	53.08	79.41	23	18	21	142	40	85
24[Ψ]	1.46	88.03	55	16.12	12.94	14.48	22.30	13.00	19.16	19.14	60.47	60.11	60.29	23	14	19	205	44	105
12	1.73	90.00	50	15.90	14.60	15.28	17.20	14.60	15.55	24.54	59.60	49.70	54.73	28	25	26	95	85	90
22	2.52	90.00	44	18.86	14.22	17.08	20.63	14.23	16.67	20.38	53.82	52.61	53.20	30	26	29	90	89	89
18	2.89	87.42	24	16.28	15.05	15.63	21.40	17.45	18.91	16.90	51.76	42.25	47.84	24	22	23	93	90	91
13	3.81	78.26	42	15.53	13.95	14.89	16.80	15.10	16.15	16.95	51.04	43.38	47.86	28	26	27	95	86	92
16*	5.60	43.89	15	9.60	8.36	9.09	10.74	9.50	9.96	15.80	46.19	27.82	34.52	31	24	27	89	87	88

Low High

Note: *Three-legged, [Ψ]OWSC (ramp); 1 meter = 3.28 feet; maximum, minimum and average is the maximum, minimum and average values considering all approaches.

Table 6-3. Examining total crashes odds ratio variation with crashes, traffic volume, and speed limit for AWSC intersections converted to mini-roundabouts.

Site # ID	Odds ratio (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	0.61	0.60	1.33	10,062	3,530	0.26	13,592	10,813	4,655	0.30	15,468	50	25
8	1.20	1.60	3.25	7,641	5,078	0.40	12,719	6,910	7,001	0.50	13,910	45	45
4	2.61	3.60	11.20	6,836	3,860	0.36	10,696	11,780	4,702	0.29	16,482	50	45
2	3.17	1.60	5.00	5,454	1,834	0.25	7,288	5,704	1,588	0.22	7,291	55	45
5	3.34	8.40	28.33	11,640	8,590	0.42	20,230	14,133	9,823	0.41	23,957	55	45
11	3.70	3.60	10.60	7,636	7,010	0.48	14,646	7,414	6,800	0.48	14,214	45	30
19	3.81	4.60	14.25	6,199	5,107	0.45	11,306	5,344	5,461	0.51	10,805	45	35
10	4.11	2.40	12.00	6,775	6,409	0.49	13,184	6,867	6,764	0.50	13,631	55	50
3	4.18	3.60	17.25	7,238	4,274	0.37	11,512	9,221	5,590	0.38	14,811	55	55
9	5.55	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 6-4. 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	0.61	89.88	42	19.64	17.51	18.78	19.09	17.19	18.20	24.06	59.37	54.43	57.22	31	23	28	92	86	90
8	1.20	90.00	50	18.12	17.15	17.54	18.72	17.04	17.97	20.60	58.34	53.39	55.66	29	21	26	98	82	89
4	2.61	87.40	50	14.93	13.25	14.20	15.54	14.04	14.89	21.09	55.07	47.40	51.15	33	21	28	91	85	88
2	3.17	70.30	30	16.59	12.50	14.41	14.96	13.67	14.22	20.71	45.20	40.50	42.22	30	20	27	92	84	90
5	3.34	77.92	38	15.88	15.39	15.68	16.32	14.75	15.67	21.83	66.72	23.18	45.56	51	10	31	133	49	90
11	3.70	79.95	45	16.05	13.86	15.21	18.30	15.23	16.40	17.89	49.97	46.52	47.92	31	26	28	91	87	89
19	3.81	75.12	40	12.59	11.54	11.99	13.73	12.16	12.67	19.23	57.20	52.30	55.01	27	16	22	96	82	88
10	4.11	82.00	35	16.94	15.60	16.31	16.43	14.29	15.36	16.53	47.69	46.09	46.86	33	26	30	93	86	89
3	4.18	88.99	48	14.20	12.50	13.55	28.19	12.75	20.16	21.77	71.77	20.81	51.24	43	11	27	135	61	110
9	5.55	90.00	52	18.50	12.92	15.56	29.93	16.50	22.84	22.08	78.57	30.40	54.68	48	13	26	125	55	75

Low … High

Note: 1 meter = 3.28 feet; maximum, minimum and average is the maximum, minimum and average values considering all approaches.

6.3 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 6-5. A 90% confidence level was considered to check the statistical significance.

From Table 6-5, 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 6-6 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 E-1 in Appendix E 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 E-2 in Appendix E 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 6-7 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 6-5. 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 6-6. 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 6-7. 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.

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.

CHAPTER 7 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 especially in areas having constraints on additional land acquisition requirements. 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 project focuses on quantifying the safety benefits of implementing mini-roundabouts by developing 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) was collected. Further, 693 reference intersections based on prior control types (TWSC, OWSC, and AWSC) were identified in the selected eight states, and 649 intersections with available crash and traffic volume data were used for calibration and jurisdiction-specific SPF development.

An observational before and after study was conducted to compute CMFs based on prior control type. Naïve before and after analysis and the EB before and after analysis were explored. For prior control type TWSC/OWSC, SPFs available in the HSM were calibrated for the considered time period and jurisdiction. Jurisdiction-specific SPFs were developed for AWSC, and OWSC (ramp) intersections. 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.
- 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.
- Mini-roundabout installation seems to be effective at TWSC/OWSC intersections exhibiting high crash frequency during the before period.
- The EB method results indicated an increase in total number of crashes, FI crashes, and PDO when AWSC intersections were converted to mini-roundabouts.
- 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.
- 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 0.83 for total crashes, 0.41 for FI crashes, and 1.09 for PDO crashes.
- The recommended CMFs for converting an AWSC intersection to a mini-roundabout are 3.25 for total crashes, 1.74 for FI crashes, and 3.83 for PDO crashes.

In this research, data for 25 mini-roundabouts converted from TWSC/OWSC and AWSC intersections were considered for analysis and CMF development. The number of intersections converted from TWSC/OWSC and AWSC to mini-roundabouts are relatively limited. 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. Also, analyzing using larger sample size and comparing CMFs with mini-roundabouts installed at intersections with speed limit less than 35 mph (~56.33 kmph) by area type merits further investigation.

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APPENDIX A

Table A-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	WSDOT: Public Disclosure Request Portal

Table A-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	WSDOT traffic volume maps, Skagit County traffic count database, Snohomish County traffic count database, Whatcom County traffic counts database, HPMS database

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

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

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

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

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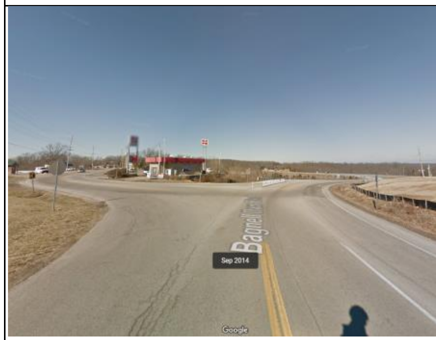
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Site ID # 14 (3-legged)</td><td colspan="2">Site ID #15</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Site ID # 16 (3-leeged)</td><td colspan="2">Site ID # 17</td></tr>
</table>

Figure A-2. 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 A-3. Before and after pictures of TWSC intersections converted to mini-roundabouts (© Google street view).

<table>
<tr><th>Before</th><th>After</th></tr>
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<tr><td colspan="2">Site ID # 23 (OWSC ramp)</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Site ID # 24 (OWSC ramp)</td></tr>
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<tr><td colspan="2">Site ID # 25 (OWSC ramp)</td></tr>
</table>

Figure A-4. 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 A-5. Before and after pictures of AWSC intersections converted to mini-roundabouts (© Google street view).

<table>
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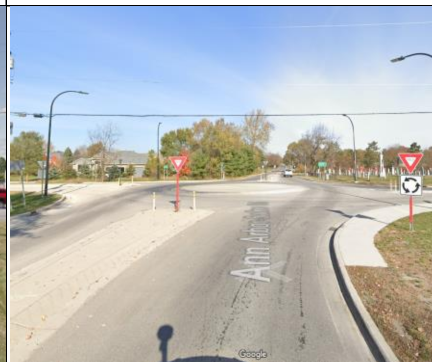
<tr><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Site ID # 9</td><td colspan="2">Site ID # 10</td></tr>
</table>

Figure A-6. 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 A-7. Before and after pictures of AWSC intersections converted to mini-roundabouts (© Google street view).

APPENDIX B

Table B-1. Naïve before and after comparison of FI crashes per year and FI crash rate - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Built year	Before period				After period			After crashes / Before crashes	After crash rate / Before crash rate	% change in traffic volume
			Control type	# of years	Crashes per year	Crash rate for 10,000 AADT	# of years	Crashes per year	Crash rate for 10,000 AADT			
1	Georgia	2016	TWSC	5	4.60	7.33	3	1.67	2.08	0.36	0.28	27.71
6	Iowa	2016	TWSC	5	1.20	1.24	3	0.67	0.53	0.56	0.42	31.14
12	Minnesota	2018	TWSC	5	1.00	0.80	1	0.00	0.00	0.00	0.00	3.30
13	Minnesota	2016	TWSC	5	0.20	0.21	3	0.00	0.00	0.00	0.00	16.09
14*	Missouri	2014	OWSC	5	1.00	1.02	5	0.00	0.00	0.00	0.00	12.02
15	North Carolina	2016	TWSC	5	1.80	1.04	3	0.00	0.00	0.00	0.00	-8.75
16*	North Carolina	2017	OWSC	5	0.00	0.00	2	0.00	0.00	-	-	4.84
17	Virginia	2018	TWSC	5	1.60	0.96	1	0.00	0.00	0.00	0.00	-3.40
18	Washington	2013	TWSC	5	0.40	0.57	5	1.40	1.43	3.50	2.51	39.51
20	Washington	2014	TWSC	5	1.00	0.94	5	0.40	0.26	0.40	0.27	46.97
21	Washington	2016	TWSC	5	1.20	1.29	3	0.67	0.69	0.56	0.53	4.65
22	Washington	2015	TWSC	5	0.40	0.38	4	0.50	0.46	1.25	1.21	2.91
23	Washington	2014	OWSC (ramp)	5	0.60	0.28	5	0.80	0.37	1.33	1.33	0.40
24	Washington	2014	OWSC (ramp)	5	0.40	0.27	5	0.40	0.24	1.00	0.92	9.13
25	Washington	2018	OWSC (ramp)	5	0.60	0.46	1	0.00	0.00	0.00	0.00	11.72

*Three-legged

Table B-2. Naïve before and after comparison of FI crashes per year and FI crash rate - AWSC intersections converted to mini-roundabouts.

Site ID	State	Built year	Before period				After period			After crashes / Before crashes	After crash rate / Before crash rate	% change in traffic volume
			Control type	# of years	Crashes per year	Crash rate for 10,000 AADT	# of years	Crashes per year	Crash rate for 10,000 AADT			
2	Georgia	2017	AWSC	5	0.40	0.55	2	1.50	2.06	3.75	3.75	0.04
3	Georgia	2015	AWSC	5	1.20	1.04	4	4.25	2.87	3.54	2.75	28.65
4	Georgia	2013	AWSC	5	1.20	1.12	5	2.20	1.33	1.83	1.19	54.09
5	Georgia	2016	AWSC	5	1.60	0.79	3	3.00	1.25	1.88	1.58	18.42
7	Michigan	2016	AWSC	5	0.00	0.00	3	0.67	0.43	-	-	13.80
8	Michigan	2015	AWSC	5	0.40	0.31	4	0.25	0.18	0.63	0.57	9.36
9	Michigan	2015	AWSC	5	0.40	0.35	4	0.75	0.70	1.88	2.02	-7.31
10	Michigan	2018	AWSC	5	0.60	0.46	1	1.00	0.73	1.67	1.61	3.39
11	Minnesota	2014	AWSC	5	1.00	0.68	5	1.20	0.84	1.20	1.24	-2.95
19	Washington	2015	AWSC	5	1.40	1.24	4	2.25	2.08	1.61	1.68	-4.43

Table B-3. Naïve before and after comparison of PDO crashes per year and PDO crash rate - TWSC/OWSC intersections converted to mini-roundabouts.

Site ID	State	Built year	Before period				After period			After crashes / Before crashes	After crash rate / Before crash rate	% change in traffic volume
			Control type	# of years	Crashes per year	Crash rate for 10,000 AADT	# of years	Crashes per year	Crash rate for 10,000 AADT			
1	Georgia	2016	TWSC	5	6.60	10.52	3	7.33	9.15	1.11	0.87	27.71
6	Iowa	2016	TWSC	5	3.80	3.93	3	3.67	2.89	0.96	0.74	31.14
12	Minnesota	2018	TWSC	5	1.40	1.12	1	4.00	3.09	2.86	2.77	3.30
13	Minnesota	2016	TWSC	5	0.20	0.21	3	2.33	2.06	11.67	10.05	16.09
14*	Missouri	2014	OWSC	5	7.40	7.58	5	1.60	1.46	0.22	0.19	12.02
15	North Carolina	2016	TWSC	5	5.40	3.11	3	4.67	2.94	0.86	0.95	-8.75
16*	North Carolina	2017	OWSC	5	0.00	0.00	2	1.00	4.05	-	-	4.84
17	Virginia	2018	TWSC	5	1.00	0.60	1	1.00	0.62	1.00	1.04	-3.40
18	Washington	2013	TWSC	5	2.20	3.14	5	7.20	7.37	3.27	2.35	39.51
20	Washington	2014	TWSC	5	1.80	1.69	5	2.60	1.66	1.44	0.98	46.97
21	Washington	2016	TWSC	5	0.60	0.65	3	1.00	1.03	1.67	1.59	4.65
22	Washington	2015	TWSC	5	0.00	0.00	4	1.25	1.15	-	-	2.91
23	Washington	2014	OWSC (ramp)	5	3.00	1.39	5	3.00	1.39	1.00	1.00	0.40
24	Washington	2014	OWSC (ramp)	5	2.00	1.33	5	3.00	1.83	1.50	1.37	9.13
25	Washington	2018	OWSC (ramp)	5	1.00	0.77	1	1.00	0.69	1.00	0.90	11.72

*Three-legged

Table B-4. Naïve before and after comparison of PDO crashes per year and PDO crash rate - AWSC intersections converted to mini-roundabouts.

Site ID	State	Built year	Before period				After period			After crashes / Before crashes	After crash rate / Before crash rate	% change in traffic volume
			Control type	# of years	Crashes per year	Crash rate for 10,000 AADT	# of years	Crashes per year	Crash rate for 10,000 AADT			
2	Georgia	2017	AWSC	5	1.20	1.65	2	3.50	4.80	2.92	2.92	0.04
3	Georgia	2015	AWSC	5	2.40	2.08	4	13.00	8.78	5.42	4.21	28.65
4	Georgia	2013	AWSC	5	2.40	2.24	5	9.00	5.46	3.75	2.43	54.09
5	Georgia	2016	AWSC	5	6.80	3.36	3	25.33	10.57	3.73	3.15	18.42
7	Michigan	2016	AWSC	5	0.60	0.44	3	0.67	0.43	1.11	0.98	13.80
8	Michigan	2015	AWSC	5	1.20	0.94	4	3.00	2.16	2.50	2.29	9.36
9	Michigan	2015	AWSC	5	1.40	1.21	4	11.25	10.52	8.04	8.67	-7.31
10	Michigan	2018	AWSC	5	1.80	1.37	1	11.00	8.07	6.11	5.91	3.39
11	Minnesota	2014	AWSC	5	2.60	1.78	5	9.40	6.61	3.62	3.73	-2.95
19	Washington	2015	AWSC	5	3.20	2.83	4	12.00	11.11	3.75	3.92	-4.43

Table B-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 B-6. HSM SPF regression coefficient and overdispersion parameter – 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.

Table B-7. SPF development summary.

State	Intersection type	Intercept	$AADT_{MS}$	$AADT_{CS}$	Overdispersion parameter (k)	Years	# samples		AIC	AICC	MAD
							Modeling	Validation			
Total crashes											
Georgia	AWSC	-4.80	0.34	0.47	0.13	2011-2013	35	12	155.79	157.08	1.52
Michigan	AWSC	-5.13	0.34	0.50	0.05	2011-2013	38	12	171.71	172.90	1.19
Minnesota	AWSC	-7.34	0.52	0.50	0.18	2011-2013	40	14	185.75	186.86	0.66
Washington	AWSC	-2.98	0.45	0.37	0.77	2011-2013	30	11	141.86	143.40	0.40
Washington	OWSC (ramp)	-2.78	0.45	0.04	0.28	2011-2013	43	12	187.21	188.36	0.90
Fatal and Injury (FI) crashes											
Georgia	AWSC	-6.03	0.24	0.62	0.01	2011-2013	32	10	92.25	93.73	1.25
Michigan	AWSC	-8.03	0.24	0.74	0.26	2011-2013	36	11	86.02	87.31	1.10
Minnesota	AWSC	-4.82	0.54	0.06	0.21	2013-2015	41	14	136.85	137.95	1.32
Washington	AWSC	-5.60	0.19	0.61	0.37	2011-2013	25	8	91.65	93.65	1.41
Washington	OWSC (ramp)	-6.70	0.49	0.32	0.15	2012-2014	38	11	112.82	113.90	0.27
PDO crashes											
Georgia	AWSC	-5.46	0.43	0.43	0.07	2011-2013	36	12	137.22	138.51	1.36
Michigan	AWSC	-5.60	0.44	0.42	0.01	2011-2013	38	12	158.42	159.64	1.28
Minnesota	AWSC	-8.28	0.34	0.75	0.17	2011-2013	41	14	157.53	158.64	1.36
Washington	AWSC	-3.73	0.47	0.01	0.19	2011-2013	32	11	105.07	106.55	1.27
Washington	OWSC (ramp)	-3.29	0.37	0.14	0.07	2011-2013	38	11	149.90	151.08	0.62

Table B-8. Reference intersections used for HSM SPFs calibration.

State	Intersection	# of reference intersections identified	# of reference intersections used for calibration	Calibration period	Total # of crashes	# of crashes per year	# of crashes per intersection per year
Georgia	4ST	50	47	2010-19	714	71.4	1.52
Iowa	4ST	59	59	2011-19	751	83.44	1.41
Michigan	4ST	55	49	2011-19	969	107.66	2.19
Minnesota	4ST	51	50	2011-19	491	54.55	1.09
Missouri	3ST	70	38	2009-19	221	20.09	0.53
North Carolina	4ST	57	57	2011-19	817	90.77	1.59
	3ST	57	57	2011-19	429	47.66	0.83
Virginia	4ST	42	40	2013-19	562	80.28	2.02

Note: 4ST – Four-legged stop-controlled at cross-street, 3ST – Three-legged stop-controlled at cross-street.

Table B-9. Calibration factors for total crashes.

Year	Calibration factor							
	Georgia	Iowa	Michigan	Minnesota	Missouri	North Carolina		Virginia
	4ST	4ST	4ST	4ST	3ST	4ST	3ST	4ST
	Rural (TWTL)	Urban/suburban	Urban/suburban	Urban/suburban	Rural (TWTL)	Urban/suburban	Rural (TWTL)	Urban/suburban
	n = 47	n = 59	n = 49	n = 50	n = 38	n = 57	n = 57	n = 40
2009	-	-	-	-	0.69	-	-	-
2010	1.30	-	-	-	1.03	-	-	-
2011	1.32	1.67	2.92	1.57	0.53	2.15	0.59	-
2012	1.48	1.84	2.95	1.14	0.70	2.30	0.66	-
2013	1.26	1.15	3.28	1.40	0.44	1.66	0.55	1.36
2014	1.40	1.65	3.22	1.30	0.74	2.48	0.92	1.73
2015	1.62	1.68	3.55	1.50	1.15	2.54	0.56	1.43
2016	1.27	1.81	3.67	0.94	0.81	2.03	0.81	1.54
2017	1.49	1.77	3.11	0.82	0.78	2.43	0.69	1.32
2018	1.41	1.73	3.40	1.22	0.54	2.47	0.83	1.67
2019	2.00	1.68	3.91	1.12	0.71	2.50	0.72	1.64

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

Table B-10. Calibration factors for FI crashes.

Year	Calibration factor							
	Georgia	Iowa	Michigan	Minnesota	Missouri	North Carolina		Virginia
	4ST	4ST	4ST	4ST	3ST	4ST	3ST	4ST
	Rural (TWTL)	Urban/suburban	Urban/suburban	Urban/suburban	Rural (TWTL)	Urban/suburban	Rural (TWTL)	Urban/suburban
	n = 47	n = 59	n = 49	n = 50	n = 38	n = 57	n = 57	n = 40
2009	-	-	-	-	0.28	-	-	-
2010	1.11	-	-	-	0.46	-	-	-
2011	0.99	2.09	2.75	2.43	0.09	3.09	0.64	-
2012	0.94	2.05	3.11	1.75	0.09	3.18	0.63	-
2013	1.18	1.16	2.52	1.80	0.19	2.19	0.41	1.58
2014	1.15	1.68	2.46	1.78	0.47	3.24	0.66	1.88
2015	2.00	1.53	2.86	2.52	0.80	3.02	0.61	1.73
2016	1.50	2.22	3.83	1.13	0.51	2.73	0.74	1.84
2017	1.32	2.28	2.77	1.44	0.16	3.49	0.55	1.61
2018	1.44	1.77	3.26	1.35	0.57	3.73	0.54	2.03
2019	1.97	1.75	3.50	1.76	0.16	3.70	0.53	1.64

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

Table B-11. Calibration factors for PDO crashes.

Year	Calibration factor							
	Georgia	Iowa	Michigan	Minnesota	Missouri	North Carolina		Virginia
	4ST	4ST	4ST	4ST	3ST	4ST	3ST	4ST
	Rural (TWTL)	Urban/suburban	Urban/suburban	Urban/suburban	Rural (TWTL)	Urban/suburban	Rural (TWTL)	Urban/suburban
	n = 47	n = 59	n = 49	n = 50	n = 38	n = 57	n = 57	n = 40
2009	-	-	-	-	0.98	-	-	-
2010	1.45	-	-	-	1.24	-	-	-
2011	1.58	1.44	3.09	1.12	0.91	1.67	0.53	-
2012	1.89	1.69	2.94	0.81	1.14	1.72	0.68	-
2013	1.32	1.14	3.50	1.18	0.61	1.38	0.61	1.21
2014	1.58	1.59	3.53	1.00	0.86	2.03	1.02	1.62
2015	1.33	1.78	3.78	0.95	1.33	2.19	0.53	1.23
2016	1.10	1.57	3.56	0.73	1.03	1.66	0.80	1.35
2017	1.63	1.49	3.35	0.50	1.22	1.80	0.79	1.13
2018	1.39	1.66	3.44	1.14	0.46	1.72	0.94	1.44
2019	2.03	1.68	4.14	0.71	1.09	1.78	0.84	1.55

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

Table B-12(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						Total exp. # of crashes	Exp. # of crashes per year
									Y1	Y2	Y3	Y4	Y5	Total		
(1)	(2)	(3)	(4)	(5)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
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	MI	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	MI	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	0.00	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	0.92	0.92	0.92	4.66	10.09	2.02
20	WA	Slater Rd / Pacific Hwy	48.817168	-122.544338	2014	5	14	2.80	1.49	1.49	1.49	1.61	1.65	7.72	12.46	2.49
21	WA	SR 546 / Northwood Rd	48.964108	-122.407553	2016	5	9	1.80	4.00	3.97	4.63	4.11	4.20	20.91	10.98	2.20
22	WA	E George Hopper Rd / S Walnut St	48.452	-122.33174	2015	5	2	0.40	1.53	1.53	1.53	1.53	1.53	7.64	3.39	0.68
23[Ψ]	WA	Slater Rd / I-5 SB Ramps	48.81707	-122.5505	2014	5	18	3.60	2.21	2.21	2.21	2.21	2.21	11.06	16.28	3.26
24[Ψ]	WA	Slater Rd / I-5 NB Ramps	48.817358	-122.546092	2014	5	12	2.40	1.72	1.72	1.73	1.74	1.76	8.67	11.02	2.20
25[Ψ]	WA	Portal Way / I-5 NB Ramps	48.858362	-122.586126	2018	5	8	1.60	1.43	1.55	1.68	1.66	1.68	8.00	8.00	1.60

*Three-legged, [Ψ]OWSC (ramp)

Table B-12(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 crashed/expected crashes)
(1)	(2)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
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	0.00	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				0.00	10.47	0.00				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	1.31	1.15	1.32	1.34	1.76	6.88	2.83	2.50	2.85	2.89	3.81	14.89	2.12	2.80	4.20	1.73	3.41	2.89
20	2014	5	15	3.00	2.28	2.29	2.30	2.31	2.33	11.52	3.68	3.70	3.72	3.74	3.75	18.59	0.81	1.62	0.27	0.27	1.07	0.81
21	2016	3	5	1.67	4.28	4.38	4.39			13.06	2.25	2.30	2.31			6.86	0.89	0.00	1.30			0.73
22	2015	4	7	1.75	1.57	1.57	1.57	1.57		6.26	0.69	0.69	0.69	0.69		2.78	1.44	1.44	2.88	4.32		2.52
23[Ψ]	2014	5	19	3.80	2.22	2.22	2.22	2.22	2.22	11.10	3.26	3.26	3.27	3.27	3.27	16.34	0.92	0.61	1.22	1.83	1.22	1.16
24[Ψ]	2014	5	17	3.40	1.79	1.80	1.82	1.84	1.91	9.17	2.27	2.29	2.32	2.34	2.43	11.66	1.32	0.87	0.43	2.56	2.06	1.46
25[Ψ]	2018	1	1	1.00	1.69					1.69	1.69					1.69	0.59					0.59

*Three-legged, [Ψ]OWSC (ramp); OR = 0 indicates observed # of crashes in the after period is zero.

Table B-13(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						Total exp. # of crashes	Exp. # of crashes per year
									Y1	Y2	Y3	Y4	Y5	Total		
(1)	(2)	(3)	(4)	(5)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
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	5.14	1.03
12	MI	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	5.29	1.06
13	MI	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	2.28	0.46
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	9.82	1.96
16*	NC	Fairplains Rd / Reynolds Rd	36.19561	-81.14437	2017	5	0	0.00	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	8.08	1.62
18	WA	Anderson Rd / Cedardale Rd	48.399471	-122.328164	2013	5	2	0.40	0.32	0.32	0.31	0.31	0.31	1.59	1.75	0.35
20	WA	Slater Rd / Pacific Hwy	48.817168	-122.544338	2014	5	5	1.00	0.54	0.54	0.54	0.59	0.61	2.83	3.98	0.80
21	WA	SR 546 / Northwood Rd	48.964108	-122.407553	2016	5	6	1.20	1.73	1.71	1.99	1.77	1.81	9.01	6.95	1.39
22	WA	E George Hopper Rd / S Walnut St	48.452	-122.33174	2015	5	2	0.40	0.56	0.56	0.56	0.56	0.56	2.79	2.37	0.47
23$^{\Psi}$	WA	Slater Rd / I-5 SB Ramps	48.81707	-122.5505	2014	5	3	0.60	0.76	0.76	0.76	0.76	0.76	3.82	3.40	0.68
24$^{\Psi}$	WA	Slater Rd / I-5 NB Ramps	48.817358	-122.546092	2014	5	2	0.40	0.57	0.57	0.57	0.58	0.58	2.87	2.49	0.50
25$^{\Psi}$	WA	Portal Way / I-5 NB Ramps	48.858362	-122.586126	2018	5	3	0.60	0.44	0.49	0.53	0.53	0.55	2.54	2.73	0.55

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

Table B-13(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 crashed/expected crashes)
(1)	(2)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
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	2.07	1.57	1.54			5.18	0.48	0.00	0.65			0.39
12	2018	1	0	0.00	1.26					1.26	1.12					1.12	0.00					0.00
13	2016	3	0	0.00	0.72	0.71	0.96			2.39	0.35	0.35	0.47			1.17	0.00	0.00	0.00			0.00
14*	2014	5	0	0.00	0.98	0.64	0.21	0.77	0.25	2.85	2.13	1.40	0.45	1.68	0.54	6.21	0.00	0.00	0.00	0.00	0.00	0.00
15	2016	3	0	0.00	3.01	3.29	3.34			9.64	2.03	2.22	2.25			6.50	0.00	0.00	0.00			0.00
16*	2017	2	0	0.00	0.22	0.21				0.43	0.17	0.17				0.34	0.00	0.00				0.00
17	2018	1	0	0.00	1.51					1.51	1.46					1.46	0.00					0.00
18	2013	5	7	1.40	0.47	0.41	0.47	0.48	0.66	2.48	0.51	0.45	0.52	0.53	0.72	2.73	3.89	0.00	3.86	1.90	2.78	2.57
20	2014	5	2	0.40	0.88	0.88	0.89	0.89	0.90	4.45	1.24	1.25	1.25	1.26	1.27	6.26	0.81	0.80	0.00	0.00	0.00	0.32
21	2016	3	2	0.67	1.85	1.89	1.89			5.63	1.42	1.46	1.46			4.34	0.70	0.00	0.68			0.46
22	2015	4	2	0.50	0.57	0.57	0.57	0.57		2.29	0.49	0.49	0.49	0.49		1.95	0.00	0.00	0.00	4.10		1.03
23$^{\Psi}$	2014	5	4	0.80	0.76	0.76	0.76	0.77	0.77	3.83	0.68	0.68	0.68	0.69	0.69	3.41	1.47	0.00	1.47	0.00	2.92	1.17
24$^{\Psi}$	2014	5	2	0.40	0.59	0.60	0.62	0.63	0.65	3.09	0.51	0.52	0.53	0.54	0.57	2.67	0.00	0.00	1.88	1.84	0.00	0.75
25$^{\Psi}$	2018	1	0	0.00	0.56					0.56	0.60					0.60	0.00					0.00

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

Table B-14(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)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
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	MI	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	MI	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	0.00	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	0.61	0.61	0.61	3.07	7.45	1.49
20	WA	Slater Rd / Pacific Hwy	48.817168	-122.544338	2014	5	9	1.80	0.96	0.96	0.96	1.03	1.05	4.95	7.64	1.53
21	WA	SR 546 / Northwood Rd	48.964108	-122.407553	2016	5	3	0.60	2.28	2.26	2.63	2.34	2.39	11.90	5.31	1.06
22	WA	E George Hopper Rd / S Walnut St	48.452	-122.33174	2015	5	0	0.00	0.98	0.98	0.98	0.98	0.98	4.89	1.65	0.33
23[Ψ]	WA	Slater Rd / I-5 SB Ramps	48.81707	-122.5505	2014	5	15	3.00	1.49	1.49	1.49	1.49	1.49	7.45	12.52	2.50
24[Ψ]	WA	Slater Rd / I-5 NB Ramps	48.817358	-122.546092	2014	5	10	2.00	1.20	1.20	1.21	1.22	1.22	6.05	8.52	1.70
25[Ψ]	WA	Portal Way / I-5 NB Ramps	48.858362	-122.586126	2018	5	5	1.00	1.01	1.09	1.16	1.15	1.17	5.59	5.23	1.05

*Three-legged, [Ψ]OWSC (ramp)

Table B-14(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 crashed/expected crashes)
(1)	(2)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
1	2016	3	22	7.33	3.36	3.03	5.20			11.59	7.57	6.82	11.71			26.10	0.79	1.17	0.68			0.84
6	2016	3	11	3.67	1.70	1.86	1.87			5.44	4.08	4.46	4.49			13.03	0.98	1.12	0.45			0.84
12	2018	1	4	4.00	0.86					0.86	1.07					1.07	3.72					3.72
13	2016	3	7	2.33	0.45	1.06	0.68			2.19	0.24	0.56	0.36			1.15	12.75	1.80	8.36			6.08
14*	2014	5	8	1.60	2.29	1.83	2.24	0.88	2.36	9.60	9.12	7.29	8.91	3.49	9.39	38.21	0.00	0.14	0.22	0.86	0.21	0.21
15	2016	3	14	4.67	2.52	2.46	2.59			7.57	4.47	4.35	4.58			13.40	0.90	1.15	1.09			1.04
16*	2017	2	2	1.00	0.22	0.20				0.42	0.15	0.14				0.29	13.17	0.00				6.96
17	2018	1	1	1.00	2.29					2.29	1.37					1.37	0.71					0.73
18	2013	5	36	7.20	0.85	0.75	0.85	0.86	1.12	4.42	2.05	1.82	2.06	2.09	2.70	10.72	1.95	3.85	4.85	1.92	4.07	3.36
20	2014	5	13	2.60	1.43	1.43	1.44	1.45	1.45	7.19	2.20	2.21	2.22	2.23	2.24	11.11	0.91	2.26	0.45	0.45	1.78	1.17
21	2016	3	3	1.00	2.44	2.49	2.50			7.43	1.09	1.11	1.12			3.31	0.92	0.00	1.79			0.91
22	2015	4	5	1.25	1.00	1.00	1.00	1.00		4.00	0.34	0.34	0.34	0.34		1.35	2.96	2.96	5.91	2.96		3.70
23$^{\Psi}$	2014	5	15	3.00	1.49	1.49	1.49	1.50	1.50	7.47	2.51	2.51	2.51	2.52	2.52	12.55	0.80	0.80	1.20	2.38	0.79	1.19
24$^{\Psi}$	2014	5	15	3.00	1.24	1.25	1.27	1.28	1.32	6.37	1.75	1.76	1.79	1.81	1.86	8.96	1.72	1.14	0.00	2.77	2.68	1.67
25$^{\Psi}$	2018	1	1	1.00	1.19					1.19	1.11					1.11	0.90					0.90

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

Table B-15(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	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)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	33.38354	-83.90331	2017	5	8	1.60	1.71	1.68	1.68	1.77	1.90	8.74	8.35	1.67
3	GA	GA36 / GA212	33.429632	-83.847068	2015	5	18	3.60	3.06	3.08	2.44	2.44	3.22	14.24	16.65	3.33
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	34.091894	-83.615688	2013	5	18	3.60	2.48	2.48	2.46	2.97	2.95	13.34	16.25	3.25
5	GA	GA 16 / GA 54	33.329808	-84.644824	2016	5	42	8.40	4.38	4.57	4.60	4.80	4.99	23.35	37.24	7.45
7	MI	Ann Arbor-Saline Rd / Textile Rd	42.19859	-83.79691	2016	5	3	0.60	2.63	2.64	2.66	2.73	2.79	13.45	9.25	1.85
8	MI	Textile Rd / Hitchingham Rd	42.201706	-83.620946	2015	5	8	1.60	2.31	2.40	2.28	3.75	3.77	14.50	11.77	2.35
9	MI	Textile Rd / Stony Creek Rd	42.20173	-83.623122	2015	5	9	1.80	2.27	2.36	2.46	2.88	2.89	12.85	11.34	2.27
10	MI	Moon Rd / Bemis Rd	42.170612	-83.738319	2018	5	12	2.40	3.09	3.10	3.19	3.17	3.28	15.84	14.14	2.83
11	MN	Vierling Dr E / Rd 79	44.783334	-93.520148	2014	5	18	3.60	1.93	1.93	1.93	1.85	1.83	9.46	14.79	2.96
19	WA	Everson Goshen Rd / E Smith Rd	48.833025	-122.37673	2015	5	23	4.60	1.23	1.23	1.23	1.07	1.08	5.84	19.86	3.97

Table B-15(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 crashed/expected crashes)
(1)	(2)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
2	2017	2	10	5.00	1.54	1.76				3.30	1.47	1.69				3.16	6.11	0.59				3.17
3	2015	4	69	17.25	3.44	3.56	3.44	3.68		14.11	4.02	4.16	4.02	4.30		16.50	5.97	3.13	2.24	5.35		4.18
4	2013	5	56	11.20	3.10	3.52	3.60	3.83	3.60	17.64	3.78	4.28	4.38	4.66	4.38	21.48	5.03	1.63	2.51	2.15	2.05	2.61
5	2016	3	85	28.33	5.08	5.42	5.45			15.95	8.10	8.65	8.69			25.44	4.32	3.70	2.07			3.34
7	2016	3	4	1.33	2.87	3.17	3.44			9.47	1.97	2.18	2.36			6.51	1.01	0.00	0.85			0.61
8	2015	4	13	3.25	3.25	3.37	3.37	3.35		13.33	2.64	2.73	2.73	2.72		10.82	1.14	1.10	1.46	1.10		1.20
9	2015	4	48	12.00	2.39	2.47	2.47	2.46		9.80	2.11	2.18	2.18	2.17		8.65	5.68	9.16	1.83	5.52		5.55
10	2018	1	12	12.00	3.27					3.27	2.92					2.92	4.11					4.11
11	2014	5	53	10.60	1.82	1.82	1.84	1.84	1.85	9.18	2.85	2.85	2.87	2.88	2.89	14.34	2.10	4.57	3.48	4.86	3.46	3.70
19	2015	4	57	14.25	1.09	1.10	1.10	1.11		4.39	3.71	3.73	3.75	3.76		14.95	4.31	5.09	2.94	2.92		3.81

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

Table B-16(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)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	33.38354	-83.90331	2017	5	2	0.40	0.63	0.62	0.62	0.65	0.71	3.25	3.19	0.64
3	GA	GA36 / GA212	33.429632	-83.847068	2015	5	6	1.20	1.29	1.29	0.96	0.95	1.35	5.84	5.85	1.17
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	34.091894	-83.615688	2013	5	6	1.20	1.02	1.02	1.01	1.19	1.18	5.42	5.46	1.09
5	GA	GA 16 / GA 54	33.329808	-84.644824	2016	5	8	1.60	1.92	1.95	1.98	2.09	2.19	10.12	9.86	1.97
7	MI	Ann Arbor-Saline Rd / Textile Rd	42.19859	-83.79691	2016	5	0	0.00	0.41	0.41	0.42	0.43	0.44	2.10	1.35	0.27
8	MI	Textile Rd / Hitchingham Rd	42.201706	-83.620946	2015	5	2	0.40	0.38	0.39	0.36	0.71	0.71	2.55	2.33	0.47
9	MI	Textile Rd / Stony Creek Rd	42.20173	-83.623122	2015	5	2	0.40	0.37	0.38	0.40	0.48	0.48	2.11	2.07	0.41
10	MI	Moon Rd / Bemis Rd	42.170612	-83.738319	2018	5	3	0.60	0.57	0.58	0.59	0.60	0.62	2.96	2.98	0.60
11	MN	Vierling Dr E / Rd 79	44.783334	-93.520148	2014	5	5	1.00	0.59	0.59	0.59	0.58	0.57	2.93	3.71	0.74
19	WA	Everson Goshen Rd / E Smith Rd	48.833025	-122.37673	2015	5	7	1.40	1.16	1.16	1.16	1.10	1.16	5.75	6.60	1.32

Table B-16(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 crashed/expected crashes)
(1)	(2)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
2	2017	2	3	1.50	0.54	0.65				1.20	0.53	0.64				1.18	5.64	0.00				2.55
3	2015	4	17	4.25	1.43	1.47	1.43	1.55		5.87	1.43	1.48	1.43	1.55		5.89	6.30	2.03	0.70	2.58		2.89
4	2013	5	11	2.20	1.18	1.39	1.42	1.55	1.42	6.97	1.19	1.40	1.43	1.57	1.43	7.02	2.52	1.43	1.39	1.28	1.39	1.57
5	2016	3	9	3.00	2.21	2.35	2.36			6.91	2.16	2.28	2.30			6.73	0.93	1.75	1.31			1.34
7	2016	3	2	0.67	0.45	0.52	0.59			1.57	0.29	0.34	0.38			1.01	0.00	0.00	5.24			1.98
8	2015	4	1	0.25	0.62	0.64	0.64	0.64		2.54	0.56	0.59	0.59	0.58		2.32	1.77	0.00	0.00	0.00		0.43
9	2015	4	3	0.75	0.39	0.41	0.41	0.41		1.61	0.38	0.40	0.40	0.40		1.58	0.00	2.50	2.50	2.51		1.90
10	2018	1	1	1.00	0.62					0.62	0.62					0.62	1.61					1.61
11	2014	5	6	1.20	0.57	0.57	0.58	0.58	0.58	2.87	0.72	0.72	0.73	0.73	0.73	3.64	1.38	0.00	2.74	1.37	2.72	1.65
19	2015	4	9	2.25	1.16	1.17	1.17	1.17		4.66	1.34	1.34	1.34	1.34		5.36	0.75	2.24	2.24	1.49		1.68

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

Table B-17(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)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
2	GA	Keys Ferry Rd / Barnetts Bridge Rd / Hwy 36	33.38354	-83.90331	2017	5	6	1.20	1.37	1.35	1.35	1.42	1.53	7.01	6.68	1.34
3	GA	GA36 / GA212	33.429632	-83.847068	2015	5	12	2.40	2.40	2.42	1.96	1.95	2.55	11.29	11.60	2.32
4	GA	Winder Hwy (SR 11) / Galilee Church Rd (SR 124)	34.091894	-83.615688	2013	5	12	2.40	1.94	1.94	1.92	2.40	2.38	10.57	11.18	2.24
5	GA	GA 16 / GA 54	33.329808	-84.644824	2016	5	34	6.80	3.48	3.69	3.71	3.86	4.00	18.73	27.39	5.48
7	MI	Ann Arbor-Saline Rd / Textile Rd	42.19859	-83.79691	2016	5	3	0.60	2.08	2.09	2.10	2.16	2.21	10.63	10.18	2.04
8	MI	Textile Rd / Hitchingham Rd	42.201706	-83.620946	2015	5	6	1.20	1.73	1.82	1.77	2.76	2.77	10.86	10.57	2.11
9	MI	Textile Rd / Stony Creek Rd	42.20173	-83.623122	2015	5	7	1.40	1.71	1.80	1.89	2.21	2.22	9.82	9.66	1.93
10	MI	Moon Rd / Bemis Rd	42.170612	-83.738319	2018	5	9	1.80	2.25	2.26	2.32	2.30	2.38	11.51	11.35	2.27
11	MN	Vierling Dr E / Rd 79	44.783334	-93.520148	2014	5	13	2.60	1.38	1.38	1.38	1.33	1.31	6.79	10.12	2.02
19	WA	Everson Goshen Rd / E Smith Rd	48.833025	-122.37673	2015	5	16	3.20	0.57	0.57	0.57	0.50	0.50	2.72	7.31	1.46

Table B-17(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 crashed/expected crashes)
(1)	(2)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
2	2017	2	7	3.50	1.26	1.42				2.68	1.20	1.35				2.55	4.99	0.74				2.74
3	2015	4	52	13.00	2.75	2.86	2.75	2.94		11.30	2.83	2.94	2.83	3.02		11.61	5.30	3.40	2.83	6.30		4.48
4	2013	5	45	9.00	2.58	2.90	2.97	3.13	2.97	14.54	2.73	3.06	3.14	3.31	3.14	15.38	5.85	1.63	2.87	2.42	2.23	2.93
5	2016	3	76	25.33	4.09	4.41	4.43			12.94	5.99	6.45	6.48			18.92	5.51	4.34	2.31			4.02
7	2016	3	2	0.67	2.27	2.47	2.64			7.37	2.17	2.36	2.52			7.06	0.92	0.00	0.00			0.28
8	2015	4	12	3.00	2.35	2.43	2.43	2.42		9.64	2.29	2.37	2.37	2.36		9.37	0.87	1.27	1.69	1.27		1.28
9	2015	4	45	11.25	1.81	1.88	1.88	1.87		7.44	1.79	1.85	1.85	1.84		7.32	6.72	10.28	1.62	5.98		6.15
10	2018	1	11	11.00	2.37					2.37	2.34					2.34	4.71					4.71
11	2014	5	47	9.40	1.31	1.31	1.31	1.32	1.32	6.57	1.95	1.95	1.96	1.96	1.97	9.80	2.56	6.67	4.08	6.62	4.06	4.80
19	2015	4	48	12.00	0.51	0.51	0.51	0.51		2.03	1.36	1.36	1.37	1.38		5.47	11.05	11.73	5.84	6.54		8.78

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

APPENDIX C

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.

$$r_{duration} = \frac{Duration\ of\ after\ period}{Duration\ of\ before\ period} \quad \text{(C-1)}$$

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

$$N_{Expected,A} = r_{duration} \times N_{Observed,B} \quad \text{(C-2)}$$

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

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

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

$$OR_i = \frac{N_{Observed,A}}{N_{Expected,A}} \quad \text{(C-3)}$$

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

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

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

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

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,

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

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

where Safety Effectiveness = overall unbiased safety effectiveness.

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

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

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

where SE(OR) = Standard error.

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

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

APPENDIX D

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.

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

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

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

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.

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

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

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

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 (1), (2) and (4).

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

where OR_i = odds ratio for intersection *i*.

$$\text{Safety Effectiveness}_i = 100 \times (1 - \text{OR}_i) \tag{D-7}$$

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

$$\text{OR}' = \frac{\sum_{All\ sites} N_{Observed,A}}{\sum_{All\ sites} N_{Expected,A}} \tag{D-8}$$

where OR′ = odds ratio of all intersections combined.

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

where OR = unbiased odd ratio estimated of effectiveness,

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

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

where Safety Effectiveness = overall unbiased safety effectiveness.

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

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

$$\text{SE(OR)} = \sqrt{Var(OR)} \tag{D-12}$$

where SE(OR) = Standard error.

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

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

APPENDIX E

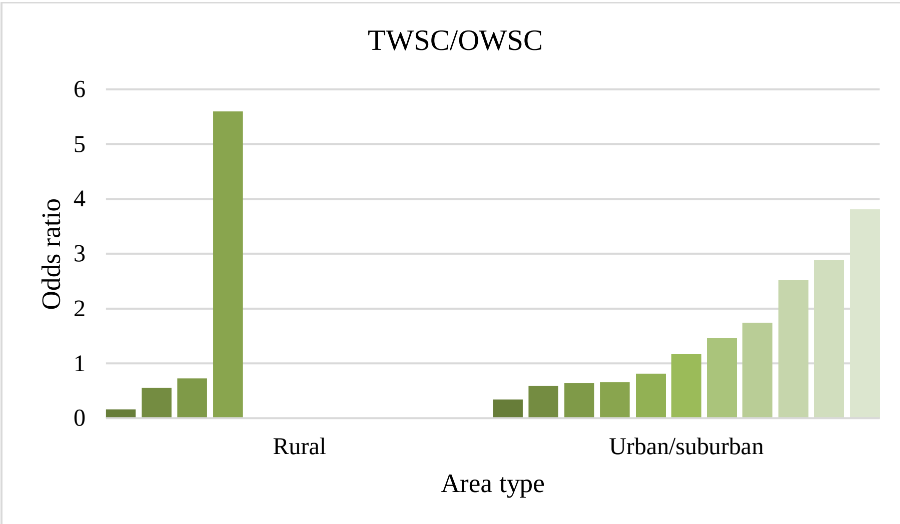

Figure E-1. Relationship between odds ratio and area type for TWSC/OWSC intersections converted to mini-roundabouts.

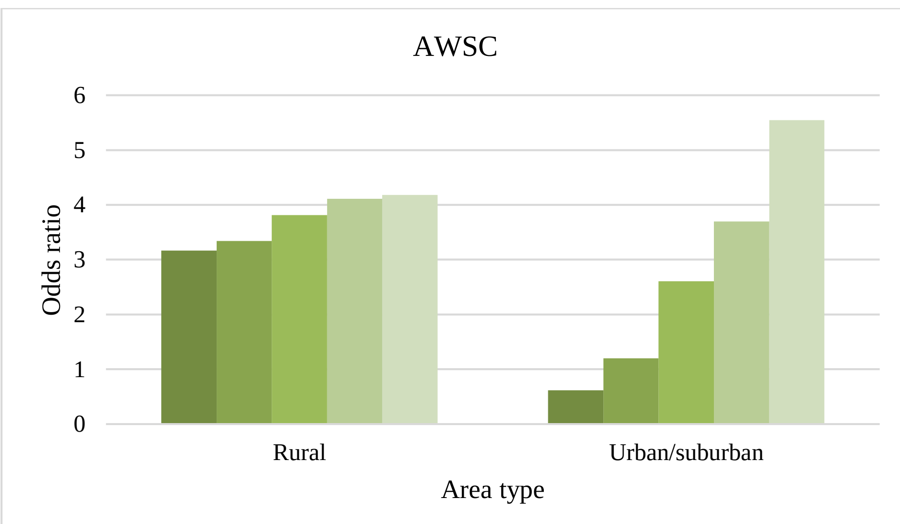

Figure E-2. Relationship between odds ratio and area type for AWSC intersections converted to mini-roundabouts.

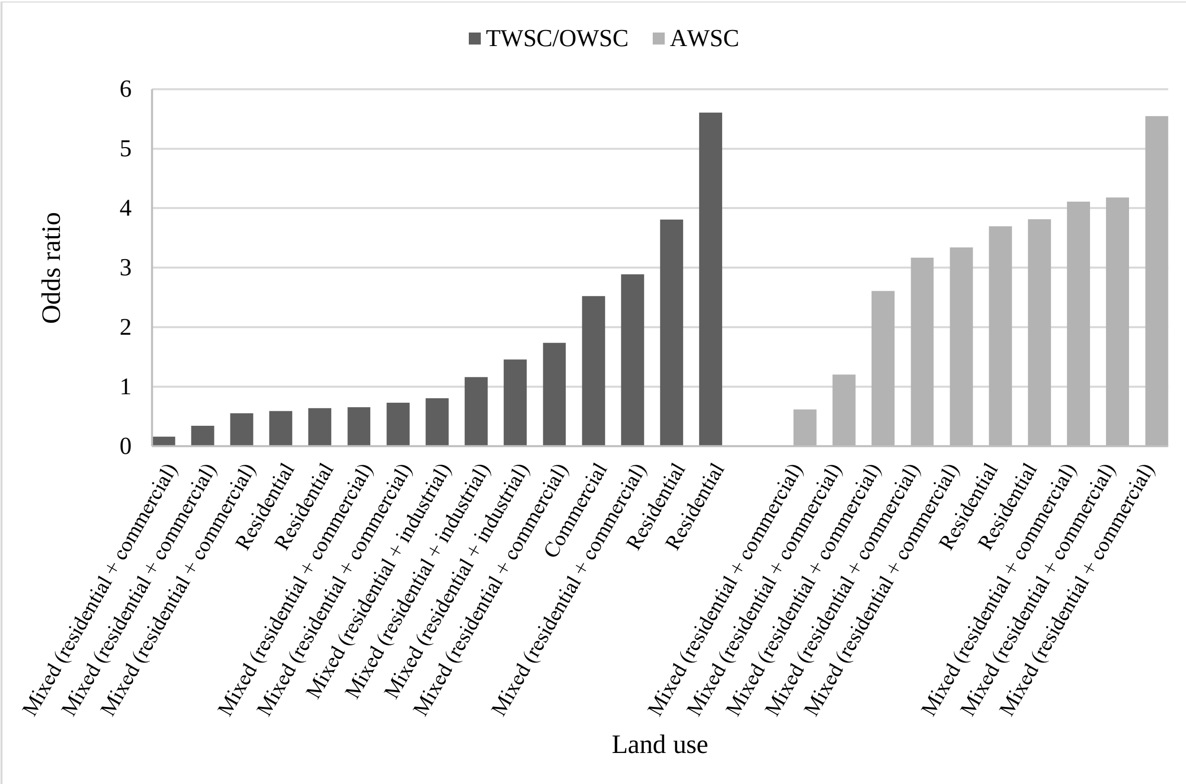

Figure E-3. Relationship between odds ratio and land use for TWSC/OWSC/AWSC intersections converted to mini-roundabouts.

Table E-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 E-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.