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Performance and safety effectiveness evaluation of mini-roundabouts in Michigan

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Abstract

This study evaluates the performance and safety effectiveness of mini-roundabouts. Crash, operational, and geometric data for 14 mini-roundabouts located in the state of Michigan were collected for both before and after installation time periods between 2007 and 2016. Three years of complete before and after installation crash data were analyzed utilizing the Before-and-After study with Comparison Group methodology. A total 28 untreated sites with similar characteristics to the 14 mini-roundabouts sites were used to account for changes in crashes unrelated to the treatment (mini-roundabout installation), evaluate the impacts of the treatment on the intersection, and develop the crash modification factors (CMFs). The results for overall safety effectiveness indicate a decrease in total crashes at signalized intersections when converted into mini-roundabouts, and an increase in total crashes at two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC) intersections when converted into mini-roundabouts. The recommended CMFs for converting a TWSC, AWSC, and signalized intersection into a mini-roundabout are 1.039, 1.051, and 0.755 for total crashes, respectively.

Keywords: Mini-roundabouts, CMF, Safety effectiveness, Crash modification factor

Introduction

Modern roundabouts are an effective intersection design alternative that can improve safety and provide traffic flow benefits, without the use of stop or signal controlled intersections [2]. In recent years, roundabouts are increasingly becoming popular in the USA, mainly because of the operational benefits they can provide, including their potential to improve safety and level of service. Although roundabouts can be used to improve intersection performance, they can be costly if additional right of way is needed [2]. As such, mini-roundabout design has captured the attention of engineers in the USA because they require relatively less right-of-way compared to modern roundabouts. A mini-roundabout as defined by the Federal Highway Administration's (FHWA) "Roundabouts: An Informational Guide," is a small roundabout that can be useful in low-speed urban environments in cases where conventional roundabout design is prohibited by right-of-way constraints [15]. Mini-roundabouts characterized by a small diameter and traversable islands [15]. their inscribed circle diameter (ICD) should not be more than 90 feet [15]. They are also becoming a common form of intersection design for communities outside the USA. Similar to modern roundabouts, mini-roundabouts can help in improving safety problems and excessive delays at minor approaches, as well as, facilitating slower speeds [7].

The safety benefits of mini roundabouts have been previously evaluated by a study in Germany, which found that the severity and number of crashes that occurred at intersections with mini-roundabouts was lower compared to those at similar unsignalized intersections. Crash reduction factor for the conversion from 13 unsignalized intersections into mini-roundabouts in Germany was found to be 29% [18]. The reduction in vehicle approach speeds is one of the major benefits of mini-roundabouts. A study in South Australia showed a decrease of about 62% in the 85th percentile speeds resulting from installation of mini-roundabouts [20]. Also, mini-roundabouts can help to reduce severity of crashes due to their reduction of the impact energy of the crash because of the lower impact angle of the mini-roundabout [1]. Overall, mini-roundabouts can reduce injury crashes by an average of 30% [6].

Due to their potential to improve safety and traffic flow, mini-roundabouts have been recommended by the FHWA's study [19] as a viable solution at stop and yield controlled intersections in the US cities. When they are properly installed, they will perform safely and efficiently. They also have low maintenance features [10]. In addition, a study by Pulugurtha et al. in 2021 aimed to quantify the safety advantages of mini-roundabouts by establishing crash modification factors (CMFs) [12]. They collected data for 25 mini-roundabouts in eight states (Georgia, Iowa, Michigan, Minnesota, Missouri, North Carolina, Virginia, and Washington) [12]. Their results showed that when a two-way stop-controlled or one-way stop-controlled (TWSC or OWSC) intersection was converted into a mini-roundabout, the number of overall crashes and fatal and injury (FI) crashes decreased [12]. However, their results also indicated an increase in property damage only (PDO) crashes [12]. Similarly, when an all-way stop controlled (AWSC) intersection was converted into a mini-roundabout, the frequency of total crashes, FI crashes, and PDO crashes increased [12]. Their recommended CMFs for converting a TWSC/OWSC intersection into a mini-roundabout are 0.83, 0.41, and 1.09 for total, FI, and PDO crashes, respectively [12]. But for converting an AWSC intersection into a mini-roundabout, the recommended CMFs are 3.25, 1.74, and 3.83 for total, FI, and PDO crashes, respectively [12].

Mini-roundabouts have recently been installed in several locations throughout Michigan. The installation of mini-roundabouts is anticipated to increase in Michigan as engineers and agencies find more sites that would benefit from their installation, particularly in areas where there are restrictions that would prevent the construction of a regular or normal-sized roundabout. The main issue with installing a mini-roundabout is that there is no enough evidence to support its safety advantages over full-sized roundabouts. Before they are widely implemented, this needs to be established. So, the development of CMFs for mini-roundabouts is required before they are installed. CMFs for mini-roundabouts were not explored extensively in the USA. These CMFs would help engineers in understanding the safety implications or benefits, such as the most probable types of crashes and the increase or decrease in crashes as a result of the installation of mini-roundabouts. The purpose of this study is to evaluate the performance and safety effectiveness of mini-roundabouts within the State of Michigan utilizing

Before-and-After study with Comparison Group methodology using the Highway Safety Manual (HSM) procedures. Specifically, the study intended to develop CMFs that can help transportation agencies in Michigan to quantify the performance and safety effectiveness of mini-roundabouts.

This paper is structured as follows. In the next section, the methods used for data collection and analysis are introduced. Afterwards, safety effectiveness analysis and evaluation are presented. The following sections deal with the analysis results and discussion. In the last section we present our conclusions and an outlook for future research.

Methods

The most common type of studies used to estimate the effectiveness of road safety countermeasures is the Before-and-After study [5]. This approach relies primarily on estimating the change in crash frequency before and after the implementation of a specific safety treatment. To generate statistically reliable results, crashes are often observed for several years (e.g., 2 to 3 years before and after the installation of the treatment). Furthermore, to account for the confounding effects of history and maturation, comparison groups (i.e., locations with no countermeasure in place but similar to the treatment sites) should be used [5]. In the Comparison Group method, it is preferable to use comparison sites from the same general area as the treatment sites to account for as many potential confounding factors with safety impacts. Matching historical crash records between comparison and treatment groups are essential for this technique [5].

The main goal of this study is to determine the change in crashes at locations where mini-roundabouts have been installed in Michigan. Achieving this objective require undertaking a statistically rigorous observational Before-and-After study with Comparison Group for these locations. The Before-and-After study with Comparison Group has special requirements on the data collection and analysis tasks, such as the need to collect a large sample size for mini-roundabouts with statistical significance to analyze.

Data collection

Selection criteria

In selecting mini-roundabouts in this study, following criteria were applied: any roundabout (1) with inscribed circle diameter (ICD) less than 90 ft, (2) with single-lane type, (3) with four-leg approaches, and (4) that has been in operation at least for three years. All geometric and operational characteristics of mini-roundabouts were collected from web aerial photographs and roundabouts database provided by agencies websites such as "Michigan Auto Law" [16] and "Kittelson and Associates, Inc." [17]. Then, the ICD for each location was verified using "Portage GIS Map" [11]. This information was used to prepare a list of mini-roundabouts for later evaluation.

The data needed for safety analysis include identification of treatment sites (mini-roundabouts), collection of mini-roundabouts installation dates, collection of crash data at treatment sites before and after mini-roundabout installation, identification of reference sites that have similar characteristics to the treated ones, and collection of geometric and operational characteristics of treatment and reference sites.

Selected treatment group data

Locations of mini-roundabout in Michigan were obtained from Michigan roundabouts map provided by Michigan Auto Law website [16] and roundabouts database provided by Kittelson and Associates, Inc. website [17]. The Michigan Auto Law website currently lists 178 roundabouts are in place and 31 roundabouts are proposed but not constructed yet. In order to apply the Before-and-After study with Comparison Group, 14 mini-roundabouts out of 178 roundabouts were qualified for this study. Some geometric and operational characteristics of these 14 locations are listed in Table 1.

Three years of complete crash data for each location before and after mini-roundabout installations are listed in Table 2. Crash data for treatment sites were collected from the "Michigan Traffic Crash Facts" website [8]. After that, mini-roundabouts crash data were summarized into three categories based on their previous traffic control type as listed in Table 3, to be ready for further analysis.

Selected comparison group data

Comparison Group data need to be similar to treated group to account for changes in crashes unrelated to the treatment (mini-roundabout installation). A way to verify the similarity is to check the geometric characteristics and historical crash frequency for the before period of both treated and reference sites. A 1:2 ratio was used for identifying the reference group (untreated) sites compared to treated group sites in order to ensure an adequate sample size for the control group. It should be noted that the number of treated sites (mini-roundabouts) was limited to 14. As a result, 28 reference sites were selected, and 3 years of complete before and after crash data were collected for them as well. Crash data for reference sites were collected from "Michigan Traffic Crash Facts" website [8]. Table 4 shows some geometric and operational characteristics of selected reference sites and Table 5 shows their collected crash data.

Table 1 Summary of selected mini-roundabouts

Treatment site ID	Area	Location	Year of installation	Previous control type
1	Grand Rapids	Cherry Street SE and Jefferson Avenue SE	2007	2-way stop controlled
2	New Hudson	New Hudson Dr./W Pontiac Trl	2010	2-way stop controlled
3	Ann Arbor	Huron Pkwy. and Nixon Road	2009	2-way stop controlled
4	Grand Rapids	Monroe Ave. NE/Guild St. NE	2014	2-way stop controlled
5	Grand Rapids	Monroe Ave. NE/Riverside Dr. NE/3 Mile Rd. NE	2014	2-way stop controlled
6	Northville	Taft Road and Morgan Blvd	2009	2-way stop controlled
7	Lansing	Michigan Ave./Washington Square	2007	2-way stop controlled
8	Grosse Pointe Park	Kercheval Ave./Wayburn St	2014	2-way stop controlled
9	Ypsilanti Township	Hitchingham Road and Textile Road	2015	All-way stop controlled
10	Mundy Township	Elms Rd./Hill Rd	2016	All-way stop controlled
11	Ypsilanti Township	Textile Road and Stony Creek Road	2016	All-way stop controlled
12	Ann Arbor	Scio Church and Wagner Roads	2016	All-way stop controlled
13	Grand Rapids	Wealthy Street SE and Lafayette Avenue SE	2007	Signalized
14	Muskegon	W. Western Avenue and 3rd Street	2008	Signalized

Table 2 Crash data for 3 years before and after mini-roundabout installation

Treatment site ID	Previous control type	Total crashes before	Total crashes after
1	2-way stop controlled	6	1
2	2-way stop controlled	2	2
3	2-way stop controlled	7	6
4	2-way stop controlled	1	3
5	2-way stop controlled	2	3
6	2-way stop controlled	1	1
7	2-way stop controlled	5	7
8	2-way stop controlled	0	5
9	All-way stop controlled	8	26
10	All-way stop controlled	5	16
11	All-way stop controlled	12	31
12	All-way stop controlled	15	23
13	Signalized	19	12
14	Signalized	3	1

Table 3 Total number of crashes for treatment sites

Control type	Total crashes before	Total crashes after
2-way stop controlled	24	28
All-way stop controlled	40	96
Signalized	22	13

Analysis

Collected Before-and-After data were analyzed utilizing Comparison Group methodology. Typically, this method is used to investigate untreated sites similar to the treated ones to account for changes in crashes unrelated to the treatment (mini-roundabout installation), and to develop crash modification factors (CMFs) for mini-roundabouts. Due to the limited information about annual average daily traffic at selected locations, Comparison Group method was selected for further analysis.

Before-and-after study analysis

Before-and-After study analysis was conducted to determine the impacts that mini-roundabouts installation had on total number of crashes occurred. Table 6 shows total number of crashes for both treatment and reference sites for before and after periods, based on their previous (for treatment sites)/current (for reference sites) traffic control type.

Calculating CMF with comparison group method

Safety effectiveness evaluation using comparison group method was done by following the procedures outlined in Highway Safety Manual [9]. Comparison Group analysis is

Table 4 Summary of selected reference sites

Reference site ID	Area	Location	Current control type
1	Northville	Taft Road and Galway Dr	2-way stop controlled
2	Northville	N Lexington Blvd and Eight Mile Rd	2-way stop controlled
3	Benton Harbor	Church St and Broad St	2-way stop controlled
4	Grand Rapids	Fulton St E and Prospect Ave NE	2-way stop controlled
5	Brighton	N 4th St and Main St and S 4th St	2-way stop controlled
6	Muskegon	Morris Ave and 1st St	2-way stop controlled
7	Ann Arbor	Aurora St and Nixon Rd	2-way stop controlled
8	Ann Arbor	N Earhart Pl and Plymouth Rd	2-way stop controlled
9	Ypsilanti Township	E Bemis Rd and Stony Creek Rd	2-way stop controlled
10	Lodi Township	W Ellsworth Rd and Wagner Rd	2-way stop controlled
11	Lodi Township	S State Rd and Hines Dr	2-way stop controlled
12	Genoa Township	Brighton Rd and Chilson Rd	2-way stop controlled
13	Genoa Township	Brighton Rd and Glenway St and Oak Pointe Dr	2-way stop controlled
14	lodi township	W Waters Rd and Wagner Rd	2-way stop controlled
15	Romeo/Bruce Twp	31 Mile Rd and Wolcott Rd	2-way stop controlled
16	Romeo/Bruce Twp	Romeo Plank Rd and 33 Mile Rd	2-way stop controlled
17	Ann Arbor	W Textile Rd and Lohr Rd and Mallard Cove Dr	All-way stop controlled
18	Grand Rapids	Lafayette Ave SE and State St SE	All-way stop controlled
19	Grand Rapids	Weston St SE and La grave Ave SE	All-way stop controlled
20	Ann Arbor	Glazier Way and Green Rd	All-way stop controlled
21	Brighton	Washington St and S 3rd St	All-way stop controlled
22	Detroit	W Columbia St and Clifford St	All-way stop controlled
23	Ypsilanti Charter Twp	William Ave and Emerson Ave	All-way stop controlled
24	Lansing	E Mount Hope Rd and Comanche Dr	All-way stop controlled
25	Grand Rapids	Romeo Plank Rd and 32 Mile Rd	Signalized
26	Ypsilanti Township	E Bemis Rd and Whittaker Rd	Signalized
27	Ann Arbor	Earhart Rd and Plymouth Rd	Signalized
28	Ann Arbor	N dixboro Rd and Plymouth Rd	Signalized

used to calculate the ratio of observed crash frequency in the after period to that in the before period. Then, expected crashes at treatment group sites assuming that no treatment had been applied ($N_{\mathrm{exp,T,A}}$) is calculated as shown in (Eq. 1). After that, expected number of crashes at treatment group sites are compared to the observed number of crashes after treatment to determine safety effectiveness as shown in (Eqs. 2 and 3).

$$\mathrm{N}_{\mathrm{exp,T,A}} = \frac{\mathrm{N}_{\mathrm{obs,C,A}}}{\mathrm{N}_{\mathrm{obs,C,B}}} * \mathrm{N}_{\mathrm{obs,T,B}} \tag{1}$$

$$\mathrm{Var}\left(N_{exp,T,A}\right) = N_{exp,T,A}^{2}\left(\frac{1}{N_{obs,T,A}} + \frac{1}{N_{obs,C,B}} + \frac{1}{N_{obs,C,A}}\right) \tag{2}$$

$$\mathrm{CMF} = \frac{\frac{\mathrm{N}_{\mathrm{obs,T,A}}}{\mathrm{N}_{\mathrm{exp,T,A}}}}{1 + \frac{Var\left(\mathrm{N}_{\mathrm{exp,T,A}}\right)}{N_{\mathrm{exp,T,A}}^{2}}} \tag{3}$$

Table 5 Crash data for selected reference sites

Reference site ID	Total crashes before	Total crashes after	Comparison year	Current control type
1	2	1	2014	2-way stop controlled
2	7	9	2007	2-way stop controlled
3	9	10	2007	2-way stop controlled
4	14	12	2009	2-way stop controlled
5	4	5	2010	2-way stop controlled
6	3	2	2014	2-way stop controlled
7	1	6	2009	2-way stop controlled
8	12	13	2009	2-way stop controlled
9	12	14	2014	2-way stop controlled
10	13	14	2010	2-way stop controlled
11	2	1	2009	2-way stop controlled
12	36	14	2007	2-way stop controlled
13	7	13	2007	2-way stop controlled
14	2	9	2014	2-way stop controlled
15	2	3	2014	2-way stop controlled
16	2	10	2014	2-way stop controlled
17	0	4	2016	All-way stop controlled
18	3	5	2016	All-way stop controlled
19	5	7	2016	All-way stop controlled
20	5	8	2016	All-way stop controlled
21	1	3	2015	All-way stop controlled
22	4	9	2015	All-way stop controlled
23	0	4	2016	All-way stop controlled
24	4	6	2016	All-way stop controlled
25	34	20	2008	Signalized
26	4	6	2007	Signalized
27	21	15	2007	Signalized
28	18	15	2008	Signalized

Table 6 Total number of crashes of before and after periods at treatment and reference sites

Control type	Time period	Treatment group	Comparison group
2-way stop controlled	Before	24	128
	After	28	136
All-way stop controlled	Before	40	22
	After	96	46
Signalized	Before	22	77
	After	13	56

Where $N_{\text{obs,T,B}}$ and $N_{\text{obs,T,A}}$ are the observed number of crashes in the before and after periods, respectively, at treatment sites group. $N_{\text{obs,C,B}}$ and $N_{\text{obs,C,A}}$ are the observed number of crashes in the before and after periods, respectively, at comparison sites group.

Results and discussion

The CMF is a multiplicative factor that is used to calculate the expected number of crashes after deploying a certain countermeasure at a specific location [4]. The ultimate objective of this study is to develop CMFs associated with mini-roundabout installations. A CMF larger than 1.0 implies that there will be an increase in crashes, whilst a value less than 1.0 suggests that there will be a decrease in crashes following the deployment of a specified countermeasure [4]. Table 7 shows a summary of the analysis results which shows a decrease in total crashes at signalized intersections when converted into mini-roundabouts, and an increase in total crashes at TWSC and AWSC intersections when converted into mini-roundabouts. The recommended CMFs for converting a TWSC, AWSC, and signalized intersection into a mini-roundabout are 1.039, 1.051, and 0.755 for total crashes, respectively.

This study is the first, to our knowledge, that measures the safety effectiveness when installing mini-roundabouts at signalized intersections. Results indicated that installing mini-roundabouts at signalized intersections was effective in reducing total crashes. However, a larger sample size can increase the generalizability of this result to a broader population, which can improve the precision of the CMF value associated with converting signalized intersections into mini-roundabouts. On the other hand, the adverse effectiveness result that was associated with installing mini-roundabouts at AWSC intersections was comparable to the finding of a prior study by [12] which demonstrated an increase in the frequency of total crashes. Nevertheless, the small sample size and limited data collection may have affected the CMF value's accuracy when converting a TWSC intersection into a mini-roundabout, producing a different outcome from that anticipated by Pulugurtha et al.'s study that demonstrated a decrease in the frequency of total crashes [12]. Moreover, further investigation could be conducted to examine the safety effectiveness at different severity crash levels. Also, mini-roundabouts that showed adverse results are recommended for further evaluation to determine if the negative effectiveness were due to installation specifications, design, geometry or any other related factors. This will allow transportation agencies to determine the important factors to consider when installing mini-roundabouts.

Additionally, CMFs can be used to assess the potential effectiveness of different safety countermeasures that are identified through proactive road safety assessments [14]. One way to conduct such assessments is by examining the characteristics of the road to identify the presence of risk factors [14]. To identify these risk factors, a proactive road safety assessment may include a combination of field observations, crash data analysis, and stakeholder engagement. For example, Riccardi et al. developed and validated a Safety Index for evaluating urban roundabouts. Their procedure detects the safety issues that are the largest contributors to crash risk in order to identify the safety measures that

Table 7 Comparison Group analysis results

Control type	$N_{Expected,T,A}$	Variance ($N_{Expected,T,A}$)	CMF
2-way stop-controlled	25.5	36.955	1.039
All-way stop-controlled	83.6364	644.899	1.051
Signalized	16	19.532	0.755

provide the greatest crash reduction at roundabouts [14]. Once safety issues have been identified, CMFs can be used to estimate the expected reduction in crashes that would result from implementing specific safety countermeasures. The findings of this study have important implications for transportation agencies seeking to allocate resources for safety improvements. Thus, they can make more educated decisions about which safety countermeasures to implement so they can prioritize their investments in enhancing road safety.

Conclusions

The Before-and-After study with Comparison Group methodology was used to quantify safety impact of mini-roundabouts that have been installed in Michigan by following HSM procedures. The Before-and-After study is the most common type of studies used to estimate the effectiveness of road safety countermeasures. This approach relies primarily on estimating the change in crash frequency before and after the implementation of a specific safety treatment. Moreover, comparison groups (i.e., locations with no countermeasure in place but similar to the treatment sites) should be used to account for the confounding effects of history and maturation [5]. In the Comparison Group method, it is preferable to use comparison sites from the same general area as the treatment sites to account for as many potential confounding factors with safety impacts. Matching historical crash records between comparison and treatment groups are essential for this technique [5].

Despite the substantial development of crash-based safety analysis, reliance on crash data has several flaws. First is the well-known availability and quality issues with crash data. Second, crashes are rare and random events (in a statistical sense); thus, they must be observed over a period of time to account for their stochastic nature and other confounding factors. Third, using crash data for safety analysis is a reactive approach: a large number of crashes must be recorded before action is made [13]. There are a few possible improvements that can be made for having more reliable results include (1) increasing the number of reference sites, this can help to increase the validity of the study, (2) controlling for other factors that might affect the crash rates and severity, such as changes in traffic volume or weather conditions, (3) collecting more detailed data such as information on the types and severity of the crashes.

The main objective of this study is to develop CMFs resulting from implementation of mini-roundabouts in Michigan. The results indicate that converting signalized intersections into mini-roundabouts would reduce total average annual crashes by 25%, while converting TWSC and AWSC intersections into mini-roundabouts would increase total average annual crashes by 4% and 5%, respectively. The findings can help transportation engineers and planners to make informed decisions when considering converting an intersection to a mini-roundabout.

The operational aspects of mini-roundabouts were not the focus of this study. In order to identify potential mitigation measures that might be useful for proper speed management, research should be performed to examine the vehicles' speeds and types (including trucks and buses) that are approaching, entering, and within mini-roundabouts. The effectiveness of mini-roundabouts for trucks and buses may vary depending on the design of the roundabout, as well as the operating characteristics of these vehicles. In addition, trucks and buses need a greater space to maneuver through mini-roundabouts which might increase the risk of conflicts with other vehicles or pedestrians. Future research in this area could address the potential challenges for larger vehicles, especially buses with longer wheelbases or trucks with longer trailers.

Furthermore, perceptual measures in the case of mini-roundabouts such as improved signage, pavement markings, and intersection lighting can be tested in a simulator environment to determine how they impact driver behavior, including speed, vehicle positioning, compliance with right-of-way rules. Simulator experiments can be used to simulate different scenarios that drivers may encounter at mini-roundabouts, such as different traffic volumes, pedestrian activity, and weather conditions [3]. Also, field tests are strongly advised to establish the perceptual measures' effectiveness on real roads [3]. This makes it possible to perform additional studies to systematically assess how perceptual measures influence driving behavior and safety under controlled conditions.

Abbreviations

AWSC	All-way stop-controlled
CMF	Crash modification factor
FHWA	Federal Highway Administration
FI	Fatal and injury
HSM	Highway Safety Manual
ICD	Inscribed circle diameter
PDO	Property damage only
TWSC	Two-way stop-controlled

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Availability of data and materials
The datasets generated and analyzed during the current study are available in the (Roundabouts Database-Kittelson and Associates Inc.) repository, (https://roundabouts.kittelson.com/), (Michigan Auto Law) repository, (https://www.michiganautolaw.com/roundabouts/), and (Michigan Traffic Crash Facts) repository, (https://www.michigantrafficcrashfacts.org/).

Declarations

Competing interests
The authors declare that they have no competing interests.

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