Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
2021, Vol. 2675(9) 1557–1572

DOI: 10.1177/03611981211008883
journals.sagepub.com/home/trr
SAGE

Are Roundabouts Safe and Economically Viable Replacing Conventional Diamond Interchange Ramp Terminals?

Boris Claros[1], Beau Burdett[1], Madhav Chitturi[1], Andrea Bill[1], and David A. Noyce[1]

Abstract

Roundabout implementations at traditional intersections have been shown to be effective at reducing severe crashes. Roundabouts have also been implemented at interchange ramp terminals; however, limited research is available. In this study, 25 roundabout ramp terminal implementations were evaluated. The methodological approach consisted of Empirical Bayes for safety effectiveness and crash cost changes, crash type weighted distribution, crash rate analysis of bypass configuration, and cost of implementation. Roundabouts were effective at reducing fatal and injury crashes when replacing existing interchange diamond ramp terminals: 65% reduction for roundabouts replacing stop-controlled ramp terminals and 41% reduction for roundabouts replacing signal-controlled ramp terminals. Observed crash type weighted distributions are provided to visualize the frequency and location of crashes within roundabout ramp terminals for design considerations. Exit ramp and outside crossroad approaches with right-turn bypass showed significantly lower crash rates than designs without bypass. The crash cost analysis showed that roundabouts replacing diamond ramp terminals yielded crash cost savings of between $95,000 and $253,000 per site per year (69% to 54% decrease in crash costs). Considering crash costs savings only, the cost of implementation should be less than $1.9 million for a roundabout replacing a stop-controlled ramp terminal and less than $5.1 million for a roundabout replacing a signal-controlled ramp terminal to accomplish benefit-cost ratios greater than one for a service life cycle of 20 years. Costs are in 2019 dollars.

Roundabouts have proven to be effective in reducing crashes at intersections (*1–3*). Implementations have expanded to different facilities with innovative designs to accommodate more traffic and turning movements (spiral design, turbo roundabouts, double, magic, cut-through, dogbone, balcony) (*4*). Roundabouts at interchange ramp terminals have become a practical alternative since using existing infrastructure and replacing conventional interchange configurations with innovative geometric designs have been on the rise.

Although design principles are the same, roundabouts at interchange ramp terminals could differ from intersection roundabouts in their traffic patterns, operations, and geometry. Approaching legs at ramp terminals typically include a bidirectional crossroad, unidirectional exit and entrance ramps, and, in some cases, additional public streets or driveways. Approach speeds on exit ramps may be significantly higher than the other approach legs and exit ramps on underpasses can involve significant downgrades. Therefore, there is a need to understand the safety performance of roundabouts specifically at interchange ramp terminals.

This paper builds on existing research to evaluate roundabouts used to replace existing diamond interchange ramp terminals (*5–8*). Only locations in which existing diamond ramp terminals were reconstructed into a roundabout were considered. The evaluation consisted of quantifying safety effects and changes in crash costs.

Literature Review

Safety benefits of roundabouts at intersections have been documented by multiple studies in the United States and

---

[1] Traffic Operations and Safety (TOPS) Laboratory, Department of Civil and Environmental Engineering, University of Wisconsin – Madison, Madison, WI

Corresponding Author:
Boris Claros, claros@wisc.edu

internationally. In the United States, for example, Gross et al. (*1*) examined the conversion of 28 signalized intersections to roundabouts using the Empirical Bayes (EB) method and found a reduction of 65.8% for injury crashes and 20.8% for total crashes (TOT). Persaud et al. (*2*) also applied the EB method to study the conversion of 23 stop-controlled and signalized intersections to roundabouts and found reductions of 80.0% for injury crashes and 40.0% for TOT crashes. Rodegerdts (*3*) found that roundabouts reduce crashes in both urban and rural areas, especially severe crashes. A primary reason for roundabout safety benefits is the reduction in speed and in the number of conflict points, including the elimination of crossing conflicts.

Using existing infrastructure and replacing conventional interchange configurations with innovative geometric designs have been on the rise. For instance, the Diverging Diamond Interchange (DDI) has proven safety and operational benefits. DDI implementations have experienced 55.0% fewer fatal and injury crashes (FI), 31.4% fewer property damage only crashes (PDO), and 37.5% fewer TOT crashes compared with conventional diamond interchanges (*9*). DDI operational benefits include increased left-turn capacity and decreased overall delay (*10–12*). Similarly, roundabouts have been implemented on freeway interchanges at ramp terminals, but limited research is available.

Existing literature on safety of interchange roundabout ramp terminals is limited. Uddin (*13*) presented a case study of an interchange with single-lane roundabouts in Oxford, Mississippi. A before-and-after EB study was conducted for the north terminal and the author found a reduction of 37.5% in TOT crashes and 60.0% in injury crashes. Qin et al. (*7*, *8*) analyzed 24 roundabouts in Wisconsin, four of which were interchange terminals. Using the EB method, the authors found a reduction in FI crashes of 49.4% (west) and 50.0% (east) for the I-43/WI-42 dual-lane roundabouts; but found an increase in FI crashes of 2.6% (west) and 88.1% (east) for the I-53/S Access Rd. single-lane roundabout. These studies predated the Highway Safety Manual (HSM) or did not use specific local calibration factors to adjust prediction models available in the HSM (*14*).

Ferguson et al. (*15*) developed roundabout specific safety performance functions (SPFs) and associated crash modification factors (CMFs). The database included 30 roundabout ramp terminals and 325 roundabout intersections. The CMF for the number of unsignalized access points ranged between 1.00 and 1.88. CMF values for roundabout intersections were about 30.0% smaller than those for roundabout ramp terminals. The outbound-only leg CMF had a value of 0.43 and it is applicable to interchange crossroad-ramp terminal roundabouts with one outbound-only leg (*15*). Looking at operations, Li et al. (*16*) specifically compared the operational performance of roundabout and conventional signalized diamond ramp terminals. Considering crossroad approaches, roundabout ramp terminals consistently had better levels of service (LOS) under any conditions.

Data Collection

Potential locations for the study were identified in the states of Missouri and Wisconsin. Through an extensive review process, a group of roundabout ramp terminals were sampled, and data were collected for analysis.

Site Selection

Through an interchange screening process and review of public records, roundabout ramp terminals were identified. A pool of 120 potential locations (26 in Missouri and 94 in Wisconsin) were identified for analysis. Ramp terminals that met the following criteria were selected:

- roundabouts replacing existing diamond interchange ramp terminal configurations;
- locations with representative number of crashes before and after implementation (at least one crash per year);
- roundabouts with similar and consistent geometric and operational traits as the rest of the group of sites under consideration;
- known date roundabout opened to traffic (year at a minimum);
- roundabout implementations that were not part of new interchanges; and
- roundabout ramp terminals that had not significantly changed the interchange geometry, operations, approaches, and surrounding area.

After an extensive review of potential sites, 25 roundabout ramp terminals were selected for the study (eight in Missouri and 17 in Wisconsin). Crash, geometric, and operational data were collected for the selected ramp terminals.

Crash, Geometric, and Operational Data

Data were obtained from Missouri Department of Transportation (DOT) Transportation Management Systems (TMS), Wisconsin DOT roundabout database (*17*) and traffic count database (*18*), and Traffic Operations and Safety Laboratory (TOPS) WisTransPortal (*19*). Crash data were collected for the functional areas of the ramp terminals including crossroads and ramps. Overall, 1,089 crashes were obtained for analysis from all sites—632 crashes in the before period and 457 in the after period. Geometric data were collected with aerial images and street view applications. Geometric data included the number of lanes by movement, median width, distance between ramp terminals, distance to adjacent public street intersections or driveways, skew angle, and presence of right-turn bay or bypass. Operational data consisted of traffic volumes for crossroad and ramps, signal control type in the before period, and posted speed limits. Available traffic volumes by year from before and after periods were collected.

Description of Study Sites

Table 1 provides geometric and operational characteristics of roundabout ramp terminals selected for this study. The roundabouts had opened to traffic between 2007 and 2016. On average, before data were available for 4.7 years and after data were available for 4.4 years. Before and after periods refer to the study periods in relation to the implementation of the roundabout. One year before and one year after roundabouts opened to traffic were removed from the data. Also, to avoid crash seasonality variations between periods of analysis, before and after periods matched the same dates of the year for the start and end of periods.

Annual average daily traffic (AADT), in vehicles per day (vpd), observed at exit ramps were between 1,300 vpd and 10,900 vpd, at entrance ramps between 647 vpd and 11,450 vpd, and at crossroad approaches between 2,060 vpd and 30,700 vpd. Available AADTs for before and after periods were used as a component of the crash prediction models, accounting for variations across the years. Posted speed limits in miles per hour (mph) for crossroads were between 25 mph and 55 mph and for freeways were between 55 mph and 70 mph. There were roundabout ramp terminals with single and multilane configurations on the crossroad and circulatory roadway.

For specific design configurations, there were eight roundabout ramp terminals with spiral designs—roundabout design with progressive lane addition/drop around the circulatory roadway to accommodate turning movements. Similarly, some roundabouts had additional features such as exit ramps and outside crossroad right-turn bypass with yield (YY) and free-flow (YF) conditions. Following the HSM nomenclature for freeway facilities, there were 14 diamond ramp terminals with stop-controlled configurations (D4/3-ST) and 11 diamond ramp terminals with traffic signal-controlled configurations (D4-SIG) before implementation of the roundabouts. Differences of region, ramp terminal configuration, geometry, operations, and signal control type were accounted for in the crash prediction models.

Some of the differences identified among roundabouts by state included geometry, weather, and the presence of roundabouts in each state which may relate to driver familiarity. Roundabouts in Missouri were characterized by having single, dual, and hybrid one- and two-lane designs compared with Wisconsin sites which had up to three lane configurations. Most roundabouts in Missouri did not have a spiral design or right-turn bypass whereas Wisconsin had several roundabouts with spiral designs and a right-turn bypass. Based on the location of the majority of the sites in each state, central Missouri experiences on average 8 to 19 in. of snow (average January temperatures: high 40°F and low 21°F) compared with an average of 36 to 51 in. of snow (average January temperatures: high 27°F and low 12°F) in eastern Wisconsin which presents different road conditions during the winter that may result in different crash patterns. As of 2020, Wisconsin had 489 roundabouts in its state highway system which is the largest of any state. The overall number of roundabouts in Missouri was not available. Thus, drivers in Wisconsin would be expected to be more familiar navigating roundabouts than Missouri drivers.

Methodology

Safety effects and crash cost changes associated with the implementation of roundabout ramp terminals replacing existing diamond interchange ramp terminal configurations were evaluated. The methodological approach consisted of observational before and after EB to estimate the safety effectiveness of treatments in crash reduction/increase and corresponding CMF. Crash reports were reviewed to classify crash types according to the frequency and locations of crashes within the ramp terminals. A crash diagram was developed with 19 weighted crash categories. Crash rates were evaluated for exit ramp and outside crossroad approaches considering right-turn bypass configuration. For the crash cost analysis, an adaption of the EB was implemented to estimate crash cost changes and overall crash cost benefit. Based on the results from the crash cost analysis, costs of implementation were estimated assuming benefit–cost ratios greater than one and a 20-year service life cycle.

Safety Effectiveness Evaluation

There is a consensus that the EB approach is a rigorous statistical method that accounts for selection and regression-to-the-mean biases in observed crash data at locations that have undergone treatments (*14*, *20*). The method determines the safety effectiveness of a treatment based on the comparison of expected crashes with no treatment with observed crashes with treatment (*20*). To obtain expected crashes in the after period, the EB uses

Table 1. Data Descriptive Statistics

No.	Location	Ramp terminal[a]	Open[b]	Years		AADT[c]			Speed[d]		Lanes[e]		Spiral design[f]	Bypass[g]		Previous configuration[h]
				Before	After	Crossroad	Exit ramp	Entrance ramp	Crossroad	Freeway	Crossroad	Roundabout		Exit ramp	Crossroad	
1	I-44/RT-E, Rolla, MO	N	2007	4	9	3,186	1,797	647	35	60	2	1	No	N	N	D4-ST
2	I-44/Kingshighway St., Rolla, MO	N	2011	4	4	7,463	1,506	3,523	35	70	2	1	No	N	N	D4-ST
3	I-44/Kingshighway St., Rolla, MO	S	2011	4	4	16,715	3,845	1,709	35	70	2	1	No	N	YF	D3-ST
4	MO-9/Briarcliff, Kansas City, MO	N	2011	4	4	6,379	2,377	3,774	25	55	4	1, 2	No	YY	N	D3-ST
5	I-41/CTH-G, DePere, WI	E	2012	5	6	17,150	4,000	10,500	25	70	4	1, 2	No	YY	YF	D4-ST
6	USH-45/STH-60, Jackson, WI	E	2012	5	6	16,300	3,925	4,867	40	70	4	1, 2	No	YY	N	D4-ST
7	USH-45/STH-60, Jackson, WI	W	2012	5	6	11,067	4,275	3,850	55	70	4	1, 2	No	YF	N	D4-ST
8	USH-14/CTH-MM, Fitchburg, WI	S	2012	5	6	14,800	4,867	2,600	35	70	4	1, 2	No	YY	YY	D4-ST
9	USH-14/CTH-MM, Fitchburg, WI	N	2012	5	6	5,400	2,650	4,550	45	70	5	1–3	Yes	YY	YY	D4-ST
10	US-63/RT-M, Ashland, MO	W	2014	4	1	2,060	3,575	1,941	35	70	2	1	No	N	N	D4-ST
11	USH-41/CTH-M, Howard, WI	E	2014	5	4	3,400	10,900	2,400	35	70	4	1, 2	No	YY	YY	D4-ST
12	USH-41/CTH-M, Howard, WI	W	2014	5	4	14,875	1,800	11,450	45	70	4	1, 2	No	YY	YF	D4-ST
13	USH-51/CTH-K, Wausau, WI	E	2015	5	3	9,800	4,700	1,500	45	65	4	1, 2	No	YY	N	D4-ST
14	USH-51/CTH-K, Wausau, WI	W	2015	5	3	8,700	1,300	4,500	45	65	4	1, 2	No	YY	N	D4-ST
15	I-435/87th St., Kansas City, MO	E	2011	4	5	15,842	3,251	2,133	40	65	4	1, 2	No	N	N	D4-SIG
16	I-435/87th St., Kansas City, MO	W	2011	4	5	7,493	2,193	2,147	45	65	4	1, 2	No	N	N	D4-SIG
17	I-41/STH-54, Green Bay, WI	E	2012	5	6	22,900	8,850	6,300	35	70	5	1–3	Yes	YY	YF	D4-SIG
18	I-41/STH-54, Green Bay, WI	W	2012	5	6	30,700	7,800	8,850	35	70	5	1–3	Yes	YF	YF	D4-SIG
19	I-41/STH-21, Oshkosh, WI	E	2012	5	6	17,134	5,467	9,267	30	70	5	1–3	Yes	YY	YY	D4-SIG
20	I-41/STH-21, Oshkosh, WI	W	2012	5	6	17,634	9,400	5,600	35	70	5	1–3	Yes	YF	YF	D4-SIG
21	MO-100/MO-109, Wildwood, MO	N	2014	4	1	16,521	5,630	2,737	45	55	3	1, 2	Yes	YF	N	D4-SIG
22	USH-10/STH-47, Appleton, WI	S	2015	5	3	22,700	3,300	5,200	35	65	4	1, 2	No	YY	YY	D4-SIG
23	USH-10/STH-47, Appleton, WI	N	2015	5	3	17,000	4,900	4,600	35	65	4	1, 2	No	YY	YY	D4-SIG
24	I-41/USH-141, Howard, WI	E	2016	5	2	15,300	7,200	2,200	35	70	5	1–3	Yes	YY	N	D4-SIG
25	I-41/USH-141, Howard, WI	W	2016	5	2	20,400	1,900	6,400	35	70	5	1–3	Yes	YY	YF	D4-SIG

Note: AADT = average annual daily traffic.

[a] Site location in relation to the freeway.

[b] Year sites opened to traffic. One year before and after were not considered in the study.

[c] Most recent AADT for reference in vehicles per day (vpd).

[d] Posted speed limit in miles per hour (mph).

[e] Total number of lanes in both directions for crossroad and number of lanes on roundabout circulatory roadway.

[f] Roundabout design with progressive lane addition/drop around the circulatory roadway to accommodate turning movements.

[g] Right turn bypass (N = No, YY = Yes-Yield, YF = Yes-Free).

[h] Previous ramp terminal configuration (D4 and D3, conventional diamond ramp terminal with four legs and three legs; ST, stopped-controlled; SIG, signal-controlled).

crash prediction models that were developed from national studies.

Crash prediction models are composed of SPFs, CMFs, and calibration factors (C). Available nationwide SPFs and CMFs in the HSM were used for crash prediction in this study. Equation 1 shows the general form of the calibrated crash prediction models (*14*).

$$N_{pred,i,j,l} = C_{i,j,l} \times N_{spf,i,j} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \tag{1}$$

where

$N_{pred,i,j,l}$ = predicted crash frequency (crashes/year) for facility i (D3-ST, D4-ST, D4-SG), severity j (FI = Fatal and Injury, PDO = Property Damage Only) and state l (MO = Missouri, WI = Wisconsin),

$C_{i,j,l}$ = calibration factor for facility i, severity j, and state l,

$N_{spf,i,j}$ = base SPF crash prediction (crashes/year) for facility i and severity j, and

CMF_n = crash modification factor for facility characteristic . n

Calibration factors for ramp terminals (before period configuration) were available from studies of statewide HSM calibration in Missouri (*21*) and Wisconsin (*22*). The calibration of the HSM crash prediction models consists of comparing the jurisdiction observed crashes with the HSM model predictions for randomly selected facilities of the same configuration. Thus, the calibration factor C is the ratio between all observed crashes and HSM model predicted crashes from all sites. Calibration factors were available by severities FI and PDO crashes. In this study, the following calibration factors were used:

Missouri (*21*)

D3/4 stopped-controlled ramp terminal

$$C_{D3/4-ST,FI,MO} = 1.23,\ C_{D3/4-ST,PDO,MO} = 2.03$$

D4 signal-controlled ramp terminal (two lanes)

$$C_{D4-SIG2,FI,MO} = 1.09,\ C_{D4-SIG2,PDO,MO} = 2.36$$

D4 signal-controlled ramp terminal (four lanes)

$$C_{D4-SIG4,FI,MO} = 0.85,\ C_{D4-SIG4,PDO,MO} = 1.83$$

Wisconsin (*22*)

D4 stopped-controlled ramp terminal

$$C_{D4-ST,FI,WI} = 0.78,\ C_{D4-ST,PDO,WI} = 1.42$$

D4 stopped-controlled ramp terminal

$$C_{D4-SIG,FI,WI} = 0.42,\ C_{D4-SIG,PDO,WI} = 0.51$$

The base SPF is a function of the measure of exposure AADT and the number of through lanes by ramp terminal type. The CMFs serve to adjust the base model SPF with specific facility traits including (*14*):

- exit ramp capacity;
- crossroad left-turn lane;
- crossroad right-turn lane;
- access point frequency;
- segment length;
- median width;
- protected left-turn operation (signalized terminals only);
- channelized right turn on crossroad (signalized terminals only);
- channelized right turn on exit ramp (signalized terminals only);
- non-ramp public street leg (signalized terminals only); and
- skew angle (unsignalized terminals only).

Ramp terminal SPFs and CMFs used in this study can be found in the HSM supplement, Chapter 19 (*14*). More specifically, over dispersion and SPF coefficients used include D3 stop-controlled ramp terminal (HSM Table 19–18, page 19–42), D4 stop-controlled ramp terminal (HSM Table 19–20, page 19–43), and D4 signal-controlled ramp terminal (HSM Table 19–15, page 19–39). CMFs for ramp terminals can also be found in the HSM supplement section 19.7.2, page 19–54 (*14*).

After obtaining predicted crashes, expected crashes can be calculated. Equation 2 illustrates how expected crashes for a facility are computed based on a weighted linear combination of predicted crashes and observed crashes. The weight (w) of contribution from predicted crashes is a function of the reliability of the model estimates (reflected by the overdispersion parameter) and the magnitude of the predicted crashes. Equation 3 shows how the weight is a function of the overdispersion or variability in prediction (every SPF has a corresponding overdispersion coefficient).

$$N_{exp,i,j,l,b} = w_{i,j} \times N_{pred,i,j,l,b} + \left(1 - w_{i,j}\right) \times N_{obs,i,j,l,b} \tag{2}$$

$$w_{i,j} = \frac{1}{1 + k_{i,j} \times N_{pred,i,j,l,b}} \tag{3}$$

where

$N_{exp,i,j,l,b}$ = expected number of crashes in the before period (b) for facility i (D3-ST, D4-ST, D4-SG), severity j (FI = Fatal and Injury, PDO = Property Damage Only) and state l (MO = Missouri, WI = Wisconsin),

$w_{i,j}$ = weight value for facility i and severity j,

$N_{obs,i,j,l,b}$ = observed number of crashes in the before period (b) for facility i, severity j, and state l,

$N_{pred,i,j,l,b}$ = predicted number of crashes in the before period (b) for facility i, severity j, and state l, and

$k_{i,j}$ = model overdispersion term for facility i and severity j.

The adjustment factor (r) is introduced to account for variations between before and after periods ($N_{pred,i,j,l,b}$ and $N_{pred,i,j,l,a}$). These variations include the duration of periods and traffic volume. Therefore, the factor in Equation 4 is the ratio of predicted crashes in the after period over predicted crashes in the before period.

$$r = \frac{N_{pred,i,j,l,a}}{N_{pred,i,j,l,b}} \tag{4}$$

Using Equation 5, the expected crashes in the after period ($N_{exp,\ i,j,l,a}$) are calculated by multiplying the adjustment factor to the expected crashes in the before period.

$$N_{exp,i,j,l,a} = r \times N_{exp,\ i,j,l,b} \tag{5}$$

The expected crashes in the after period ($N_{exp,i,j,l,a}$) are then compared with the actual observed crash frequency in the after period ($N_{obs,i,j,l,a}$). Equation 6 shows the comparison designated as OR'.

$$OR' = \frac{N_{obs,i,j,l,a}}{N_{exp,i,j,l,a}} \tag{6}$$

Since OR' is potentially biased, it is adjusted using Equation 7 to remove bias and account for regression-to-the-mean using the variance of the expected crashes in the after period.

$$OR = \frac{OR'}{1 + \frac{Var\left[N_{exp,i,j,l,a}\right]}{\left[N_{exp,i,j,l,a}\right]^2}} \tag{7}$$

where

$$Var\left[N_{exp,i,j,l,a}\right] = \left[(r)^2 \times N_{exp,i,j,l,b} \times \left(1 - w_{i,j}\right)\right] \tag{8}$$

The unbiased OR is used for deriving the safety effectiveness (SE), as shown in Equation 9. When crash frequency decreases after a treatment, the SE is positive. When crash frequency increases, the SE is negative.

$$SE(\%) = 100 \times (1 - OR) \tag{9}$$

Crash Type Weighted Distribution

Crash type diagrams provide a visual representation of common crashes observed at different locations within a roadway facility such as roundabout ramp terminals. To categorize crashes by crash type, location, and severity, each individual crash report was reviewed. The crash diagram in the crash reports and narrative statements by the officer, driver, and other witnesses were especially helpful to understand the crash type and location. Computer-aided design (CAD) drawings were generated with the geometry footprint of roundabouts and each crash was mapped according to severity and crash type. Resulting roundabout drawings with crashes were reviewed to identify clusters of frequent crash types at locations within roundabouts. Based on the frequency of crash types observed, the following 19 categories were defined.

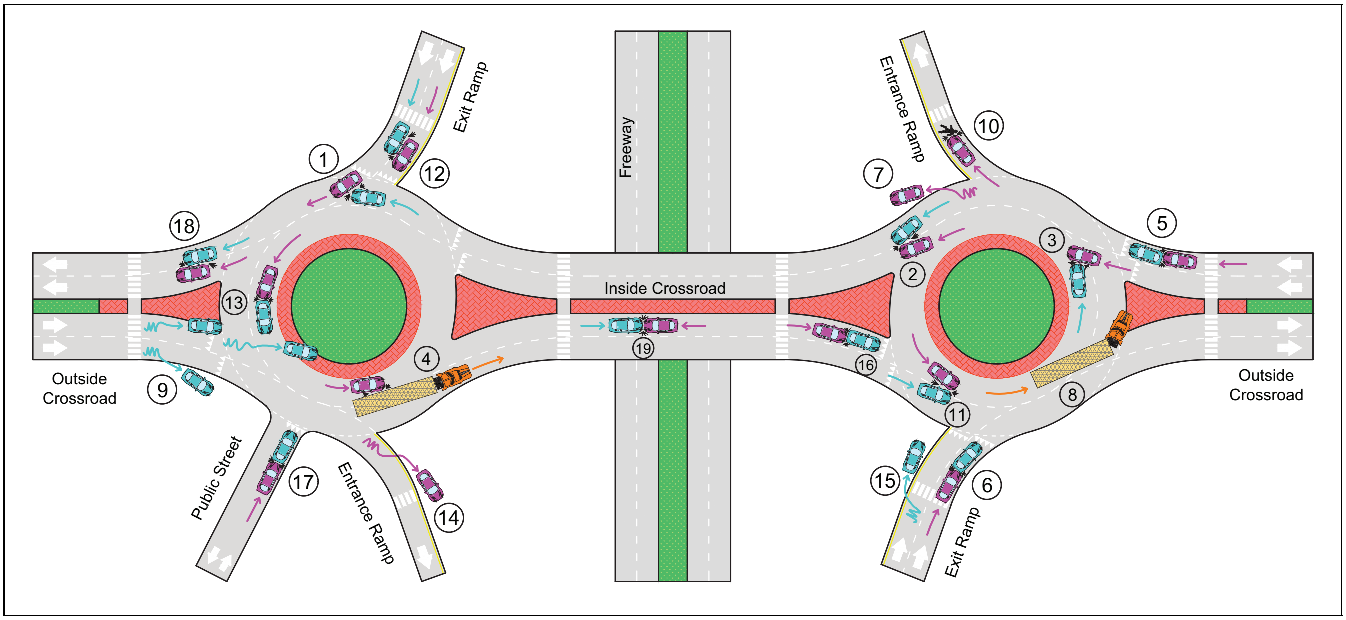

Figure 1. Roundabout ramp terminal crash types.
Note: Numbers in the figure refer to Table 2.

Table 2. Roundabout Ramp Terminal Crash Type Weighted Distribution.

No.	Description	FI (%)	PDO (%)	TOT (%)
1	Angle crash exit ramp and circ. roadway	14.9	21.3	19.5
2	Sideswipe departing circ. roadway	20.6	12.0	14.4
3	Angle crash crossroad and circ. roadway	15.5	11.5	12.6
4	Truck sideswipe	NA	14.9	10.7
5	Rear-end outside crossroad	6.7	11.3	10.0
6	Rear-end exit ramp	11.6	4.0	6.1
7	Loss of control circ. roadway	3.5	6.6	5.7
8	Truck loss of control	2.6	5.5	4.7
9	Loss of control outside crossroad	4.4	3.2	3.5
10	Ped/bike at exit/entrance ramp	10.5	NA	2.9
11	Sideswipe entering circ. roadway	0.2	3.5	2.5
12	Sideswipe exit ramp	2.6	2.5	2.5
13	Rear-end circ. roadway	4.5	0.6	1.7
14	Loss of control entrance ramp	0.1	1.7	1.2
15	Loss of control exit ramp	0.4	1.0	0.8
16	Rear-end inside crossroad	2.1	0.2	0.7
17	Rear-end public street	NA	0.1	0.1
18	Sideswipe outside crossroad	NA	0.1	0.1
19	Wrong-way crash	NA	0.1	0.1

Note: FI = fatal and injury crashes; PDO = property damage only crashes; TOT = total crashes; circ. = circulatory roadway; NA = not available.

Figure 1 illustrates each category and Table 2 provides the results of the analysis.

Since the periods of analysis and AADTs for each roundabout were different, crash type distributions were adjusted. Therefore, weighted estimates were obtained for the 19 crash type categories as a function of period duration, exit ramp AADT, entrance ramp AADT, and crossroad AADT:

$$\bar{N}_{j,r} = \frac{\sum_{i,j}^{n,m} N_{i,j,r} \times P_{i,yr} \times P_{i,ex} \times P_{i,en} \times P_{i,xrd}}{\sum_{i}^{n} P_{i,yr} \times P_{i,ex} \times P_{i,en} \times P_{i,xrd}} \tag{10}$$

$$Q_{j,r} = \frac{\bar{N}_{j,r}}{\sum_{j,r}^{m,t} \bar{N}_{j,r}} \times 100\ (\%) \tag{11}$$

where

$\bar{N}_{j,r}$ = weighted arithmetic mean number of crashes by severity j (FI = Fatal and Injury, PDO = Property Damage Only, TOT = Total crashes) and crash type r (categories 1–19),

$Q_{j,r}$ = percentage of crash type r by severity j,

$P_{i,j,r}$ = number of crashes for facility i, severity j, and crash type r,

$P_{i,yr}$ = period of duration weight for facility i (in years),

$P_{i,ex}$ = exit ramp AADT weight for facility i (in vpd),

$P_{i,en}$ = entrance ramp AADT weight for facility i (in vpd), and

$P_{i,xrd}$ = crossroad-ramp AADT weight for facility i (in vpd).

Crash Rate by Approach and Configuration

The SE evaluation provides aggregated estimates of the overall safety performance of sites with the implementation of the treatment. However, analysis at the approach level is more appropriate to investigate the safety effect of more specific design configurations. Exit ramp and outside crossroad approaches were evaluated as a function of crash types and right-turn bypasses. From the review of crash reports, crashes by severity related to exit ramps and outside crossroad approaches were identified. Crash rates were computed using the following equation (*23*):

$$CR_{w,x,y,z} = \frac{1,000,000 \times N_{obs,w,x,y,z}}{365 \times N_{yr,w,x,y,z} \times TEV_w} \quad (Crashes\ per\ MEV) \tag{12}$$

where

$CR_{w,x,y,z}$ = crash rate for approach type w (ex = exit ramp, xrd = outside crossroad), severity x (FI = Fatal and Injury, PDO = Property Damage Only, TOT = Total crashes), crash type y (categories 1, 3, 5, 6, 9, 12, 15, and all), and right-turn bypass z (N = No bypass, YY = Yes-Yield, YF = Yes-Free Flow),

$N_{obs,w,x,y,z}$ = number of observed crashes for approach type w, severity x, crash type y, and right-turn bypass z,

$N_{yr,w,x,y,z}$ = number of years for approach type w, severity x, crash type y, and right-turn bypass z,

TEV_w = total entering vehicles per day for approach type w, and

MEV = million entering vehicles per day.

Total entering vehicles per day was computed with available AADTs in the after period. In the case of exit ramps, TEV_{ex} was the sum of the exit ramp AADT and crossroad AADT in one direction. For the outside crossroad road approach, the TEV_{xrd} was derived from the crossroad and entrance ramp AADTs. Crash rate estimates were evaluated to determine if there were any particular trends as a function of approach type, crash type, and bypass configuration.

Crash Cost Evaluation

Although SE results provide a measure of the safety effect of the treatment, it does not fully capture the overall benefit since crashes are evaluated as crash counts. Accounting for the weight of severity of each crash with crash costs is an alternative to assess the overall benefit of the treatment. Change in crash costs caused by the implementation of roundabouts replacing diamond ramp terminals was estimated. Based on the method used for the SE described in this paper, the EB method can be adapted to measure the difference between expected crash costs without treatment and observed crash costs with treatment (*24*, *25*). The crash cost modification factor (θ_{cost}) is a measure quantifying the change in crash cost with the treatment:

$$\theta_{cost} = \frac{\frac{M_{obs,a}}{M_{exp,a}}}{\left\{1 + \left[\frac{Var\left(M_{exp,a}\right)}{M_{exp,a}^{2}}\right]\right\}} \tag{13}$$

$$Var(\theta_{cost}) = \frac{\theta_{cost}^{2}\left\{\left[\frac{Var(M_{obs,a})}{M_{obs,a}^{2}}\right] + \left[\frac{Var\left(M_{exp,a}\right)}{M_{exp,a}^{2}}\right]\right\}}{\left\{1 + \left[\frac{Var\left(M_{exp,a}\right)}{M_{exp,a}^{2}}\right]\right\}^{2}} \tag{14}$$

where

θ_{cost} = crash cost modification factor,
$M_{obs,a}$ = crash cost of observed crashes with the roundabout in the after period (a),
$M_{exp,a}$ = crash cost of expected crashes without roundabout in the after period (a), and
$Var(\theta_{cost})$ = variance of the cost modification factor.

Additionally, the change in crash cost (ϕ_{cost}) and variance can be estimated in dollar costs:

$$\phi_{cost} = M_{exp,a} - M_{obs,a} \tag{15}$$

$$Var\ (\phi_{cost}) = Var\left(M_{exp,a}\right) + Var(M_{obs,a}) \tag{16}$$

Since police reports may not accurately describe injuries because perceptions of injury, reporting thresholds, and severity definitions differ among states; Council et al. (*26*) used the National Highway Traffic Safety Administration (NHTSA) national data sets, which included both police reported KABCO and medical descriptions of injury in the Occupant Injury Coding system (OIC), to develop crash costs. Council et al. (*26*) defined "cost estimate" as both human capital cost and comprehensive cost. Crash cost estimation requires information on the number of people involved in a given crash, severity of injuries each person suffered in the crash, costs associated with the injuries, and costs related to vehicle damage and travel delay. As part of the calculation of comprehensive crash costs, medically related, emergency services, property damage, lost productivity, and monetized quality-adjusted life years (QALY) costs were included (*26*). Cost estimates were provided as a function of geometry, area (urban/rural), and severity. Based on the needs of safety analysis and available data at the time, six different costs levels were defined (*26*). Council et al. (*26*) attempted to estimate the standard error of each average cost; however, the variance of some costs such as medical, property damage, emergency service, travel delay, or insurance administration were not available. Thus, standard errors were obtained from the variance in crash costs caused by differences in the number of people involved in crashes of the same type, the severity of injuries suffered, and the age and sex of the victims (*26*).

For this roundabout ramp terminal safety evaluation, assumed crash costs from Council et al. (*26*) were from Level 5, for each KABCO crash severity, with and without speed limit categorization, and without regard to crash geometry. Assumed crash costs were in 2001 dollars. Thus, crash costs were adjusted to 2019 dollars for this study using the consumer price index (CPI) (all urban consumers, all items, annual average index, unadjusted) to update economic costs and the median usual weekly earnings (MUWE) (current dollar usual weekly earnings of wage and salary workers, total, 16 years and older, not seasonally adjusted) to update QALY costs (*27*). Crash costs and adjustment measures used are presented in Table 4.

Although the procedure to update crash cost estimates was intended for five years or until the next update of crash cost data and methods, the update procedure has been used beyond the intended time period which introduces some uncertainty in updated crash cost estimates. The procedure assumes that crash costs only change as a result of economic performance which may not reflect the effect of changes in crash reporting, crash data management, hospital records linkage, vehicle safety technologies, and road design over time. Despite advancements in crash and hospital data availability and the development of more rigorous statistical methods in safety analysis, there has not been an update of crash cost estimates with national level data and crash cost estimates published in 2005 which continue to be updated or used as reference despite the limitations of the procedure. Estimating crash cost is not a simple task and requires a significant amount of data, resources, and effort that state or local agencies may not be able to accurately and regularly develop on their own.

Cost of Implementation

Many factors influence the amount of economic investment justified for the implementation of a roadway facility such as roundabouts. Benefits may include crash cost savings, reduced delay, stops, fuel consumption, and emissions (*3*). At a roundabout, vehicles must yield at entry, but are not required to stop if it is clear, which eliminates some stop-and-go traffic associated with stop or traffic signal-controlled ramp terminals. Following that reasoning, roundabouts are expected to reduce emissions and fuel consumption in comparison to stop or signal-controlled intersections.

Roundabouts were found to significantly reduced fuel consumption by 5.6% to 19.4% and reduce CO_2 emissions by 5.5% to 19.5% (*28*). Similarly, Mandavilli et al. (*29*) found that roundabouts reduced control delay, queue, and proportion of vehicle stops in comparison to signal-controlled intersections. Reductions of CO_2 emissions were between 16.0% and 59.0%. Other gas emissions were also evaluated, and similar percent reductions were observed. Ahn et al. (*30*) concluded that with increased traffic volume, roundabouts were less effective in reducing overall delay and signal-controlled intersections were a better alternative. Similarly, Hallmark et al. (*31*) suggested that air quality benefits are much more complex to quantify since there are several factors to be considered and each location has particular traits. Most of these studies include limited data.

Estimating the economic benefit of roundabouts in relation to operational and environmental benefits is a complex task that is highly dependent on site-specific conditions, assumptions made, and methodological approach that goes beyond the scope of this study. Therefore, in this paper, the benefits account for crash costs savings only. Cost of implementation refers to all costs associated with the implementation of a roundabout to replace an existing ramp terminal including design, land acquisition, construction, and maintenance costs. Cost of implementation estimates in this paper are provided by type of diamond ramp terminal replaced (stop or signal-controlled), total entering traffic range, benefit–cost ratios greater than 1 at five-,10-, and 20-year service life cycles.

Results

As part of the safety analysis, CMFs were developed, crash types weighted distribution were provided, and the crash rates illustrate the differences among exit and crossroad approaches by bypass configuration. The crash cost analysis provides measures of change in crash cost before and after implementation (cost modification factors) and the estimated cost of implementation. Statistical significance was evaluated at the 0.05 significance level.

Safety Effectiveness Results

Results in Table 3 show that roundabouts replacing stop-controlled ramp terminals (STOP to RAB) reduced FI crashes by 64.9%, PDO crashes by 32.9%, and TOT crashes by 39.6% (all statistically significant).

In the case of roundabouts replacing signal-controlled ramp terminals (SIGNAL to RAB), there was a statistically significant reduction of 40.6% in FI crashes, a not statistically significant increase of 13.7% in PDO crashes, and a not statistically significant decrease of 4.6% in TOT crashes.

An aggregated SE evaluation of all roundabouts replacing all ramp terminal types (ALL to RAB) showed a reduction of 47.2% in FI crashes (statistically significant), a reduction of 5.8% in PDO crashes (not statistically significant), and a reduction of 17.8% in TOT crashes (statistically significant).

The SE results showed that roundabouts replacing stop-controlled ramp terminals were very effective at reducing crashes for all severities. On the other hand, roundabouts replacing signal-controlled ramp terminals were effective at reducing FI crashes and had a slight, although not statistically significant, increase in PDO crashes. These differences are also related to the measures of exposure since locations with stop-controlled ramp terminals had a total entering traffic between 4,983 vpd and 21,150 vpd compared with signal-controlled ramp terminals with total entering traffic between 9,686 vpd and 38,500 vpd. Similarly, roundabouts with single or dual lanes on the circulatory roadway mostly replaced stop-controlled ramp terminals, and roundabouts with multilane and spiral designs were mainly observed replacing signal-controlled ramp terminals. There were some roundabout ramp terminals with statistically significant increase in crashes which were reviewed in more detail.

A significant increase in crashes was observed at sites 15 and 16 (both at the I-435/87th St. interchange in Kansas City, MO), so each individual crash report was carefully reviewed, and operational data were collected during an evening peak period. The majority of crashes were rear-end crashes at the exit ramp and the outside crossroad approach (categories 6 and 8, Figure 1) and angle crashes at outside crossroad approach and circulatory roadway (category 3, Figure 1). Results of field data collection showed that 533 vehicles (3.5% were trucks) made left turns from the inside crossroad toward the entrance ramp in one hour (81.5% of traffic from

Table 3. Safety Effectiveness Results

			OBS			EXP			Safety effectiveness (p-value)[a]		
Location/ramp terminal			FI	PDO	TOT	FI	PDO	TOT	FI	PDO	TOT
1	I-44/RT-E, Rolla, MO	N	3	12	15	3	14	17	21.9% (0.681)	21.5% (0.485)	18.8% (0.489)
2	I-44/Kingshighway St., Rolla, MO	N	1	9	10	3	10	13	71.5% (0.021)	14.1% (0.703)	25.1% (0.386)
3	I-44/Kingshighway St., Rolla, MO	S	4	12	16	6	27	33	34.3% (0.365)	57.1% (<0.001)	52.0% (<0.001)
4	MO-9/Briarcliff, Kansas City, MO	N	2	9	11	1	5	6	−105.6% (0.586)	−68.3% (0.399)	−86.7% (0.257)
5	I-41/CTH-G, DePere, WI	E	4	7	11	4	12	16	23.4% (0.641)	46.2% (0.070)	36.8% (0.131)
6	USH-45/STH-60, Jackson, WI	E	NA	11	11	4	20	24	NA	47.8% (0.015)	56.7% (<0.001)
7	USH-45/STH-60, Jackson, WI	W	2	10	12	4	25	29	58.0% (0.082)	60.7% (<0.001)	59.5% (<0.001)
8	USH-14/CTH-MM, Fitchburg, WI	S	NA	9	9	5	11	16	NA	23.3% (0.497)	46.0% (0.042)
9	USH-14/CTH-MM, Fitchburg, WI	N	NA	4	4	1	9	10	NA	57.7% (0.017)	62.0% (0.004)
10	US-63/RT-M, Ashland, MO	W	NA	2	2	0	2	2	NA	0.8% (0.991)	16.7% (0.789)
11	USH-41/CTH-M, Howard, WI	E	NA	7	7	1	7	8	NA	9.6% (0.821)	23.4% (0.505)
12	USH-41/CTH-M, Howard, WI	W	NA	9	9	2	5	7	NA	−45.6% (0.547)	−12.4% (0.815)
13	USH-51/CTH-K, Wausau, WI	E	NA	6	6	6	11	17	NA	46.2% (0.054)	65.2% (<0.001)
14	USH-51/CTH-K, Wausau, WI	W	NA	5	5	4	9	13	NA	44.1% (0.110)	60.5% (0.001)
STOP to RAB[7]			**16**	**112**	**128**	**44**	**167**	**211**	**64.9% (<0.001)**	**32.9% (<0.001)**	**39.6% (<0.001)**
15	I-435/87th St., Kansas City, MO	E	14	54	68	14	31	45	3.3% (0.922)	−69.5% (0.078)	−49.3% (0.085)
16	I-435/87th St., Kansas City, MO	W	19	50	69	9	32	41	−109.2% (0.105)	−53.1% (0.146)	−68.0% (0.036)
17	I-41/STH-54, Green Bay, WI	E	6	15	21	18	30	48	66.9% (<0.001)	50.9% (<0.001)	56.1% (<0.001)
18	I-41/STH-54, Green Bay, WI	W	12	18	30	30	33	63	61.2% (<0.001)	47.1% (0.002)	53.1% (<0.001)
19	I-41/STH-21, Oshkosh, WI	E	4	30	34	13	26	39	70.9% (<0.001)	−13.1% (0.661)	12.6% (0.422)
20	I-41/STH-21, Oshkosh, WI	W	6	12	18	14	37	51	58.0% (0.003)	68.1% (<0.001)	64.9% (<0.001)
21	MO-100/MO-109, Wildwood, MO	N	NA	9	9	2	10	12	NA	12.1% (0.710)	27.6% (0.293)
22	USH-10/STH-47, Appleton, WI	S	3	29	32	6	6	12	53.8% (0.059)	−332.3% (0.015)	−147.3% (0.022)
23	USH-10/STH-47, Appleton, WI	N	6	21	27	5	9	14	−5.8% (0.904)	−112.9% (0.081)	−78.2% (0.062)
24	I-41/USH-141, Howard, WI	E	NA	5	5	3	8	11	NA	39.5% (0.174)	54.0% (0.014)
25	I-41/USH-141, Howard, WI	W	NA	16	16	4	6	10	NA	−158.6% (0.049)	−63.7% (0.171)
SIGNAL to RAB[7]			**70**	**259**	**329**	**118**	**228**	**346**	**40.6% (<0.001)**	**−13.7% (0.171)**	**4.6% (0.493)**
ALL to RAB[7]			**86**	**371**	**457**	**162**	**395**	**557**	**47.2% (<0.001)**	**5.8% (0.376)**	**17.8% (<0.001)**

Note: Bold indicates aggregated estimates. OBS = observed crashes; EXP = expected crashes; FI = fatal and injury crashes; PDO = property damage only crashes; TOT = total crashes; RAB = roundabout ramp terminal; STOP = stop-controlled ramp terminal; SIGNAL = signal-controlled ramp terminal; ALL = all ramp terminals; NA = not available.

[a] Negative values represent increase in crashes and positive values represent decrease in crashes.

approach). From all vehicles at the entrance ramp, 83.2% came from the inside crossroad approach. Also, 151 vehicles (8.3% were trucks) coming from the exit ramp made a left turn toward the inside crossroad in an hour (85.6% of exit ramp traffic). Exit ramp average approaching speed at the gore was 52 mph and at 300 ft from the yield line marking was 38 mph.

Similarly, ramp terminals 20 and 22 located at USH-10/STH-47 interchange in Appleton, WI, showed significant increase in crashes. A detailed review of crash reports showed that crashes were mainly associated with exit, outside crossroad approaches, and trucks. For instance, the ramp terminal south of the freeway had between three and five crashes for categories 1 to 5 (Figure 1) over a period of three years. The ramp terminal north of the freeway showed 10 rear-end crashes at the outside crossroad approach (category 5) and seven sideswipe crashes (category 2) over a three-year period.

Thus, predominant traffic conditions with left-turn movement from the inside crossroad approach and exit ramps in addition to a high rate of speed from the exit ramp may result in an increase of rear-end crashes, sideswipe, and angle crashes at exit ramps and outside crossroad approaches.

Crash Type Distribution Results

A weighted crash type distribution was conducted for roundabout ramp terminals. Results of the analysis are provided in Figure 1 and Table 2 for FI, PDO, and TOT crashes. The most common TOT crashes observed at roundabout ramp terminals were angle crashes at the exit ramp and circulatory roadway (19.5%), sideswipe departing circulatory roadway (14.4%), angle crash at crossroad and circulatory roadway (12.6%), truck sideswipe (10.7%), and rear-end outside crossroad (10.0%). Also, vehicle and truck loss of control accounted for 15.9% of TOT crashes. It is worth mentioning that pedestrian or cyclist crashes at the exit or entrance ramps were 10.5% of FI crashes (2.9% of TOT crashes) and there were a couple of wrong-way crashes (0.1% of TOT crashes).

Crash Rate Results

Crash rate analysis focused on evaluating exit ramps, outside crossroads, and bypass configurations. Crash rates were obtained by approach and the average crash rate by configuration was computed to visualize any trends. Figures 2 and 3 illustrate the impact of a right-turn bypass on crash rates for exit ramps and outside crossroad approaches, respectively.

Results of the crash rate analysis showed that exit ramps had a higher crash rate compared with outside crossroad approaches. For both approach types, configurations with no right-turn bypass had the highest crash rates. Approaches with free flow bypass had the lowest crash rate of all configurations. The effect of right-turn bypass on exit ramps is much higher than on crossroad approaches. The average crash rate for an exit ramp with no bypass is 1.02 crashes per million entering vehicles (MEV) which reduces to 0.12 crashes per MEV with the presence of a free flow bypass.

For crash types, associated with exit ramps, the rear-end crash rate was significantly higher than the rest of the crash types when there was no right-turn bypass (Figure 2*b*). For outside crossroad approaches, with free flow bypass, crash rates for angle, rear-end, and loss of control crashes were the lowest compared with the other configurations (Figure 3*b*).

Crash Cost Change

The change in crash costs as a result of the implementation of roundabouts replacing diamond ramp terminals was estimated. Crash costs by severity, coefficients to update crash costs, and results of the crash cost analysis are provided in Table 4.

Results are provided by ramp terminal type replaced and severities of FI, PDO, and TOT. Crash cost analysis showed that roundabouts replacing stop-controlled ramp terminals (STOP to RAB) yielded a TOT crash cost difference of $6,199,378 from all sites, which resulted in 68.9% decrease in all crash costs—translated into crash cost savings of $94,517 per site per year. For roundabouts replacing signal-controlled ramp terminals (SIGNAL to RAB), there was a TOT crash cost difference of $11,427,773 from all sites which resulted in a reduction of crash costs of 53.9%—crash cost savings of $252,547 per site per year. Similar to the SE results for roundabouts replacing signal-controlled ramp terminals, the crash cost increased for PDO crashes by 14.1% (statistically significant), which results in crash cost losses of $7,498 per site per year. However, FI crash costs savings significantly offset any PDO crash cost losses, and the TOT overall crash cost clearly reflects the massive crash cost benefit at these sites. The results of the crash cost analysis provide the benefit of roundabout ramp terminals in crash costs (in 2019 dollars), which can be used to estimate the cost of implementation of roundabouts to accomplish benefit-cost ratios higher than one based on operational features and service life cycles.

Cost of Implementation Estimates

As discussed in the methodology section, the benefits considered in this paper only account for crash cost savings. Since there is evidence of operational and

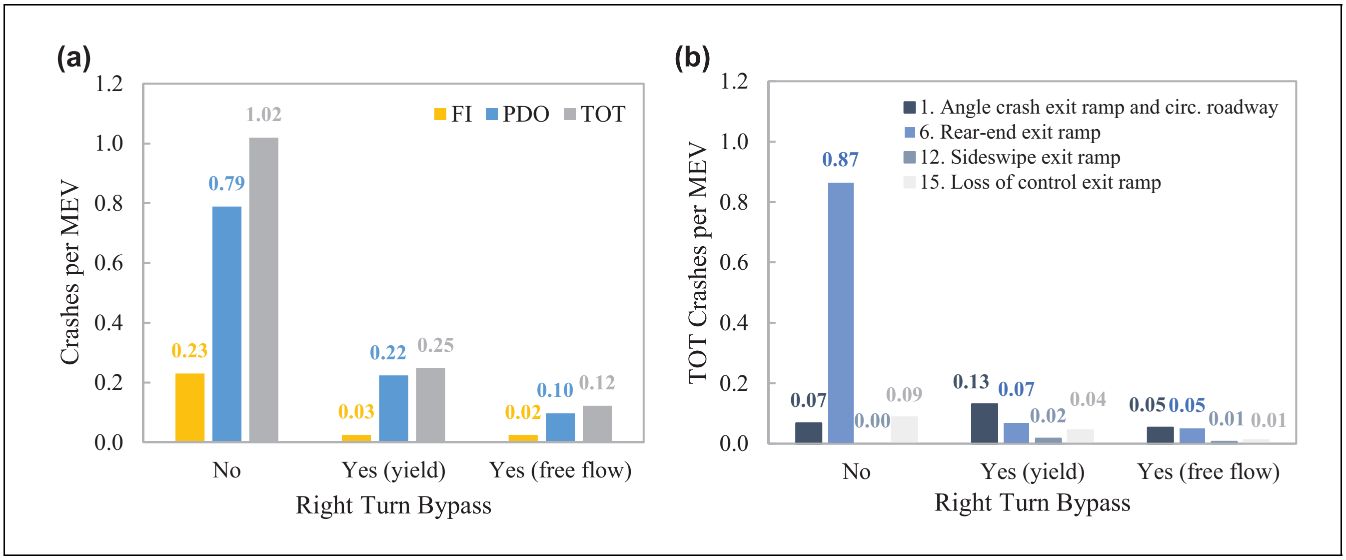

Figure 2. Exit ramp: (*a*) crash rate by severity; and (*b*) total crash rate by crash type.
Note: FI = fatal and injury crashes; PDO = property damage only crashes; TOT = total crashes; MEV = million entering vehicles. 2*b* crash types are illustrated in Figure 1.

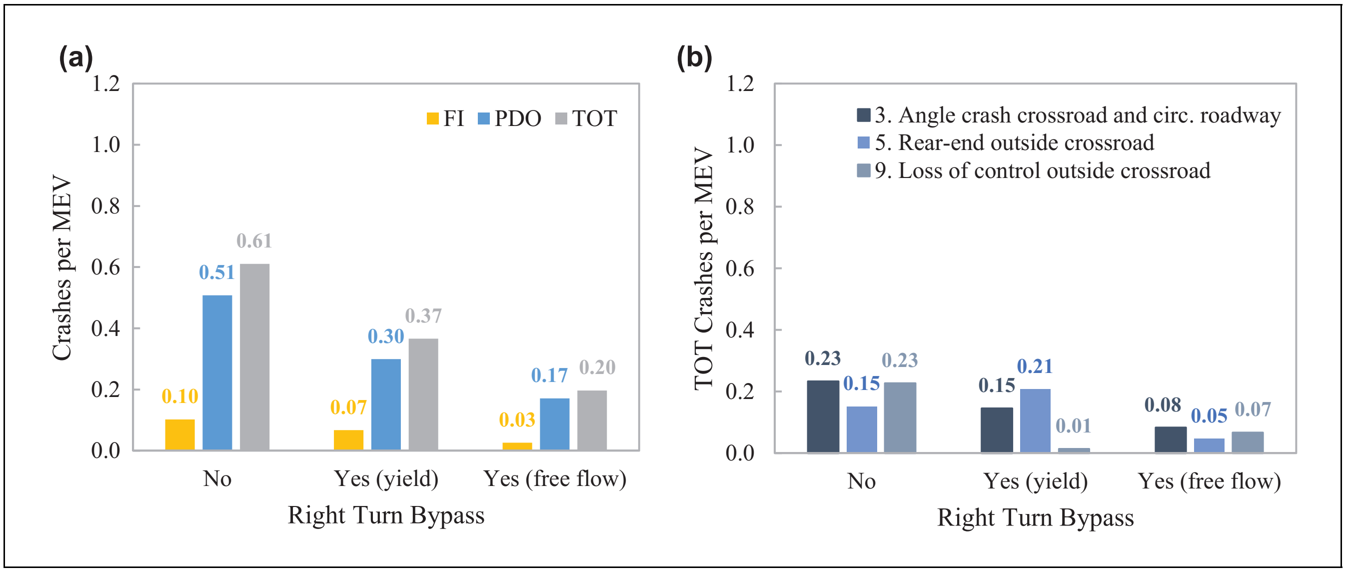

Figure 3. Outside crossroad: (*a*) crash rate by severity; and (*b*) total crash rate by crash type.
Note: FI = fatal and injury crashes; PDO = property damage only crashes; TOT = total crashes; MEV = million entering vehicles. 3*b* crash types are illustrated in Figure 1.

environmental benefits of roundabouts, costs of implementation provided in this paper reflect a lower bound estimate which is only expected to increase if operational and environmental benefits are included. Costs of implementation were estimated based on the ramp terminal type replaced, service life cycle, and benefit–cost ratios (B/C) greater than one.

Results for roundabouts replacing stop-controlled ramp terminals (STOP to RAB) and total entering traffic between 5,000 vpd to 20,000 vpd are presented in Figure 4*a*. These results indicate that the cost of implementation of roundabouts under the specified operational conditions should be less than $1.9 million per ramp terminal to accomplish benefit–cost ratios greater than one for a service life cycle of 20 years.

Results for roundabouts replacing signal-controlled ramp terminals (SIGNAL to RAB) and total entering traffic between 20,000 vpd and 40,000 vpd are presented

Table 4. Crash Cost Analysis Results

Description	2001	2019	Ratio	Severity	Crash cost$_{2001}$[a]	Standard error$_{2001}$[a]	Crash cost$_{2019}$[b]	Standard error$_{2019}$[b]
CPI (*32*)	177.10	249.22	1.41	K	$4,008,885	$45,148	$5,977,138	$55,570
MUWE (*33*)	592.00	905.00	1.53	A	$216,059	$16,506	$316,763	$20,164
				B	$79,777	$8,636	$116,869	$10,590
				C	$44,868	$4,254	$65,140	$5,144
				O	$7,428	$548	$10,579	$663

Description		FI	PDO	TOT
STOP to RAB	Crash cost with previous design	$7,238,820	$1,756,669	$8,995,488
	Crash cost with roundabouts	$1,611,255	$1,184,855	$2,796,110
	Crash cost difference (ϕ_{cost}, all sites)	$5,627,565 (<0.001)	$571,813 (<0.001)	$6,199,378 (<0.001)
	Crash cost difference (ϕ_{cost}, site/yr)	$85,799 (<0.001)	$8,718 (<0.001)	$94,517 (<0.001)
	Crash cost modification factor (θ_{cost})	0.223 (<0.001)	0.674 (<0.001)	0.311 (<0.001)
	Change in crash cost (1–θ_{cost}, %)	**77.7%**	**32.6%**	**68.9%**
SIGNAL to RAB	Crash cost with previous design	$18,802,828	$2,400,676	$21,203,504
	Crash cost with roundabouts	$7,035,753	$2,739,977	$9,775,731
	Crash cost difference (ϕ_{cost}, all sites)	$11,767,075 (<0.001)	fdeminus;339,302 (<0.001)	$11,427,773 (<0.001)
	Crash cost difference (ϕ_{cost}, site/yr)	$260,046 (<0.001)	fdeminus;7,498 (<0.001)	$252,547 (<0.001)
	Crash cost modification factor (θ_{cost})	0.374 (<0.001)	1.141 (<0.001)	0.461 (<0.001)
	Change in crash cost (1–θ_{cost}, %)	**62.6%**	**–14.1%**	**53.9%**
ALL to RAB	Crash cost with previous design	$26,041,648	$4,157,345	$30,198,992
	Crash cost with roundabouts	$8,647,008	$3,924,833	$12,571,841
	Crash cost difference (ϕ_{cost}, all sites)	$17,394,640 (<0.001)	$232,512 (<0.001)	$17,627,152 (<0.001)
	Crash cost difference (ϕ_{cost}, site/yr)	$156,935 (<0.001)	$2,098 (0.228)	$159,032 (<0.001)
	Crash cost modification factor (θ_{cost})	0.332 (<0.001)	0.944 (0.202)	0.416 (<0.001)
	Change in crash cost (1–θ_{cost}, %)	**66.8%**	**5.6%**	**58.4%**

Note: Bold indicates aggregated estimates. Crash cost analysis results are in 2019 US$ dollars. CPI = consumer price index; MUWE = median usual weekly earnings; RAB = roundabout ramp terminal; STOP = stop-controlled ramp terminal; SIGNAL = signal-controlled ramp terminal; ALL = all ramp terminals; yr = years; FI = fatal and injury crashes; PDO = property damage only crashes.

[a] Mean comprehensive cost per crash in 2001 US$ dollars, Level 5: For each level of crash severity (with and without speed limit categorization), Table 13, page 58 (*26*).

[b] Mean comprehensive cost per crash updated to 2019 US$ dollars (*26, 27*).

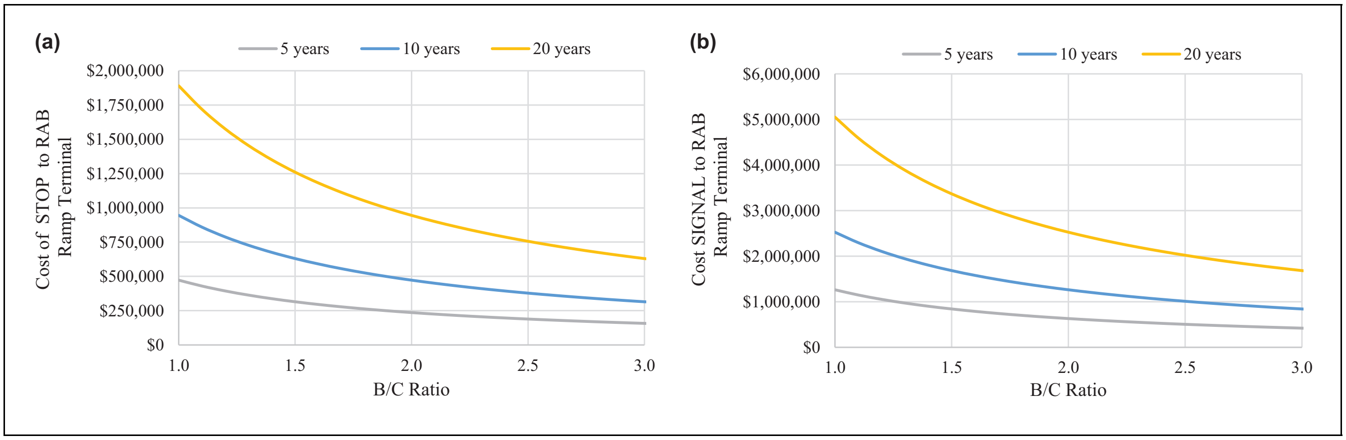

Figure 4. Cost of implementation of roundabout ramp terminals as a function of benefit–cost ratio (B/C) and service life periods: (*a*) total entering traffic between 5,000 vpd and 20,000 vpd; and (*b*) total entering traffic between 20,000 vpd and 40,000 vpd.
Note: RAB = roundabout ramp terminal; STOP = stop-controlled ramp terminal; SIGNAL = signal-controlled ramp terminal; total entering traffic = ramp terminal crossroad and exit ramp traffic; vpd = vehicles per day. Costs in 2019 US dollars.

in Figure 4*b*. Results for these conditions indicate that the cost of implementation of roundabouts should be less than $5.1 million per ramp terminal to accomplish benefit–cost ratios greater than one for a service life cycle of 20 years. Costs are in 2019 dollars.

Summary of Findings

Safety effects and crash cost changes associated with roundabouts replacing existing diamond interchange ramp terminal configurations were evaluated. A total of 25 locations in Missouri and Wisconsin were used in the analysis.

The SE results showed that roundabouts replacing stop-controlled ramp terminals were very effective at reducing crashes (statistically significant) for all severities (reduced 64.9% of FI, 32.9% PDO, and 39.6% of TOT crashes). On the other hand, roundabouts replacing signal-controlled ramp terminals were effective at reducing FI crashes (40.6% FI crash reduction, statistically significant) and had a slight increase in PDO crashes (increased 13.7% of PDO crashes, not statistically significant) which resulted in 4.6% reduction of TOT crashes (not statistically significant). Even though the SE results provide a measure of the safety effect of the treatment, it does not fully capture the overall benefit since crashes are evaluated as crash counts.

The crash cost analysis showed that roundabouts replacing stop-controlled ramp terminals yielded crash cost savings of $95,000 per site per year (69.0% decrease in crash costs). For roundabouts replacing signal-controlled ramp terminals, there were crash cost savings of $253,000 per site per year (54.0% decrease in crash costs). Similar to the SE results for roundabout replacing signal-controlled ramp terminals, the crash cost increased for PDO crashes by 14.0% (statistically significant) which resulted in PDO crash cost losses of $7,500 per site per year. However, FI crash cost savings significantly offset any PDO crash cost losses, resulting in massive crash cost benefit at these sites. Accounting for safety benefits only, to accomplish benefit–cost ratios greater than one for a service life cycle of 20 years, the cost of implementation should be less than $1.9 million for roundabouts replacing stop-controlled ramp terminals (STOP to RAB, 5,000–20,000 entering vpd) and $5.1 million for roundabouts replacing signal-controlled ramp terminals (SIGNAL to RAB, 20,000–40,000 entering vpd) per ramp terminal. Costs are in 2019 dollars. These cost thresholds are conservative because the thresholds will increase if operational and environmental benefits were to be included.

The most common crashes observed at roundabout ramp terminals were angle crashes at the exit ramp and circulatory roadway (19.5%), sideswipe departing circulatory roadway (14.4%), angle crash at crossroad and circulatory roadway (12.6%), truck sideswipe (10.7%), and rear-end outside crossroad (10.0%). Also, vehicle and truck loss of control accounted for 15.9% of TOT crashes. There were also pedestrian or cyclist crashes at the exit or entrance ramps (10.5% of FI, 2.9% of TOT crashes) and a couple of wrong-way crashes (0.1% of TOT crashes).

Exit ramps had a higher crash rate compared with outside crossroad approaches. Configurations with no right-turn bypass had the highest crash rates. Approaches with bypass and yield conditions had lower crash rates than without a bypass. Approaches with free flow bypasses had the lowest crash rate of all configurations. Rear-end crash rates at exit ramps without bypasses were overwhelmingly higher than the rest of the crash types.

Conclusions and Recommendations

The results of this study provide strong evidence of the positive safety benefits of roundabout ramp terminal implementations in Missouri and Wisconsin. Roundabout ramp terminals were very effective at reducing crashes, especially FI crashes. Designs with a right-turn bypass provide lower crash rates at exit and outside crossroad approaches. Predominant traffic conditions with left-turn movements from the inside crossroad approach and exit ramps, in addition to high rates of speed on exit ramps may result in an increase of rear-end (*34*), sideswipe, and angle crashes at exit ramps and outside crossroad approaches. This research considered only crash cost benefits in computing the roundabout installation cost thresholds. Future studies should also consider operational and environmental benefits. Additionally, crash costs were assumed to change over time only as a result of economic performance which may not reflect the effect of other related factors such as changes in crash reporting, crash data management, hospital records linkage, vehicle safety technologies, and road design.

Ramp terminal configuration selection should be made on a site-by-site basis considering operational and safety measures. Operational measures may be addressed with the use of microsimulation of several geometric and traffic scenarios. Safety measures obtained with rigorous crash prediction models and statistical methods such as the Empirical Bayes should be considered. Practitioners can use crash and crash cost CMFs, the crash type diagram, bypass crash rate trends, and the threshold of cost of implementation provided in this study for design considerations and assess safety effects and economic value of proposed roundabout implementations.

Acknowledgments

The authors are thankful for the assistance provided by Myrna Tucker and Darrell Knierim from the Missouri Department of Transportation for providing crash reports. We would also like to thank the Wisconsin Department of Transportation for providing access to the roundabout, traffic, and crash data in Wisconsin. The authors would like to acknowledge the support of Profs. Praveen Edara and Carlos Sun from the University of Missouri, Columbia with data collection in Missouri. We would like to acknowledge the assistance of Jacob Berry from Olsson Associates with data collection from Missouri.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Boris Claros, Madhav Chitturi; data collection: Boris Claros, Beau Burdett; analysis and interpretation of results: Boris Claros, Madhav Chitturi, Andrea Bill, David A. Noyce; draft manuscript preparation: Boris Claros, Madhav Chitturi, Andrea Bill, David A. Noyce. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

1. Gross, F., C. Lyon, B. Persaud, and R. Srinivasan. Safety Effectiveness of Converting Signalized Intersections to Roundabouts. *Accident Analysis & Prevention*, Vol. 50, 2013, pp. 234–241.
2. Persaud, B. N., R. A. Retting, P. E. Garder, and D. Lord. Safety Effect of Roundabout Conversions in the United States: Empirical Bayes Observational Before-After Study. *Transportation Research Record: Journal of the Transportation Research Board*, 2001. 1751: 1–8.
3. Rodegerdts, L. A. *Roundabouts: An Informational Guide*. Transportation Research Board, Washington, D.C., 2010.
4. All about Roundabout Society. Types of Roundabouts. 2020. https://nomorecorners.wordpress.com/types-of-roundabouts/. Accessed June 19, 2020.
5. Claros, B., J. Berry, C. Sun, and P. Edara. Safety Performance Analysis of Roundabout Interchanges in Missouri. Presented at 98th Annual Meeting of the Transportation Research Board, Washington, D.C., 2018.
6. Berry, J. A. *Safety Evaluation of Roundabouts at Freeway Ramp Terminals and HSM Calibration*. MS thesis. University of Missouri-Columbia, 2017.
7. Qin, X., G. Khan, A. Bill, and D. A. Noyce. Comprehensive Safety Evaluation of Roundabouts in Wisconsin. *Journal of Transportation Safety & Security*, Vol. 3, No. 4, 2011, pp. 289–303.
8. Qin, X., A. Bill, M. Chitturi, and D. A. Noyce. Evaluation of Roundabout Safety. Presented at 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2013.
9. Claros, B., P. Edara, and C. Sun. When Driving on the Left Side Is Safe: Safety of the Diverging Diamond Interchange Ramp Terminals. *Accident Analysis & Prevention*, Vol. 100, 2017, pp. 133–142.
10. Bared, J. G., P. K. Edara, and R. Jagannathan. Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange. *Transportation Research Record: Journal of the Transportation Research Board*, 2005. 1912: 31–38.
11. Edara, P. K., J. G. Bared, and R. Jagannathan. Diverging Diamond Interchange and Double Crossover Intersection–Vehicle and Pedestrian Performance. *Proc., 3rd International Symposium on Highway Geometric Design*, Chicago, IL, 2005.
12. Chlewicki, G. Learning from Eight Operational Diverging Diamond Interchanges in the United States. Presented at 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2013.

13. Uddin, W. *Performance Evaluation of Roundabouts for Traffic Delay and Crash Reductions in Oxford, MS*. Report No. MO-DOT-RD-11-213. Mississippi Department of Transportation, 2011.
14. American Association of State Highway and Transportation Officials. *Highway Safety Manual (HSM) with Supplement*. AASHTO, Washington, D.C., 2014.
15. Ferguson, E., J. Bonneson, L. Rodegerdts, N. Foster, B. Persaud, C. Lyon, and D. Rhoades. *NCHRP Research Report 888: Development of Roundabout Crash Prediction Models and Methods*. Transportation Research Board of the National Academies, Washington, D.C., 2018.
16. Li, Z., M. V. Chitturi, A. R. Bill, and D. A. Noyce. Operational Evaluation of Two-Lane Roundabouts at Freeway Ramp Terminals: Comparison between Roundabout and Signalized Interchanges. *Transportation Research Record: Journal of the Transportation Research Board*, 2017. 2637: 99–113.
17. Wisconsin Department of Transportation. *Wisconsin Roundabouts - Existing and Proposed*. Google Maps, 2018. https://www.google.com/maps/d/viewer?mid = 1kRgB04jjoXd6tLLe0r20FJoxJMI&ll = 46.43665050559848%2C-90.48454165934518&z = 7. Accessed June 12, 2020.
18. Wisconsin Department of Transportation. TCMap - Traffic Count Map [Mapping Application]. 2020. https://wisdot.maps.arcgis.com/apps/webappviewer/index.html?id = 2e12a4f051de4ea9bc865ec6393731f8. Accessed June 12, 2020.
19. Wisconsin Traffic Operations and Safety (TOPS) Laboratory. The WisTransPortal Data Hub [Information System]. 2020. http://transportal.cee.wisc.edu/. Accessed June 12, 2020.
20. Hauer, E. *Observational Before-After Studies in Road Safety: Estimating the Effects of Highway and Traffic Engineering Measures on Road Safety*. Emerald Group Publishing Limited, Bingley, 1997.
21. Sun, C., P. Edara, H. Brown, C. Nemmers, B. Claros, and A. Khezerzadeh. *Highway Safety Manual Applied in Missouri - Freeway/Software*. Report No. 25-1121-0003-279. Missouri Department of Transportation, Jefferson City, 2016.
22. MSA Professional Services, Persaud, and Lyon. *Highway Safety Manual Intersection Calibration Factors and Safety Performance Function Development*. Project ID 0072-40-56. Wisconsin Department of Transportation, Madison, 2019.
23. Federal Highway Administration. Roadway Safety Information Analysis. https://safety.fhwa.dot.gov/local_rural/training/fhwasa1210/s3.cfm. Accessed June 13, 2020.
24. Council, F. M., B. Persaud, C. Lyon, K. Eccles, M. Griffith, E. Zaloshnja, and T. Miller. Implementing Red Light Camera Programs: Guidance from Economic Analysis of Safety Benefits. *Transportation Research Record: Journal of the Transportation Research Board*, 2005. 1922: 38–43.
25. Council, F. M., B. N. Persaud, K. A. Eccles, C. Lyon, and M. S. Griffith. *Safety Evaluation of Red-Light Cameras*. Report No. FHWA-HRT-05-048. Federal Highway Administration, McLean, VA, 2005.
26. Council, F. M., E. Zaloshnja, T. Miller, and B. N. Persaud. *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometrics*. Report No. FHWA-HRT-05-051. Turner-Fairbank Highway Research Center, McLean, VA, 2005.
27. Harmon, T., G. B. Bahar, and F. B. Gross. *Crash Costs for Highway Safety Analysis*. Report No. FHWA-SA-17-071. Federal Highway Administration, Washington, D.C., 2018.
28. Ariniello, A., and B. Przybyl. Roundabouts and Sustainable Design. In *Proc., Green Streets and Highways 2010: An Interactive Conference on the State of the Art and How to Achieve Sustainable Outcomes* (N. Weinstein, ed.), Denver, CO, November 14–17, 2010, American Society of Civil Engineers, Reston, VA, pp. 82–93.
29. Mandavilli, S., M. J. Rys, and E. R. Russell. Environmental Impact of Modern Roundabouts. *International Journal of Industrial Ergonomics*, Vol. 38, No. 2, 2008, pp. 135–142.
30. Ahn, K., N. Kronprasert, and H. Rakha. Energy and Environmental Assessment of High-Speed Roundabouts. *Transportation Research Record: Journal of the Transportation Research Board*, 2009. 2123: 54–65.
31. Hallmark, S. L., B. Wang, A. Mudgal, and H. Isebrands. On-Road Evaluation of Emission Impacts of Roundabouts. *Transportation Research Record: Journal of the Transportation Research Board*, 2011. 2265: 226–233.
32. United States Bureau of Labor Statistics. Consumer Price Index Historical Table for the United States. 2020. https://www.bls.gov/regions/midwest/data/consumerpriceindexhistorical_us_table.pdf. Accessed June 14, 2020.
33. United States Bureau of Labor Statistics. Usual Weekly Earnings of Wage and Salary Workers Archived News Releases. 2020. https://www.bls.gov/bls/news-release/wkyeng.htm. Accessed June 14, 2020.
34. Burdett, B., I. Alsghan, L. H. Chiu, A. R. Bill, and D. A. Noyce. Analysis of Rear-End Collisions at Roundabout Approaches. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2585: 29–38.