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Inconsistent Results of Roundabout Implementation: A Case Study in Louisiana, USA

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Abstract

Because of its historically good performance in many European countries, roundabout has been promoted in the United States since 1990's. Generally roundabout provides an opportunity to improve traffic flow efficiency and reduce traffic conflicts when designed and located appropriately. Louisiana currently has 25 roundabouts in operation and more than couple of hundreds of roundabouts in design and planning stage. Although the advantages of roundabout have been documented in the U.S., the safety benefits may vary significantly due to uniqueness of each location's conditions and detailed design selections.

A study conducted in Louisiana has revealed some interesting results on the safety benefits of roundabout applications from 15 locations. Minimum six years of crash information for each location were used in the analyses including not only the crash database, but also the original crash reports. Through reading the original crash reports, the research team obtained many interesting information from the narratives and collision diagram of original crash report, which proved to be very beneficial in identifying design issues and human factors relating to crash occurrences and consequences (severity).

The combined analysis (before-and-after and reviewing crash report) generally demonstrated that the level of success of a roundabout depends on the design details and local driving behavior. With inconsistent results in changes of total crashes before and after roundabout implementation, the analyses show that all roundabout intersections experienced a reduction in severe crashes, but increase in single-vehicle running-off-roadway crashes. The changes in total crashes varied by type of previous traffic control and design details. The significant increase of non-collision crashes (single vehicle crashes) at all roundabout intersections during the first three years of operation may result from unfamiliarity with roundabout operation, distracted drivers, large vehicles with difficulties negotiating curvature and application policy, i.e., lack of intersection lighting at rural areas. By and large, it is clear that the safety effectiveness of roundabout varied with location and design details. In order to optimize roundabout benefit at a particular location, designers must pay close attention to location geometric layout, surrounding environment, and land use. Failure to recognize the unique characteristics at each individual location may lead to unintended results.

Keywords: Roundabout; Louisiana; Intersection; Safety Benefit; Crash Modification Factor.

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1. Introduction

Since the first roundabout was introduced to Lafayette, Louisiana eighteen years ago, the traveling public has gradually fallen in love with this type of intersection. There are, currently, more than 25 roundabouts in operation statewide and hundreds of roundabouts are in the planning and designing stage. The benefits of a roundabout are twofold: improving traffic flow efficiency and reducing crashes, particularly injury and fatal crashes. Properly designed, a roundabout can guide all vehicles operating at a lower speed while negotiating the circle for the intended exit approach. By giving more maneuvering freedom to drivers, i.e., letting drivers decide when to enter an intersection, the human factor plays a bigger role in roundabout operation than in other types of intersection traffic control. Considering the state's goals for "Destination Zero Deaths" and with more roundabouts proposed for state and local roadways in the future, it is important for the state to evaluate the roundabout operation experience and its impact on roadway safety.

2. Literature Review

The safety performance of roundabout in the U.S and elsewhere in the world has been well documented in Bonneson et al (2010). One of the notable studies comes from Rodegerdts et al (2007), which analyzed 310 roundabout performance based on the data from previous research conducted between 1997 and 2007 with roundabouts from a variety of settings including: 6% in rural areas and 94% in urban and suburban areas, 9% signalized intersections, 51% one-way or two-way stop intersection, 10% all-way stop intersections and a remaining 30% being newly constructed roundabout intersections. The same study selected 55 roundabouts that had complete design and AADT information as well as a sufficient number of pre- and post-construction crash data (pre- 3.7 years and post- 3.4 years). The total number of crashes from all 55 roundabouts decreased 37% (from 1,159 to 726). This included a reduction of 59% in fatal crashes and a 76% reduction in injury crashes. As the study revealed**,** the crash reductions represented a difference among the intersections with different traffic control types before. By utilizing the Empirical Bayes (EB) before-after analysis method, the study shows the expected reductions in total crash and injury crash to be 45% and 76%, respectively, for signalized intersections, and a 44.2% and 81.8% reduction, respectively, for stop-on-minor street intersections. For the all-way stop sign intersections, the total and injury crashes increased 3.3% and 28%, respectively. The first edition of the Highway Safety manual (HSM) uses the results of this NCHRP study to list the roundabout CMF as 0.56 for total crashes and 0.18 for injury and fatal crashes for a roundabout with the two-way stop sign control before. For signalized intersections, the CMF from the HSM is 0.52 for total crashes and 0.22 for injury and fatal crashes. For all-way stop intersections, the CMF from HSM is 1.03 for total crashes.

Because of the variances in design, the local safety culture and road user behavior, not all roundabout studies yield similar results. The Wisconsin roundabout studies by Qin et al (2011) and Qin et al (2010) indicated that even though roundabouts significantly reduced the severity of crashes from more than 50 selected roundabouts as the studies found a 38% reduction in injury and fatal crashes, the changes in Property Damage Only (PDO) crashes varied by location and there was an overall crash increase of 12%. The intersections with stop signs on minor streets had the largest reductions in total and injury crashes after converting to a roundabout. At the signalized and all-way stop intersections, the injury crashes dropped 59% and 51%, and the total crashes rose 5.5% and 23.5%, respectively.

Two follow-up Wisconsin studies investigated the roundabout impact on the type of crash. The study published in 2016 by Burdett et al examined the manner of collisions at roundabouts and non-roundabout intersections in Wisconsin with a focus on the rear-end collision (according to Burdett et al (2016)) and single-vehicle crashes (according to Burdett et al (2017)). The rear-end collisions and single-vehicle crashes are the two most common types of crashes associated with the roundabout. They represent 20% and 29% of the total crashes at a roundabout respectively. While rear-end collision is common in all types of intersections, single vehicle crash is only common in the roundabout. The results from the Burdett's study indicate that younger drivers, between 16 to 24 years old, have a 50% higher probability to be involved in rear-end and single-vehicle crashes in roundabout than mid-aged and aged drivers do. Additionally, the research concludes that the proper pavement marking on the approaching lane might significantly reduce the number of rear-end collisions, and the landscaped central island has a positive impact on reducing single vehicle crashes and severity.

The above reference review shows a big variation in roundabout safety effectiveness. One study indicates that the previous traffic control makes the difference, while others mainly looked at type of crashes and crash severity. Previous studies that present the detailed characteristics and safety performance of individual roundabouts have not been identified. Roundabouts are recognized as a complex intersection design, requiring special expertise in design and a knowledge of operation. Very few of the previous studies mentioned design factors in the performance evaluation. Considering Louisiana's roadway safety objectives and needs, the evaluation of roundabout safety issues for future roundabout development is apparent.

3. Data Analysis

To minimize the effect of regression-to-the-mean, 19 roundabouts that have been in operation for at least three years by 2016 were selected for the analysis. All selected roundabouts are one-lane roundabouts except one that has mixed lane configuration (50% one-lane and 50% 2-lane). All roundabouts are located in urban and suburban areas based on the data provided by the Louisiana Department of Transportation and Development, and all roundabouts meet the requirements in signs, pavement markings, and inscribed circle radius. To accurately analyse intersection crashes, the study did not just rely on the information from the crash database in the crash location settings (coded 1 for intersection and 0 for non-intersection). For each intersection, all crashes within 500 feet radius were examined through reviewing the crash narratives from the original crash reports to see if they were intersection related or not. The radius for analysis even went to 3,000 feet for one intersection that has the highest AADT and is well known for its server peak-hour traffic congestion. Going through the painstaking process made it possible to identify more intersection-related crashes and to correct several crash coding errors in the review of more than 1,000 individual crash reports. The original crash reports were a great source of information, which provided the additional information on what and how the crash happened as well as the driver (or road user) and environmental conditions occurring before, during and after a crash. The basic information and the observed crashes for the 19 selected intersections before and after a roundabout project are listed in Table 1.

Table 1. Observed Crashes by Severity Before and After Roundabout.

Intersection	Project Year	Average AADT (Vehicles per Day)		Fatal Crashes		Injury Crashes		PDO Crashes	
				Before	After	Before	After	Before	After
1	2011	14,800	21,300	1	0	18	12	13	55
2	2007	23,400	25,267	0	0	3	3	11	6
3	2012	29,800	29,700	0	0	8	2	12	25
4	2012	18,367	17,733	0	0	8	1	18	8
5	2013	24,833	18,300	0	0	2	0	8	6
6	2013	11,617	12,100	0	0	9	3	26	7
7	2013	6,133	6,000	0	0	24	4	19	0
8	2011	9,433	9,500	0	0	3	2	7	6
9	2012	18,300	22,833	0	0	1	0	5	8
10	2012	13,000	13,500	0	1	0	1	0	3
11	2007	6,555	6,997	0	0	0	0	0	3
12	2011	6,897	7,900	0	0	1	0	2	0
13	2008	10,702	11,469	0	0	0	3	1	16
14	2013	800	800	0	0	2	1	0	1
15	2011	40,533	35,033	0	0	8	8	26	29
16	2011	22,400	23,767	0	1	5	3	13	10
17	2011	7,277	7,277	0	0	3	0	3	8
18	2010	8,333	9,300	1	0	3	2	4	21
19	2010	20,833	22,500	0	0	1	2	1	0
Overall				2	2	99	47	169	212

The intersections' traffic control methods varied before converting to a roundabout and the majority of these intersections (16 out of 19) had an AADT less than 25,000 and three of them had an AADT bigger than 25,000. Based on the FHWA design guideline by Rodegerdts et al (2010), one-lane roundabout is suitable for an AADT less than 25,000 and two-lanes are acceptable for an AADT between 25,000 and 45,000.

As shown in Table 1, there is a 53% reduction in injury crashes and a 25% increase in the PDO crashes at aggregated level. However, there are evidently big variations among individual intersections, particularly by traffic control type before. In general, the safety benefit of a roundabout comes from the reduced operating speed, the changed traffic control method for the conflicting flow and reduced number of conflicting points compared to the prior type of traffic control methods. Intersections with stop-sign on the minor street experienced the biggest reduction in number of conflicting points. Signalized and all-way stop intersections handle the conflicting points by signals and rules of the right-of-way (ROW). After converting to a roundabout, drivers have the freedom to decide when to enter an intersection. More freedom comes with more responsibility. Table 2 lists the changes in crash severity by four groups categorized by the type of traffic control and Table 3 shows the changes by the type of crash and group. The angle-crash in Table 3 includes: right-angle crash, right-turn crash and sideswipe crash.

Table 2. Changes in Crashes by Group.

Previous Traffic Control	Fatal Crash		Injury Crash			PDO Crash			Overall
(number of intersections in each group)	Before	After	Before	After	Change	Before	After	Change	Change
Signalized (3)	1	0	29	17	-41%	36	86	+139%	+56%
Stop Sign on Minor Road without Layout Change (5)	0	0	46	10	-78%	78	27	-65%	-70%
Stop Sign on Minor Road with Layout Change (6)	0	1	4	5	+25%	8	31	+287%	+208%
All Way Stop (5)	1	1	20	15	-25%	47	68	+45%	+24%

Table 3. Changes in Crashes by Crash Type and Group.

Previous Traffic Control	Angle-Crash [1]			Rear-End			Single-Vehicle		
	Before	After	Change	Before	After	Change	Before	After	Change
Signalized (Group 1)	35	72	+106%	24	16	-33%	7	15	+114%
Stop Sign on Minor Road without Layout Change (Group 2)	83	11	-87%	29	16	-45%	12	10	-17%
Stop Sign on Minor Road with Layout Change (Group 3)	6	11	83%	2	12	+500%	4	12	+200%
All Way Stop (Group 4)	25	18	-28%	31	39	+26%	10	27	+170%
Overall	149	112	-25%	86	83	-3%	33	64	+94%

1 Left turn, right angle, and right turn crash

The initial results show a large crash increase in Groups 1, 3 and 4, which somewhat indicates not all drivers could handle the freedom properly (brought by the roundabout) in intersections previously controlled by signals and stop-signs. The poor performance of group 3 may also be explained by increased number of conflicting points, which will be discussed later. In summary, the above crash characteristics analysis basically reveals the followings:

- Roundabouts reduced the injury crashes significantly because of the elimination of left-turn and head-on collisions and reduced right-angle, right-turn and sideswipe collisions (Table 1 and 3);
- Single vehicle running off roadway crashes increased significantly in the three underperforming groups (Table 3);
- The prior traffic control makes a big difference in crash change by severity and type (Table 2);
- Roundabouts produced the biggest safety benefit in every aspect for intersections with stop sign on minor roadways without layout change (Table 2 and 3).

Two questions arose from the initial findings: Does the prior traffic control alone impact the roundabout safety performance? Should the state DOTD (the Department of Transportation and Development) reconsider converting a signalized or an all-way stop-sign controlled intersection to a roundabout only for safety improvement? Considering the inconsistent results within the same traffic control group, an in-depth investigation on each intersection was conducted to explore other potential compounding factors, producing more interesting and even intriguing site-specific observations.

4. In-Depth Investigation

One intersection from each of the three groups that had the largest crash increase in both the absolute numbers and percentage was selected for discussion in this paper. For the group 4 (all-way stop control before), the focus was on single-vehicle crashes. According to Table 3, single-vehicle running off roadway (ROR) crashes increased the most in this group, and Table 4 shows this type of crashes mainly occurred at night.

Table 4. Changes in Crashes by Crash Type and Group.

Roundabout Group	Daylight			Dark			Traffic Light Installed
	Before	After	Change	Before	After	Change	(Yes / No)
Group 1	42	81	+93%	24	22	-8%	All Yes
Group 2	90	23	-74%	34	14	-59%	3 Yes; 2 No
Group 3	9	16	+78%	3	21	+600%	3 Yes; 3 No
Group 4	48	44	-8%	20	40	+100%	All No
Overall	189	164	-13%	81	97	+20%	9 Yes; 10 No

Clearly, there is a problem at night for the ROR crashes for the roundabouts in Groups 3 and 4. All five roundabouts in the group 4 have no intersection lighting. Intersection 18 is a typical roundabout converted from the all-way stop control with the AADT less than 10,000. The number of crashes at this roundabout increased 188% while the traffic volume only increased by 12%, and ROR crashes increased from zero to nine in the first three years, and eight including one fatal motorcycle crash between the 4th and the 6th year in operation. It was found that all 17 (nine plus eight in the six after-roundabout years) ROR crashes occurred at night, which is very telling for a poor visibility problem. It is possible that before roundabout, very few careless or aggressive drivers did not stop at night when passing through the intersection but that bad behavior did not result in collisions due to the low traffic volume. The roundabout somewhat has punished the bad driving behavior at this intersection and sufficient lighting could most likely help those drivers to avoid ROR crashes. Based on the Louisiana intersection design policy, intersection lighting is not mandatory. From the analysis, it is clear that lighting would provide greater visibility for motorists, thus reducing, if not totally eliminating, the number of ROR crashes at night.

The intersection from the signalized group that experienced the highest crash increase —from 32 to 67 — is shown in Fig. 1 (see next page). This intersection was changed from a three-approach to a four-approach intersection because of a new supermarket at the west-north corner. Several elements in this roundabout violate the common roundabout design guidelines. First, it has the mixed number of lanes, (between one and two lanes), which causes confusion even with the pavement marking showing that the inner lane is for through and left-turn vehicles. Entering the roundabout from the left, highlighted in red, left-turn vehicles must make a quick and correct decision to swiftly move to the inner lane in a very short distance. There is no directional or lane designation sign on this approach. Additionally, as shown in Fig. 1, there are severe sight distance problems for entering vehicle from the north and south approaches. The angle between the exiting and entering vehicles makes the maneuver extremely challenging, particularly for the entering vehicles on the right lane. This explains why there were so many Failed to Yield citations (increased from 16 to 45 after roundabout installing) issued at these entrances. The FHWA roundabout design guidelines by Rodegerdts et al (2010) specifically say, "*Yield lines should be located along the inscribed circle at all roundabouts except mini-roundabouts*".

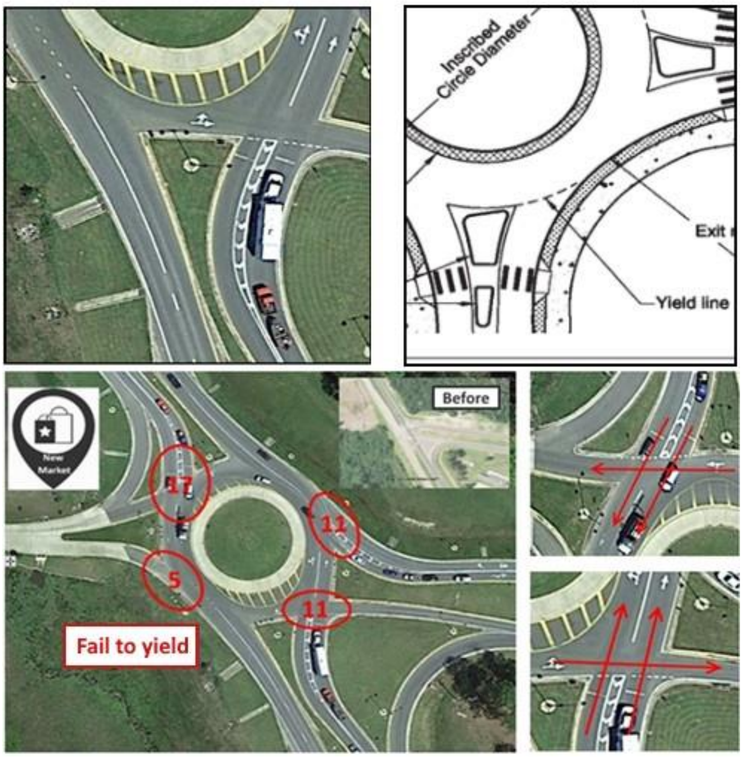

Fig. 1 The substandard entrance layout design and number of fail-to-yield citations issued at entrances of Intersection 1.

The intersection 13 experienced the largest crash increase in Group 3 (stop on minor road with the number of approaches increasing from three to four). The land use surrounding all six intersections in this group has changed particularly at Intersection 13, which was the reason to increase number of approaches from three to four with the roundabout. The southbound extension of the minor roadway made the intersection an important gateway to a rapidly growing community at the time of roundabout construction that is now a vibrant small town. After the roundabout construction, this minor road also becomes a major connector linking the newly developed township (beyond the scope of picture showing in Fig. 2) to a major metropolitan arteria highway. The crashes increase from one to 19 in the first three years of roundabout operation while the official AADT only increase 15%. The total number of crashes increases from 19 to 21 between the first and second three years of roundabout operation but injury crashes reduced from three to one in the same time periods. The most alarming fact is the night-time crashes kept increasing between the first and second three years of roundabout operating. This roundabout has no street light. It is clear that the changes in land use and road functionality are mainly responsible for the crash increase.

Fig. 2 Land use development around Intersection 13 before and after the roundabout.

Table 5 lists all potential compounding factors at each intersection where the problems were identified by the study.

Table 5. Summary of Potential Compounding Factors.

Roundabout	Change in Total Crashes	Potential Compounding Factors for Changes
Group 1: Signalized		
1	+35	Design elements (as discussed in this paper)
3	+7	It should be a two-lane roundabout with higher than 25,000 AADT. Design alignment (intersecting angle) is not desirable
Group 2: Stop Sign on Minor Road without Layout Change		
7	-39	Merging two-lanes in each direction into one-lane road before the roundabout serves very well for this roundabout
Group 3: Stop Sign on Minor Road with Layout Change		
9	+2	One street connection within 150 feet
10	+5	The problem was corrected by adding an exclusive right-turn lane to a new shopping center with the proper signage and pavement markings in May 2017 (after more than 3 years of roundabout operation)
11	+3	Inside a new subdivision with substandard sign and pavement marking
12	-3	With excellent lighting (inside a Casino area)
13	+18	Huge land use change (as discussed in the paper)
Group 4: All Way Stop		
15	+3	Due to the ROW limit, this roundabout is limited to a one-lane with AADT higher than 35,000, three driveways within 150 feet including a car dealer right by the circle.
18	+15	Lack of lighting (as discussed in the paper)

5. CMF Development

To develop the CMF, the well-accepted EB method was used. This method can precisely describe the safety change between the before and after periods by considering the regression-to-the-mean effect while normalizing changes in AADT, type of traffic control, number of approach lanes and different area setting (2, 8-11). In this study, the CMF for the group 2 roundabouts (converted from stop-sign on a minor road before without a layout change) was derived.

In accounting for regression-to-the-mean effect, $N_{expected,\ before}$ is the weighted average from two crash numbers:

$$N_{expected,\ before} = w_i \times N_{predicted,\ before} + (1 - w_i) \times N_{observed,\ before} \quad (1)$$

$N_{expected,\ before}$ = Number of crashes expected at an intersection before conversion to roundabout;
$N_{predicted,\ before}$ = Predicted number of crashes calculated from the intersection with similar characteristics;
$N_{observed,\ before}$ = Observed number of crashes at an intersection before conversion to roundabout;
w_i= weighted adjustment to be placed on the predictive model estimate for each intersection.

The safety performance function (SPF) for the stop on minor road intersections was applied to estimate the weights (w) and the number of crashes expected at an intersection ($N_{expected,\ before}$). The SPF is a statistical model that predicts the mean crash frequency for similar locations with the same characteristics, which include traffic volume, traffic control type, geometric design etc. The weighted adjustment parameter can be derived from the following equation:

$$w = \frac{1}{1 + N_{predicted} \times k} \quad (2)$$

Where,
w = Weighted adjustment to be placed on the predictive model estimate;
k = Over dispersion parameter of the associated SPF (from *HSM table 12-10* and *table 12-12*).

It is noted that with the increment of the over dispersion parameter, the weighted adjustment factor decreases; thus, more emphasis is placed on the observed crashes rather than the SPF predicted crash frequency. The adjusted value of the EB $N_{expected,\ after}$, and its variance is calculated by the following equations:

$$N_{expected,\ after} = N_{expected,\ before} \times \frac{N_{predicted,\ after}}{N_{predicted,\ before}} \quad (3)$$

$$Var(N_{expected,\ after}) = N_{expected,\ after} \times \frac{N_{predicted,\ after}}{N_{predicted,\ before}} \times (1-w) \quad (4)$$

$N_{expected,\ after}$ = Expected number of crashes would have occurred without roundabout in the after years.

The CMF and its variance can be calculated from the following equation:

$$CMF = \frac{\frac{N_{observed,\ after}}{N_{expected,\ after}}}{1 + \frac{Var(N_{expected,\ after})}{(N_{expected,\ after})^2}} \quad (5)$$

$$Var(CMF) = (CMF)^2 \frac{\frac{1}{N_{observed,\ after}} + \frac{Var(N_{expected,\ after})}{(N_{expected,\ after})^2}}{\left[1 + \frac{Var(N_{expected,\ after})}{(N_{expected\ ,after})^2}\right]^2} \quad (6)$$

Where,
$N_{observed,\ after}$ = Observed number of crashes that occurred at the converted roundabout in the after years.

Table 6 enlists the value of CMF, standard deviations, and 95% confidence interval (CI) of the CMF for five roundabouts using this EB method. The CMF values range from 0.21 to 0.83. The 95% values are lower than 1 in most cases except in roundabout 5. The CMF for a stop on minor road intersection converted to a roundabout without layout change is 0.28, which indicates an expected 72% reduction of total crashes after conversion.

Table 6. CMF and the Variance of CMF.

Roundabout	CMF	Var(CMF)	S.D. (CMF)	95% of CMF
4	0.39	0.021	0.144	(0.10, 0.68)
5	0.83	0.147	0.384	(0.06, 1.59)
6	0.20	0.005	0.069	(0.06, 0.34)
7	0.21	0.011	0.105	(0, 0.41)
8	0.23	0.009	0.096	(0, 0.52)
Overall	0.28	0.0029	0.054	(0.12, 0.45)

6. Benefit Cost Analysis

The design-construction costs of a roundabout vary between $555,000 and $1,2000,000 based on the data available by the LaDOTD, and other local government agencies. The benefit is calculated by the crashes reduced during the first three years in operation using the latest Louisiana data by injury severity. The benefit-cost ratio for Group 2 (stop-sign on the minor street before) is 0.91 in three years without considering benefit from the reduced travel delay. The actual ratio would be much bigger than one in a longer term.

7. Conclusions

This study confirms that the roundabout is a proven intersection type that can reduce injury and fatal crashes. This is due to the reduced angle-collisions and eliminations of head-on and left-turn crashes. As revealed in the investigation, the roundabout is a complex intersection type. The improvement in safety for a roundabout depends on the previous traffic control type as well as other design specifics. The biggest safety benefit for a roundabout occurs at intersections with two-way stop-sign control (without the layout change) due to the reduced number of conflicting points and the similar degree of maneuvering freedom. Table 7 lists the changes in the number of conflicting points and their control mechanism at each intersection before and after the roundabout conversion.

Table 7. CMF and the Variance of CMF.

Roundabout	Before					After				
	# conflicting points				Controlled by	# conflicting points				Controlled by
	D[1]	M[2]	C[3]	T[4]		D	M	C	T	
1	3	3	3	9	Traffic signal with LT phase	7	10	4	21	Yield sign at entrance with conflicting crossing points
2	8	8	16	32		4	4	0	8	Yield sign control at entrance
3	8	8	16	32		7	8	0	15	
4, 5, 6 (T-intersection before and cross after)	3	3	3	9	Stop sign on minor road	3	3	0	6	
7, 8 (cross intersection before and after)	8	8	16	32		4	4	0	8	
9, 10, 11, 12, 13, 14 (T-intersection before and cross after)	3	3	3	9		4	4	0	8	
15, 16, 17, 18	8	8	16	32	All-way stop	4	4	0	8	
19 (T-intersection before and after)	3	3	3	9		3	3	0	6	

1 Diverging, 2 Merging, 3 Crossing, 4 Total

All intersections had a reduction in the number of conflicting points except Intersection 1. The results in Table 7 explains why intersection 1, with a traffic signal to separate all conflicting flows before, experienced more than a 50% crash increase. This is attributed to the increased number of conflicting points currently controlled by yield signs. Roundabouts should eliminate all crossing conflicting points, but the design of Intersection 1 did not - as illustrated in Fig. 3. The intersections with the same initial traffic control (stop sign on a minor road) but with a changed layout (three approaches before and four after roundabout conversions) did not gain the same safety benefit because of the smaller reduction in conflicting points. For the all-way stop-sign controlled intersection, the freedom to maneuver seems to challenge a very small percentage of drivers.

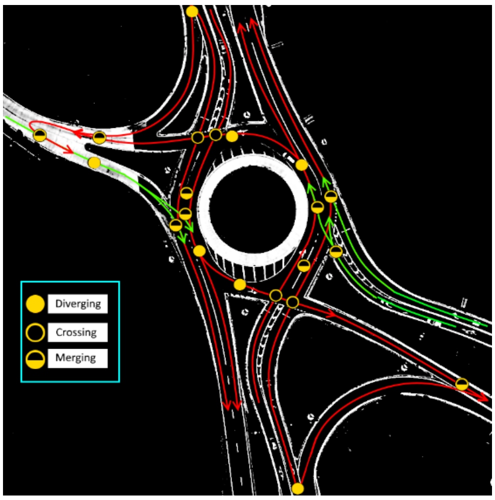

Fig. 3 Illustration of conflicting points at Roundabout 1.

Although the results showed no reductions in the total number of crashes at the aggregate level for Groups 1, 3, and 4, the in-depth analysis at the individual roundabout shows the promise for a better performance with these roundabouts. The features specific to each individual roundabout determines its safety performance. The detailed geometric design is more critical to the roundabout than to the non-roundabout intersections. It is possible for a roundabout to reduce not only injury crashes but also total crashes at intersections originally controlled by traffic signal or by all-way stop-signs if the roundabout is properly designed with adequate lighting. It is important to recognize that the key difference between a roundabout and the other two control methods (signalized or all-way stop-sign) are drivers' freedom in deciding when to enter the intersection. This requires more consideration to the human factors in the design of the roundabout.

To investigate if the time length of roundabout operation has any impact on the intersection safety performance, this study also analyzed the crashes for roundabout being in operation for six years. Table 8 shows the changes in the AADT and crashes at 11 intersections that had crash increase in the first three years of the roundabout operation. The results indicate that while the fatal and injury crashes continuously decreased, the total crashes still show an increase trend. For the three intersections with six years of roundabout operation in Group 2, there is either no change or a crash reduction.

Table 8. Changes in AADT and crash count between before and after roundabout in two post-construction periods.

Element	% Changes between Before and After Three Years	% Changes between Before and the Post Three to Six Year Time Period
AADT	4.70%	+8%
Total Crashes	+71%	+88%
Fatal Crashes	-50%	-50%
Injury Crashes	-21%	-37%
PDO Crashes	+133%	+171%
Single-Vehicle	+229%	+186%
Rear-End	+28%	+21%
Angle	+71%	+138%
Day time	+58%	+75%
Night time	+103%	+157%

Only the CMF for the Group 2 intersections was developed in this study because other groups did not show a crash reduction at the aggregate level, and had variations within the group due to the difference in design and operating conditions among the roundabouts in the same group. Thus, it is important or maybe even critical to conduct an in-depth analysis at the disaggregate level when developing the CMF for a complex crash countermeasure like roundabout to avoid the potential risk of deriving a CMF that does not reflect the situation accurately.

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