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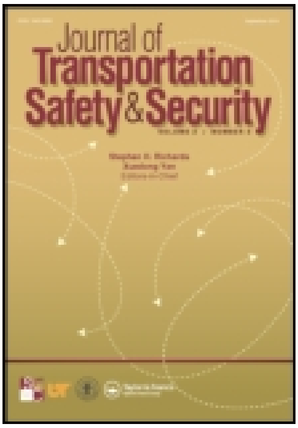

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This article provides a safety analysis on Wisconsin roundabouts using crash records and field video data. Crash records at 41 roundabouts were retrieved from an online database, and field video data were collected at two multilane roundabouts. The percentages of each of the seven identified crash types is estimated by averaging the crash type percentage of all 41 roundabouts. It is found that the most common crash type at single-lane roundabouts is entering-circulating crashes, whereas sideswipe crashes have a higher percentage at multilane roundabouts than at single-lane roundabouts. To examine the relationship between driver behavior and crash patterns at multilane roundabouts, field video data from two multilane roundabouts were used to quantify 12 types of undesired negotiation activities. The ratio of the number of undesired negotiations to the traffic count is defined as the exposure rate (to conflicts). The exposure rate can be utilized to estimate the crash type percentage. Although the chi-squared statistical test did not support the hypothesis of same crash type distribution between the expected crashes and actual ones, the exposure rates successfully identified the entering-circulating and sideswipe (in circulating lanes) crashes as the two major crash types.

Keywords roundabouts, crash type distribution, exposure rate to conflicts, undesired negotiation

1. Introduction

A modern roundabout is a new type of intersection designed to reduce crash risk and lower crash severity. The “drive-around” mode, also used by other circular intersections, is applied at roundabouts to eliminate all crossing vehicular conflicts. Additionally, approaches to a roundabout are deflected to a certain degree to reduce approaching speed and facilitate weaving and merging maneuvers between entering and circulating vehicles, avoiding direct collisions. Further, with the yield-to-circulating rule at a roundabout entrance, roundabouts aim to create an altogether safer driving experience when compared to conventional intersections.

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Despite the advantages in the roundabout geometric design, crashes still occur. Data collection for this study identified 358 roundabout crashes between 2001 and 2008 in the State of Wisconsin, at a rate of 45 crashes per year. The roundabout design simplifies complicated interactions between vehicle movements by defining all vehicle paths into three stages: entering, circulating, and exiting. Such simplification limits crashes to certain types with some being more common than the others. Roundabout crash patterns have been thoroughly studied in previous research. However, a literature review suggests that the previous crash type percentages were calculated in a problematic way. This study presented an improved calculation of crash type percentages and reevaluated crash patterns of single-lane roundabouts and multilane roundabouts. Moreover, this study proposed a proactive safety performance measurement based on vehicle negotiations. The relationship between the proposed measurement and actual crashes was validated with the chi-squared test.

2. Literature Review

Early roundabout crash patterns were extensively studied in Europe and Australia. In the 1980s, researchers studied crashes at 84 four-leg roundabouts in the United Kingdom (Maycock & Hall, 1984). Entering-circulating crashes were found to be most prevalent (71.1%) among all types of crashes for "small" roundabouts, that is, roundabouts with a central island no smaller than 13 feet (3.96 meters) in diameter and a large ratio of inscribed circle diameter to center island diameter. For conventional roundabouts, that is, those having a larger diameter than "small" roundabouts, entering-circulating crashes, approaching crashes (within approaches only), and single-vehicle crashes were found to be the three main crash types, proportioned as 20.3%, 25.3%, and 30.0%, respectively. A later study based on 492 crashes at 100 roundabouts in Queensland, Australia, found that 50.8% of crashes were entering-circulating, whereas 18.3% were rear-end (in entrances and circulating roadways, hereafter if not specified) and 18.3% were single vehicle crashes (Arndt & Troutbeck, 1998). Further evidence of major crash types was given in an Italian study (Montella, 2007). The researcher summarized 22 frequent crash types based on the 2003 to 2005 crash data at 15 roundabouts in Italy. Angle-at-entry (entering-circulating/exiting) crashes presented the highest portion of all crashes (27.6%), followed by rear-end-at-entry crashes (14.6%) and each of the rest crash types (no more than 6%). Roundabouts started relatively late in the United States, and most studies were more recent. A study in Maryland classified 283 crashes at 38 roundabouts into eight distinct types including an "other" type (Mandavilli et al., 2009). Run-off-road, rear-end (at entry), entering-circulating, and sideswipe (in circulation) were found to be the four major crash types. A nationwide study conducted at 39 U.S. roundabouts by the Federal Highway Administration (FHWA) reported four major roundabout crash types as entering-circulating (23%), exiting-circulating (31%), rear-end on leg (31%), and loss of control on leg (13%) (Rodegerdts et al., 2010). A major limitation shared by all the above studies is the use of simple aggregation when calculating the crash type percentage. More specifically, when calculating the percentage of a certain crash type, crash count of that type aggregated across all sample roundabouts was divided by the total numbers of crashes at these roundabouts. If the analysis views the sampling area as a unit, such aggregation might be acceptable because individual roundabout characteristics are not of interest. However, if the analysis is to investigate the crash pattern of a certain type of roundabouts, for example, single-lane roundabouts, the average crash type percentage across all sample sites is preferred.

Beyond crash data, visual field observation is an effective approach to identifying crash contributing factors. Field observations were conducted in the Maryland study, and guidance was provided for crash countermeasures (Mandavilli et al., 2009). Speeding resulted from inadequate delineation, and landscaping was observed to be a potential leading reason for crash types such as run-off-road. Field observations often served as a safety review tool when historical crash data were not available or not sufficient. With the increasing number of roundabouts, more quantitative research efforts have been dedicated to developing predictive crash regression models. Annual average daily traffic (AADT), approaching speed, sight distance, and other geometric elements were commonly used as independent variables for predicting crashes (Angelastro et al., 2012; Arndt & Troutbeck, 1998; Maycock & Hall, 1984). For instance, crash frequencies were found to increase as sight distance increases, possibly because higher speeds are encouraged by larger sight distances (Angelastro et al., 2012). Field studies and crash modeling help to gain a better understanding of the various causes of roundabout crashes.

Safety issues are generally the combined outcome of inferior roadway design and undesired driver behavior, although either can cause its own problems. Geometric improvement can only increase highway safety to a certain level as human factors eventually account for most of the crashes (Dewar & Olson, 2002). A poorly designed roundabout can operate reasonably safely when traffic flows are low, whereas a well-designed roundabout may experience safety problems when its capacity is exceeded (Lenters, 2005). How drivers cope with roundabouts and interact with each other in a roundabout offers direct answers to some of the roundabout safety questions. Among different techniques, traffic conflict study is often considered a proactive approach to identifying potential safety issues and concerns (Gettman & Head, 2003). A conflict is formally defined by FHWA as an "observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged" (Gettman & Head, 2003, p. 8). An early researcher placed conflicts between undisturbed passages and crashes in terms of vehicle interaction risk and further categorized conflicts into potential conflicts, slight conflicts, and near-crashes (Hydén, 1987). Conflict study has been used to investigate roundabout safety issues (Guido et al., 2011) and evaluate proposed changes to roundabout layouts (Al-Ghandour et al., 2011). Difficulties and debates in traffic conflict studies lie in how to accurately define a conflict. Common surrogate conflict measures include but are not limited to deceleration rate, proportion of sight distance, and time to collision (Gettman & Head, 2003). A previous study has shown that the assessment of roundabout safety was sensitive to the selected measures (Guido et al., 2011). Choosing measures, as well as corresponding thresholds, for conflict identification should be done with caution; otherwise, situations that are not conflicts could be wrongly reported (Bachmann et al., 2011).

The limitation of a traffic conflict study motivates the need for a more straightforward way to study driver behavior, but the general consensus is that higher conflict frequencies indicate lower safety levels (Gettman & Head, 2003). At roundabouts, some human factors can lead to certain unexpected vehicle movements to achieve minimal deceleration and turning effort and hence, a more comfortable driving experience. Sometimes, through drivers entering a roundabout from an outer approaching lane would cut across the inner circulating lane (which is generally prohibited) to avoid curvature. Such a relatively flat path is commonly referred to as the fastest path (Inman et al., 2003). Other than the desire for the fastest path, unfamiliarity with roundabout rules could cause erroneous maneuvers, for example, failure to yield to circulating traffic. According to FHWA, legal and illegal maneuvers can create conflicts, whereas most serious crashes are a result of violating the traffic control rules (Rodegerdts et al., 2010). Hence, the frequency of unexpected vehicle negotiations can be a good indicator of drivers' exposure to traffic conflicts or crash risk.

3. Method

To perform a crash pattern analysis, this study adopts seven out of the eight crash types from a previous study (Mandavilli et al., 2009). The seven crash types are

1. Run-off-road (or loss of control)
2. Rear-end (at entry)
3. Entering-circulating
4. Sideswipe (in circulating lanes)
5. Exiting-circulating
6. Pedestrian/bike
7. Other.

3.1. Estimate of Percentages

To construct a crash pattern, the percentage of each type of crashes needs to be calculated. The current study sampled 41 ($K = 41$) roundabouts (24 single-lane roundabouts and 17 multilane roundabouts) for crash analysis. For the kth roundabout, the following variables are defined:

$p_k^{(i)}$ = the percentage of the ith type of crash, %
n_k = the total number of crashes at this roundabout
$n_k^{(i)}$ = the number of the ith type of crash at this roundabout.

It is assumed that $p_k^{(i)}$ is a non-negative variable independent from n_k and subject to $\sum_{i=a}^{g} p_k^{(i)} = 1$. The variable $n_k^{(i)}$ is expressed in Equation 1:

$$n_k^{(i)} = \frac{p_k^{(i)} n_k}{100} \quad (1)$$

In practice, one can only directly observe $n_k^{(i)}$ and n_k. The observed $p_k^{(i)}$ can be derived from Equation 1. After the $p_k^{(i)}$ of each sample site is calculated, the percentage of the ith type of crash is estimated as the average of all $p_k^{(i)}$'s (Equation 2). It can be easily proven that $\sum_{i=a}^{g} p^{(i)} = 1$, which ensures the basic validity of the estimate.

$$p^{(i)} = \frac{\sum_{k=1}^{K} p_k^{(i)}}{K} \quad (2)$$

To illustrate the advantage of Equation 2, a previous way of estimating the percentage of the ith type of crash was expressed in Equation 3 (Arndt & Troutbeck, 1998; Mandavilli et al., 2009; Maycock & Hall, 1984; Montella, 2007; Rodegerdts et al., 2010).

$$p_{previous}^{(i)} = \frac{\sum_{k=1}^{K} n_k^{(i)}}{\sum_{k=1}^{K} n_k} \times 100 \quad (3)$$

Equation 3 introduces an inappropriate weighting effect for calculating the average percentage of a crash type: that is, roundabouts with larger numbers of total crashes are overrepresented in the result. For example, given two roundabouts A and B, A is well designed to avoid sideswipe crashes, and the crash records show two sideswipes out of 10 total crashes ($p_A^{(d)} = 20\%$); B is poorly designed and the crash records show 34 sideswipes out of 50 total crashes ($p_B^{(d)} = 68\%$). When considering the average sideswipe crash proportion of A and B, the result should reflect a tradeoff between superior and inferior designs. According to Equation 2, $p^{(d)} = 44\%$, which lies in the middle of 20% and 68%. However, the result of Equation 3 is $p^{(d)} = 60\%$, emphasizing the poor safety characteristic of roundabout B. Therefore, Equation 2 was chosen over Equation 3 in this study, unless otherwise specified.

3.2. *Estimate of Crash Frequencies*

The crash frequency of the ith type of crash at the kth roundabout is:

$$f_k^{(i)} = \frac{n_k^{(i)}}{T_k} \tag{4}$$

where,

T_k = the number of years from the completion of construction of the *kth* roundabout to the year of 2008

Further, the average crash frequency of the ith type of crash is:

$$f^{(i)} = \frac{\sum_{k=1}^{K} f_k^{(i)}}{K} \tag{5}$$

3.3. *Measure of the Exposure to Conflicts*

A conflict may or may not lead to a crash but is considered an important indicator of traffic safety (Gettman & Head, 2003). Conflicts are difficult to measure, and no consensus has been reached on what surrogate measures should be used to identify a conflict (Guido et al., 2011). In this study, rather than measuring the number of conflicts directly, a simple measure of vehicle negotiation is used to quantify the amount of exposure to conflicts.

Violating the traffic control rules is a major reason in causing conflicts or crashes (Gettman & Head, 2003). At roundabouts, "yield-to-circulating" is required whereas lane-changing in circulating roadways is discouraged. Field videos collected for this study have shown a certain amount of scenes when conflicts occurred due to drivers' violation to the above two rules. As a result, the amount of such violations, or undesired negotiations, is an indicator to the exposure to conflicts. In this study, the following undesired negotiations are defined to investigate the exposure to conflicts within a multilane roundabout quadrant (Figure 1):

1. C1→C2;
2. C1→Ex2;
3. C2→C1;
4. C2→Ex1;
5. En1→C2;

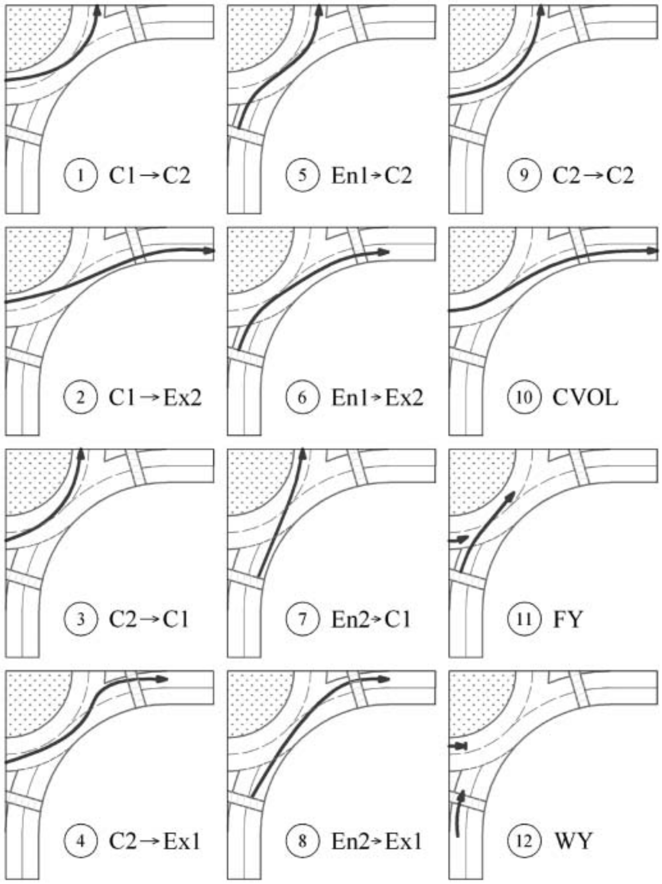

Figure 1. Undesired negotiations.

6. En1→Ex2;
7. En2→C1;
8. En2→Ex1;
9. C2→C2;
10. CVOL (Circulating vehicle on lane line): A vehicle enters the quadrant in either of the circulating lanes, travels on the lane line for a while, and exits mostly in the right exiting lane. This is similar to C1→Ex2;
11. FY: An entering vehicle fails to yield to the upcoming circulating vehicle;
12. WY: A circulating vehicle wrongly yields to the entering vehicle.

Negotiations 1 through 9 were denoted in the following way: The text on the left side of the arrow stands for the lane in which the vehicle enters the quadrant and the text on the right stands for the lane in which the vehicle exits the quadrant. C1 and C2 stand for left (inner) and right (outer) circulating lanes, respectively, En1 and En2 stand for left and right entering lanes, and Ex1 and Ex2 stand for left and right exiting lanes. C1→Ex2, for example, stands for the situation when a vehicle enters the quadrant in the inner circulating lane but exits in the outer exiting lane.

When traffic flow increases, the chance of observing undesired negotiations may increase. To standardize the measure of exposure to conflicts, the exposure rate to conflicts is proposed and formulated as

$$CER_i = \frac{CE_i}{Volume_i} \tag{6}$$

where,

CER_i = the exposure rate to conflicts of the ith type of undesired negotiation
CE_i = the count of the ith type of undesired negotiations during the given time period
$Volume_i$ = the count of vehicles that get into the quadrant from the same lane(s) where the undesired negotiations start during the given time period; for negotiations 10–12 the count includes both lanes.

With the above definition of exposure rate to conflicts (or exposure rate, for short hereafter), quantitative analyses can be attempted to interpret the crash pattern at multilane roundabouts and short-term assessments of roundabout safety performance can be conducted in a straightforward way.

3.4. Data Collection

Two sets of data are used in the study: one is crash data and the other is field counts of the undesired negotiations defined in the Method section. Crash data are categorized by crash type and roundabout type.

3.4.1. Crash Data. The crash data were retrieved from the WisTransportal online crash data system, a combination of data from Wisconsin Department of Transportation (WisDOT) and Milwaukee Traffic Operation Centers and the WisDOT MV4000 crash database. The areas searched contained all the roundabout sites constructed before 2008 in Wisconsin, with crash records dating from March 2001 to August 2008.

After the raw data were retrieved, four steps of categorization were conducted manually by reviewing the scanned police reports. First, for each of the retrieved crashes, the location was labeled as "roundabout" or "not roundabout." Second, if a crash was identified as a roundabout crash, a crash type (a–g mentioned in the Method section) was assigned to it according to the narration and drawing in the police report. Third, the roundabout crash was further labeled "single-lane" or "multilane" based on the number of circulating lanes in the roundabout. Last, depending on the relationship between the crash date and the roundabout opening year, each roundabout crash was further labeled as A, B, or M. *A* stands for a crash after the roundabout open year, *B* stands for a crash before the roundabout open year, and *M* stands for a crash which happened in the roundabout open year.

Only those crashes labeled with *A* and assigned a crash type were selected for analysis use. The total number of selected crashes was 358, with 132 crashes at 24 single-lane roundabouts and 226 crashes at 17 multilane roundabouts.

3.4.2. Video Data. The undesired negotiation data were reduced from videos collected at two 4-leg multilane roundabouts. The video recording system consisted of a video camera on a 25-foot tripod and a Miovision^{TM} unit. The system was located about 15 feet from the sidewalks at a corner between two roundabout approaches. The video camera fixed at the top of the tripod captured the whole roundabout area and stored the video in the Miovision^{TM} unit. Because the video system was located between two adjacent approaches, the view of the roundabout quadrant where the video was located was relatively larger and more focused (Figure 2), leading to a quadrant-based video review.

Figure 2. Video review system.

After obtaining the video data, a computer program (Figure 2) was used to assist human review of the videos and record the time stamps of two groups of events: (1) vehicles entering the quadrant and (2) undesired negotiations. The reviewed quadrants of the two roundabouts are illustrated in Figure 3. The selected time periods were 7:00 a.m. to 9:00 a.m. and 2:00 p.m. to 4:00 p.m. for both roundabouts. The final counts of different events are summarized in Table 1.

3.5. *Crash Pattern Analysis*

In this section, both crash type percentages and crash frequencies are estimated. They provide the insights to the roundabout crash type distributions as well as absolute amounts.

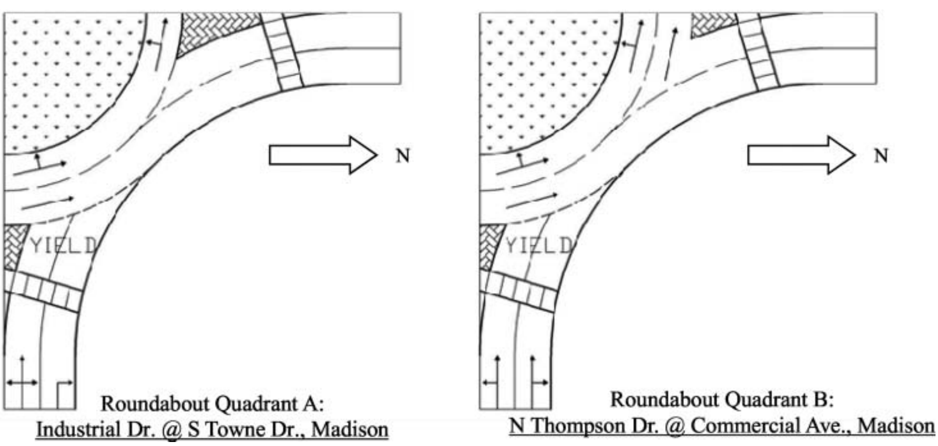

Figure 3. Channelization of reviewed roundabout quadrants.

Table 1
Conflict exposure–related event counts

	Quadrant A		Quadrant B	
	7:00 a.m.– 9:00 a.m.	2:00 p.m.– 4:00 p.m.	7:00 a.m.– 9:00 a.m.	2:00 p.m.– 4:00 p.m.
Traffic counts				
C1	354	676	642	875
C2	420	677	239	360
En1	54	147	767	466
En2	185	239	126	119
Undesired negotiations				
C1→C2	—	—	2	4
C1→Ex2	132	324	28	57
C2→C1	0	0	0	1
C2→Ex1	1	1	0	0
En1→C2	—	—	1	0
En1→Ex2	0	1	0	0
En2→C1	3	1	8	9
En2→Ex1	6	5	1	3
C2→C2	—	—	2	7
CVOL	82	53	38	23
FY	0	1	2	3
WY	0	0	1	0

Dash (—) indicates data not applicable.

3.5.1. Estimate of Crash Type Percentages. Figure 4 shows the results of crash patterns at single-lane roundabouts and at multilane roundabouts. First of all, both types of roundabouts have equivalently high percentages of run-off-road crashes and rear-end crashes, around 30% and 20%, respectively. The similarity could be explained by the fact that these two types of crashes generally happen when a vehicle approaches the roundabout, a similar maneuver regardless of the number of circulating lanes. Second, single-lane roundabouts have a significant portion of entering-circulating crashes whereas it is not the case at multilane roundabouts. A logical explanation is that for single-lane roundabouts, it is difficult for entering vehicles to determine in advance whether a circulating vehicle will exit or continue through the adjacent quadrant, resulting in a potential entering-circulating conflict. Third, multilane roundabouts have a large portion of sideswipe crashes while single-lane roundabouts have few. This is because sideswipe crashes generally happen between vehicles in adjacent circulating lanes.

3.5.2. Estimate of Crash Frequencies. Crash frequencies are estimated and shown in Figure 5 to illustrate the absolute amounts of different types of crashes. The crash frequencies of all crash types are higher at multilane roundabouts than at single-lane roundabouts. Although the percentages of run-off-road and rear-end crashes are similar between multilane roundabouts and single-lane roundabouts (Figure 4), the frequencies at multilane

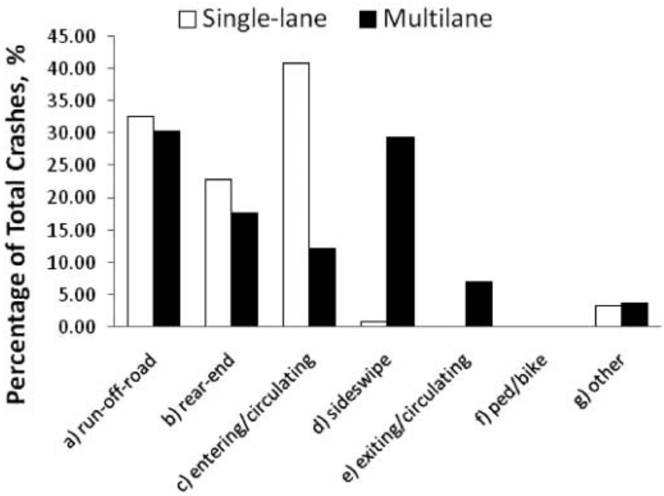

Figure 4. Crash type percentages.

roundabouts are twice of those at single-lane roundabouts. This might be a result of higher approaching traffic at multilane roundabouts.

3.6. Exposure Rate Analysis

The exposure rates to conflicts were calculated with Equation 6 and presented in Table 2. The results show that both roundabout quadrants have high exposure rates of C1→Ex2 and CVOL. C1→Ex2 was the most common undesired negotiation observed by the previous studies (Arndt & Troutbeck, 1998; Mandavilli et al., 2009). By taking C1→Ex2, a vehicle creates a possible conflict if another vehicle travels close to it from the outer circulating lane,

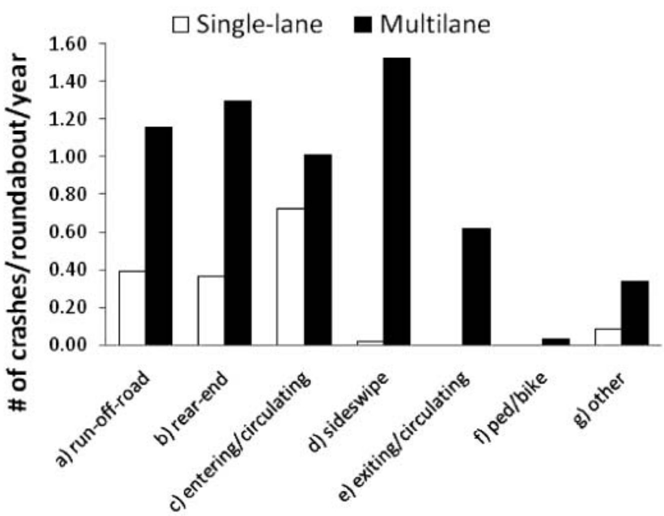

Figure 5. Crash frequencies.

Table 2
Exposure rates to conflicts

	Quadrant A				Quadrant B			
Undesired Negotiation	7:00 a.m.‖ 9:00 a.m.	2:00 p.m.‖ 4:00 p.m.	Average	Percentage (%)	7:00 a.m.‖ 9:00 a.m.	2:00 p.m.‖ 4:00 p.m.	Average	Percentage (%)
C1→C2	—	—	—	—	0.003	0.005	0.004	2.03
C1→Ex2	0.373	0.479	0.426	78.53	0.044	0.065	0.055	27.92
C2→C1	0.000	0.000	0.000	0.00	0.000	0.003	0.0015	0.76
C2→Ex1	0.002	0.001	0.0015	0.28	0.000	0.000	0.000	0.00
En1→C2	—	—	—	—	0.001	0.000	0.0005	0.25
En1→Ex2	0.000	0.007	0.0035	0.65	0.000	0.000	0.000	0.00
En2→C1	0.016	0.004	0.010	1.84	0.063	0.076	0.070	35.53
En2→Ex1	0.032	0.021	0.027	4.98	0.008	0.025	0.017	8.63
C2→C2	—	—	—	—	0.008	0.019	0.014	7.11
CVOL	0.106	0.039	0.073	13.46	0.043	0.019	0.031	15.74
FY	0.000	0.003	0.0015	0.28	0.002	0.005	0.0035	1.78
WY	0.000	0.000	0.000	0.00	0.001	0.000	0.0005	0.25

Dash (—) indicates data not applicable.

possibly resulting in a sideswipe or exiting-circulating crash. The CVOL negotiation has a similar effect as C1→Ex2. The exposure rate of En2→C1 is also high in both roundabout quadrants, being the highest in quadrant B and fourth highest in A. This is because there are two circulating lanes to exit quadrant B, and lane En2 is also used for through movements. Meanwhile, quadrant A has only one circulating lane to exit and all vehicles in lane En2 are supposed to take a right-turn. A vehicle making En2→C1 is exposed to conflicts with circulating vehicles in both lanes. En2→C1 followed by C1→Ex2 forms a through path in the roundabout, which allows the driver to avoid the small deflection radius by taking the fastest path (Arndt & Troutbeck, 1998). En2→Ex1 also shows high exposure rates in both quadrants. This type of negotiation increases the subject vehicle's interaction with the circulating lanes and hence exposes the subject vehicle to the conflict with circulating vehicles. C2→C2 only applies to quadrant B and the corresponding exposure rate is considerable. In high-traffic volume scenarios, this type of negotiation could trigger exiting-circulating conflicts or crashes, because an exiting vehicle from the inner circulating lane might not expect the vehicle in the outer lane to continue circulating.

A question is raised regarding the relationship between the exposure rates of undesired negotiations and crash patterns (distribution of crash types) at a roundabout. A chi-squared test was formulated with the null hypothesis that the observed crash pattern is identical to an expected crash pattern derived from the exposure rates of undesired negotiations. The observed crash pattern can be obtained through the actual crash type percentages. The derivation of expected crash patterns is described below.

First of all, a relation matrix was constructed (Table 3). Each row of the matrix stands for a certain crash type, whereas each column of the matrix stands for an undesired negotiation. The undesired negotiation type of "others" is used to account for all other negotiations that could possibly exist but are not defined in this study. For each cell, the value *1* means that if there are legal vehicle movements in other lanes, the undesired negotiation would result in a conflict causing the corresponding crash type; otherwise, the value is *0*. The cells under the column of "others" all have the value of 1. The authors argue that such an assumption is conservative because the "others" type may involve a wide range of possibilities.

The next step is to choose a test site. The roundabout containing quadrant A showed only one rear-end crash and two sideswipe crashes during the data collection period, which was not adequate in providing decent samples. The roundabout containing quadrant B showed a total of 50 crashes, with at least two crashes in each crash type and was chosen for the statistical analysis. Similar to the relation matrix, the effect matrix of quadrant B is illustrated in Table 4. When a cell in the relation matrix is 0, the corresponding cell in the effect matrix is 0. All cells in a same column with value 1 in the relation matrix have equal splits of the undesired negotiation's exposure rate in the effect matrix. For example, the cells corresponding to entering-circulating crashes, sideswipe crashes, and exiting-circulating crashes under C1→C2 negotiation have equal values of 0.0013 in the effect matrix, adding up to 0.004, which is the average exposure rate of C1→C2 at quadrant B. For the "others" undesired negotiations, the exposure rate needs to be assumed. Table 4 represents the case of assuming the exposure rate of "others" to be 0.197, which is the sum of the 12 defined undesired negotiations' exposure rates.

The last step of deriving the expected crash pattern is calculating the expected crash type percentages. The expected crash type percentage is the ratio of the summation of row values to the summation of all cell values in the effect matrix. For example, for exiting-circulating crashes, the expected crash type percentage is $(0.0013 + 0.00075 + 0.014 + 0.028)/0.394 = 11.22\%$.

Table 3
Relation matrix

	Undesired Negotiations												
Crash Type	C1-> C2	C1-> Ex2	C2-> C1	C2-> Ex1	En1-> C2	En1-> Ex2	En2-> C1	En2-> Ex1	C2-> C2	CVOL	FY	WY	Others
Run-off-road (or loss of control)	0	0	0	0	0	0	0	0	0	0	0	0	1
Rear-end (at entry)	0	0	0	0	0	0	0	0	0	0	0	1	1
Entering-circulating	1	1	0	0	0	0	1	1	0	1	1	0	1
Sideswipe (in circulating lanes)	1	1	1	1	1	1	1	1	0	1	0	0	1
Exiting-circulating	1	0	1	1	0	0	0	0	1	0	0	0	1
Pedestrian/bike	0	0	0	0	0	0	0	0	0	0	0	0	1
Other	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 4
An effect matrix of Quadrant B

	Undesired Negotiations												
Crash Type	C1-> C2	C1-> Ex2	C2-> C1	C2-> Ex1	En1-> C2	En1-> Ex2	En2-> C1	En2-> Ex1	C2-> C2	CVOL	FY	WY	Others
Run-off-road (or loss of control)	0	0	0	0	0	0	0	0	0	0	0	0	0.028
Rear-end (at entry)	0	0	0	0	0	0	0	0	0	0	0	0.0005	0.028
Entering-circulating	0.0013	0.0275	0	0	0	0	0.035	0.0085	0	0.0155	0.0035	0	0.028
Sideswipe (in circulating lanes)	0.0013	0.0275	0.00075	0	0.0005	0	0.035	0.0085	0	0.0155	0	0	0.028
Exiting-circulating	0.0013	0	0.00075	0	0	0	0	0	0.014	0	0	0	0.028
Pedestrian/bike	0	0	0	0	0	0	0	0	0	0	0	0	0.028
Other	0	0	0	0	0	0	0	0	0	0	0	0	0.028

Table 5
Actual and expected crash patterns of Quadrant B and chi-squared test results

Crash Type	Actual Crash Count	Actual Crash Type Percentage (%)	Expected Crash Type Percentage (%)
Run-off-road (or loss of control)	6	12.00	7.14
Rear-end (at entry)	11	22.00	7.27
Entering-circulating	17	34.00	30.32
Sideswipe (in circulating lanes)	8	16.00	29.75
Exiting-circulating	4	8.00	11.22
Pedestrian/bike	2	4.00	7.14
Other	2	4.00	7.14
p value of chi-squared test		8.69 E-08	

The actual and expected crash patterns are summarized in Table 5. The standard chi-squared test using the CHISQ.TEST function of Excel 2010 was performed. The *p* value of the chi-squared test is listed at the bottom of Table 5. The result cannot accept the hypothesis at a significance level of 5% or lower, so the expected crash pattern derived from exposure rates of undesired negotiations is not statistically significant in predicting the actual crash pattern. However, Table 5 shows that the proportion of expected crash types is similar to the observed ones. Particularly, entering-circulating and sideswipe are captured to be two major crash types as observed at field.

4. Conclusions

The crash pattern analysis reveals different safety performances between single-lane roundabouts and multilane roundabouts. For single-lane roundabouts, entering-circulating crashes are the major crash type, possibly because it is difficult for entering drivers in single-lane roundabouts to determine in advance whether a circulating vehicle will exit or continue. Multilane roundabouts have more sideswipe crashes between circulating vehicles. Multilane roundabouts have higher frequencies in all types of crashes than single-lane roundabouts, possibly explained by the heavier traffic at multilane roundabouts.

The exposure rate to conflicts is defined on 12 types of undesired negotiations. The exposure rate provides a simple short-term assessment of roundabout safety. Exposure rates are measured for two sample multilane roundabouts. A procedure is designed to estimate an expected crash pattern based on the measured exposure rates. However, a standard chi-squared test shows limited agreement between the observed crash pattern and the derived expected crash pattern. Although in this case study the difference between the actual crash pattern and expected crash pattern using measured exposure rates is statistically significant, more locations can be further tested when data become available. The method of calculating expected crash pattern from the measured exposure rates can be improved. Nevertheless, the exposure rates successfully identified the entering-circulating and sideswipe (in circulating lanes) crashes as two major crash types due to the high exposure rates of undesired lane changing negotiations.

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