Identifying crash patterns on roundabouts: an exploratory study

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Summary

Objectives: Roundabouts are a type of circular intersection control generally associated with a favourable influence on traffic safety. International studies of intersections converted to roundabouts indicate a strong reduction in injury crashes, particularly for crashes with fatal or serious injuries. Nevertheless, some crashes still occur at roundabouts. The present study aims to improve the understanding of roundabout safety by identifying crash types, locations and factors that are associated with roundabout crashes.

Methods: An analysis of 399 crashes on 28 roundabouts in Flanders-Belgium was carried out based on detailed crash descriptions, i.e. crash data and collision diagrams. The crashes are sampled from police-reported crashes at roundabouts in the region of Flanders, Belgium. Collision diagrams of the registered crashes were used to distinguish 8 different crash types. The roundabout itself is divided into 11 detailed and different typical segments, according to previously established knowledge on the occurrence of crashes at roundabouts. This procedure allows to include the detailed crash location for systematic analysis. The exact crash location of each crash is determined by using the location information in the collision diagrams to assign every crash to the corresponding segment. The 8 roundabout crash types are examined by injury severity, crash location within the roundabout, external factors (weather/ light conditions) type of roundabout (single-lane, double-lane), type of cycle facility (mixed, cycle lanes within the roundabout, separate cycle paths and grade-separated cycle paths) and type of involved road user.

Results: Four dominant crash types are identified: rear-end crashes, collisions with vulnerable road users, entering-circulating crashes and single-vehicle collisions with the central island. Crashes with vulnerable road users and collisions with the central island are characterised by significantly higher proportions of injury crashes. About 80% of the crashes occurred on the entry lanes and the circulatory road (segment 1-4 and 6). Specific crash types at double-lane roundabouts are collisions with the central island and sideswipe crashes. Road users that are the most at risk to be involved in serious injury crashes at roundabouts are cyclists, motorcycles, mopeds and pedestrians.

Recommendations: To reduce the number of crashes with vulnerable road users, it is desirable that future roundabouts are constructed without integrated cycle lanes. Severe single-vehicle collisions with the central island can be reduced by securing the visibility of the central island. Since, the majority of these crashes take place at night it is important that the roundabout and central island are well-illuminated. From the safety point of view, it is also crucial that roundabouts are constructed in such a way that the speeds of the approaching road users are reduced.

Nederlandse Samenvatting

Titel: Het identificeren van verkeersongevallenpatronen op rotondes: een exploratieve studie

Dit rapport is de neerslag van een gedetailleerde analyse van verkeersongevallenpatronen op rotondes. De ongevallenpatronen van 28 rotondes zijn geanalyseerd door gebruik te maken van de exacte locatie van ongevallen en manoeuvrediagrammen. Dankzij deze verrijkte ongevallendata wordt de ongevalsproblematiek op rotondes geanalyseerd op een gedetailleerder niveau door de rotondes verder op te delen in locatiesegmenten. De ongevallen worden onderzocht door a.d.h.v. de manoeuvrediagrammen de ongevallen in te delen in 8 verschillende ongevalstypes.

Vervolgens worden de ongevallen toegewezen aan een locatiesegment waarna de ongevallen worden geanalyseerd naar ernst, betrokken weggebruikers, locatie en rotonde-ontwerp (type fietspad, aantal rijstroken). De ongevallenpatronen worden onderzocht door middel van chi-kwadraattoetsen om mogelijke verschillen tussen de verschillende locatiesegmenten en ongevalskenmerken vast te stellen. Door de ongevallendata op het gedetailleerde niveau van rotondelocatiesegmenten te analyseren wordt een beter inzicht geboden in de ongevallenpatronen en hun locatie op de verschillende rotondesegmenten.

De analyses tonen aan dat vier dominante ongevalstypes plaatsvinden op rotondes: kop-staartongevallen, eenzijdige aanrijdingen met het middeneiland, ongevallen met zwakke weggebruikers en voorrangsongevallen bij het oprijden van de rotonde. De ongevalsernst is gerelateerd aan het ongevalstype aangezien ongevallen met zwakke weggebruikers en eenzijdige aanrijdingen met het middeneiland significant vaker resulteren in ernstige letsels.

Een andere interessante vaststelling is dat de ongevalsgebeurtenis afhankelijk is van het rotondesegment. Kop-staartongevallen vinden hoofdzakelijk plaats op de toerit (segment 1-2) terwijl bijna alle eenzijdige ongevallen gebeuren in de omgeving van het middeneiland (segment 4). De ongevallen met zwakke weggebruikers vinden plaats op de afrit (segment 6-7) waar het gemotoriseerde verkeer de rotonde verlaat en in contact komt met de zwakke weggebruikers. Segment 3 op de toerit wordt voornamelijk gekenmerkt door voorrangsongevallen bij het oprijden van de rotonde.

Verschillende rotonde-ontwerpeigenschappen blijken een invloed uit te oefenen op de dominante ongevalstypes. Kop-staartaanrijdingen en ongevallen met zwakke weggebruikers gebeuren vaker op enkelstrooksrotondes terwijl dubbelstrooksrotondes leiden tot meer aanrijdingen met het middeneiland. Rotondes met aanliggende fietspaden resulteren in meer ongevallen met fietsers en bromfietsers.

Op basis van de resultaten van dit onderzoek doen de auteurs enkele aanbevelingen voor de implementatie van rotondes in Vlaanderen. Om het aantal ongevallen met zwakke weggebruikers aan te pakken is het wenselijk dat toekomstige rotondes niet meer worden aangelegd met aanliggende fietspaden. Ernstige eenzijdige aanrijdingen met het middeneiland kunnen verminderd worden door de herkenbaarheid en zichtbaarheid van het middeneiland te garanderen. Doordat de meerderheid van deze ongevallen ’s nachts plaatsvinden is het belangrijk dat de rotonde en het middeneiland goed verlicht zijn. Daarnaast is het vanuit verkeersveiligheidsoogpunt cruciaal dat rotondes zodanig worden aangelegd dat de snelheid van het toekomende verkeer voldoende wordt afgeremd.

1 Introduction

Roundabouts are a type of circular intersection control generally associated with a favourable influence on traffic safety. International studies of intersections converted to roundabouts indicate a strong reduction in injury crashes, particularly for crashes with fatal or serious injuries (Persaud et al., 2000; Robinson et al., 2000; Brüde and Larsson, 2000; Elvik, 2003; Rodegerdts et al., 2007; De Brabander et al., 2005; Elvik et al., 2009). Brüde and Larsson (2000) found that the number of crashes is directly proportional to the speed whereas a quadratic relationship exists between the number of injured and the measured speeds.

The intersection design prior to the introduction of a roundabout also plays a role since larger crash reductions were found on converted priority-controlled intersections than on signalized intersections (Schoon and van Minnen, 1993; Persaud et al., 2000; Elvik, 2003; Elvik et al., 2009). Furthermore, single-lane roundabouts result in larger crash reductions than double or multiple lane roundabouts since the number of conflict points increases with the number of lanes (Brüde and Larsson, 2000; Persaud et al., 2000).

Unfortunately, the safety effects of roundabouts are not equally distributed across the different types of road users. Schoon and van Minnen (1993) indicate a 95% reduction in the number of injury crashes for car occupants. The safety effects for pedestrians amount to a 78% decrease in injury crashes (Schoon and van Minnen, 1993; Brüde and Larsson, 2000) and single-lane roundabouts are safer for pedestrians than multiple-lane roundabouts (Brüde and Larsson, 2000; Persaud et al., 2000). For bicyclists, roundabouts appear to induce less optimistic safety effects. A British study revealed that the involvement of bicyclists in crashes at roundabouts was 10-15 times higher compared to car occupants, taken into account the exposure rates (Maycock and Hall, 1984). Other studies also confirmed that the number of bicyclist and moped injuries increases at roundabouts irrespective of the type of cycle facility (Daniels et al., 2008; Daniels et al., 2009). The design of the cycle facilities appears to matter: roundabouts with separate cycle paths are safer than roundabouts with cycle lanes close to the roadway (Daniels et al., 2009). Bicyclist crashes at roundabouts are often characterised by a circulating cyclist and a car that enters or exits the roundabout (Herslund and Jørgensen, 2003; Møller and Hels, 2008).'Looked-but-failed-to-see' plays an important role in these crashes (Räsänen and Summala, 1998; Herslund and Jørgensen, 2003). This phenomenon is related to the behavior of the car driver before the crash when the driver looked in the direction of the bicyclist but did not perceive the presence of the vulnerable road user. This situation is very common at roundabouts since the approaching traffic needs to give way to the circulating traffic. Roundabouts improve road safety by reducing the number of conflict points by 75%, eliminating hazardous conflicts such as right angle and left turn head-on crashes and lower operating speeds (Flannery and Elefteriadou, 1999; Persaud et al., 2000; Robinson et al., 2000). The lower operating speeds give road users more time to react to potential conflicts, thereby leading to a reduction of most crashes. Previous studies identified three dominant crash types: crashes between entering and circulating vehicles, run-off road crashes and rear-end crashes (Robinson et al., 2000; Maycock and Hall, 1984; Rodegerdts et al., 2007; Mandavilli et al., 2009; Montella, 2011).

A lot of studies have already focused on the road safety performance of roundabouts but little is known about the exact location of the crashes. Therefore, this study focuses on identifying and analysing the crash patterns at roundabouts by taking into account detailed information about the location of the crash. In this way, it becomes possible to detect and to analyse the dominant crash types for each roundabout segment and to determine whether the crash patterns differ according to the infrastructural design characteristics. Mandavilli et al. (2009) and Montella (2011) analysed crash patterns at roundabouts by taking the crash location into account. We elaborated on this approach and tried to delineate the crash location on the roundabout itself in more detail. Since this study uses more detailed roundabout segmentations than previous studies, a better insight is gained into the crash patterns and their exact location on the roundabout. This method identifies the dominant crash type inside each segment and enables us to link the crash occurrence with the roundabout infrastructural design characteristics. As a result, the findings of this study lead to a detailed description of the crash patterns at roundabouts which provides insights into the safety impact of the roundabout design and leads to the formulation of targeted policy recommendations with regard to the dominant crash patterns. Other studies have also applied this method to other locations including intersections (Retting et al., 2003; Gstalter and Fastenmeier, 2010), freeway ramps (McCartt et al., 2004) and work zone crashes (Khattak and Targa, 2004).

2 Method

2.1 Crash Data

This study investigated 28 roundabouts in the region of Flanders for which at least 2 years of crash data were available. The crashes are sampled from police-reported crashes at roundabouts in the region of Flanders, Belgium. The national crash database could not be used to sample the crashes since it does not contain detailed information about the crash location at the roundabout. Therefore, several police zones were selected that registered detailed information about the crash location. The data collection process revealed that designing a collision diagram of a crash is a post processing step that is not executed by every police zone and is not a mandatory standard procedure. Ultimately, seven police zones met the research demands and provided the crash data. This approach resulted in a convenience sample of roundabout locations.

The crashes occurred in the period 2005-2010. In total, 399 crash reports containing injury and property-damage-only crashes were obtained, including 290 crashes at twenty-five single-lane roundabouts and 109 crashes at three double-lane roundabouts. The mean number of injury and property-damage-only crashes per year amounted to 3,9 for single-lane roundabouts and to 12,1 for double-lane roundabouts. The police reports provided basic and detailed information about the registered crashes (table 1).

Table 1 Collected variables and observed frequencies

Variable	Number of crashes
Weather circumstances	Dry: 214 Wet: 82 Fog: 1 Snow, glazed frost: 7 Unknown: 95
Light conditions	Day: 198 Night: 155 Dusk: 19 Unknown: 27
Crash severity (severest injury)	Property-damage-only: 254 Slightly injured: 132 Severely injured: 10 Fatally injured: 2
Obstacle – collision with an obstacle during the crash?	Yes: 134 No: 265
Driving under influence – one of the road users was under the influence of alcohol or drugs at the time of the crash	Yes: 47 No: 352

Road user – type of road user involved in the crash	Car : 554 Truck: 30 Bus: 2 Motorcycle: 12 Moped: 14 Cyclist: 51 Pedestrian: 4 Other: 6
Crash type – division of the roundabout crash in certain crash types	Run-off-road: 43 Collision with central island: 79 Wrong-way: 4 Rear-end: 115 Loss-of-control: 41 Vulnerable road user: 50 Entering-circulating: 54 Sideswipe: 13
Roundabout segment – the segment or location on the roundabout where the crash took place (see figure 1)	Segment 1: 65 Segment 2: 52 Segment 3: 75 Segment 4: 83 Segment 5: 32 Segment 6: 53 Segment 7: 27 Segment 8: 8 Segment 9: 0 Segment 10: 4 Segment 11: 0
Roundabout arms – the number of roundabout arms	Three: 28 Four: 344 Five: 27
Number of lanes	Single lane: 290 Double lane: 109

Cycle facility – type of cycle facility at the roundabout	Mixed traffic: 21 Cycle lanes within the roundabout: 131 Separate cycle paths: 138 Grade separated cycle paths: 109

Collision diagrams of the registered crashes were used to develop the crash types. This method was also used by other roundabout studies to determine the crash patterns at roundabouts (Mandavilli et al., 2009; Montella, 2011). Retting et al. (2003) also applied this approach to investigate crash patterns at stop sign-controlled intersections in the United States. A collision diagram can be defined as a schematic representation of all crashes that occurred at a given roundabout or other location over a specific period, in this case one year (Ogden, 1996). Every crash is depicted as a group of arrows, one for every involved road user, representing the crash type and travel directions. These arrows can be labelled with codes for date, time, day/night, weather, road user type,…(McShane and Roess, 1990, cited in Ogden, 1996). The collision diagram indicates the dominant crash types at a roundabout and the manoeuvres that lead to these crashes while providing detailed information about the crash location at the roundabout. Therefore, every crash was assigned a crash type by means of the descriptions in the corresponding collision diagrams. The identified crash types are analysed by type of road user, roundabout design, crash location within the roundabout and crash severity.

2.2 Roundabout Segments

Crashes or crash patterns can be related to certain geometrical design or infrastructural characteristics which are inherent to the roundabout. For example, a central island with a large radius can lead to more single-vehicle collisions. In order to include the detailed crash location for systematic analysis, it was decided to divide the roundabouts into different typical segments, according to previously established knowledge on the occurrence of crashes at roundabouts (Maycock and Hall, 1984; Robinson et al., 2000; Rodegerdts et al., 2007; Mandavilli et al., 2009; Montella, 2011). Figure 1 depicts the selected 11 segments. The segments can be described as follows:

- Segment 1: 20-100 meters off the roundabout. Oncoming traffic, queues associated with congestion.
- Segment 2: 20 meters before the roundabout until the yield markings. Pedestrian and cyclist crossings.
- Segment 3: beyond the yield markings. Crashes associated with entering the roundabout.
- Segment 4: continuation of segment 3. Collisions with the central island.
- Segment 5: location on the circular part of the roundabout.
- Segment 6: location on the circular part of the roundabout where drivers start the action to leave the roundabout. Possible exiting conflicts (for example with vulnerable road users) belong to this segment.
- Segment 7: 20 meters beyond the circulating part of the roundabout. Includes pedestrian and cyclist crossings if present.
- Segment 8: 20-100 meters off the roundabout. Leaving traffic.
- Segment 9: the beginning of the bypass, if present.
- Segment 10: the middle section of the bypass which includes pedestrian and cyclist crossings, if present.
- Segment 11: the end section of the bypass, if present.

Segments 9, 10 and 11 are optional and are only relevant when the roundabout is characterised by a bypass.

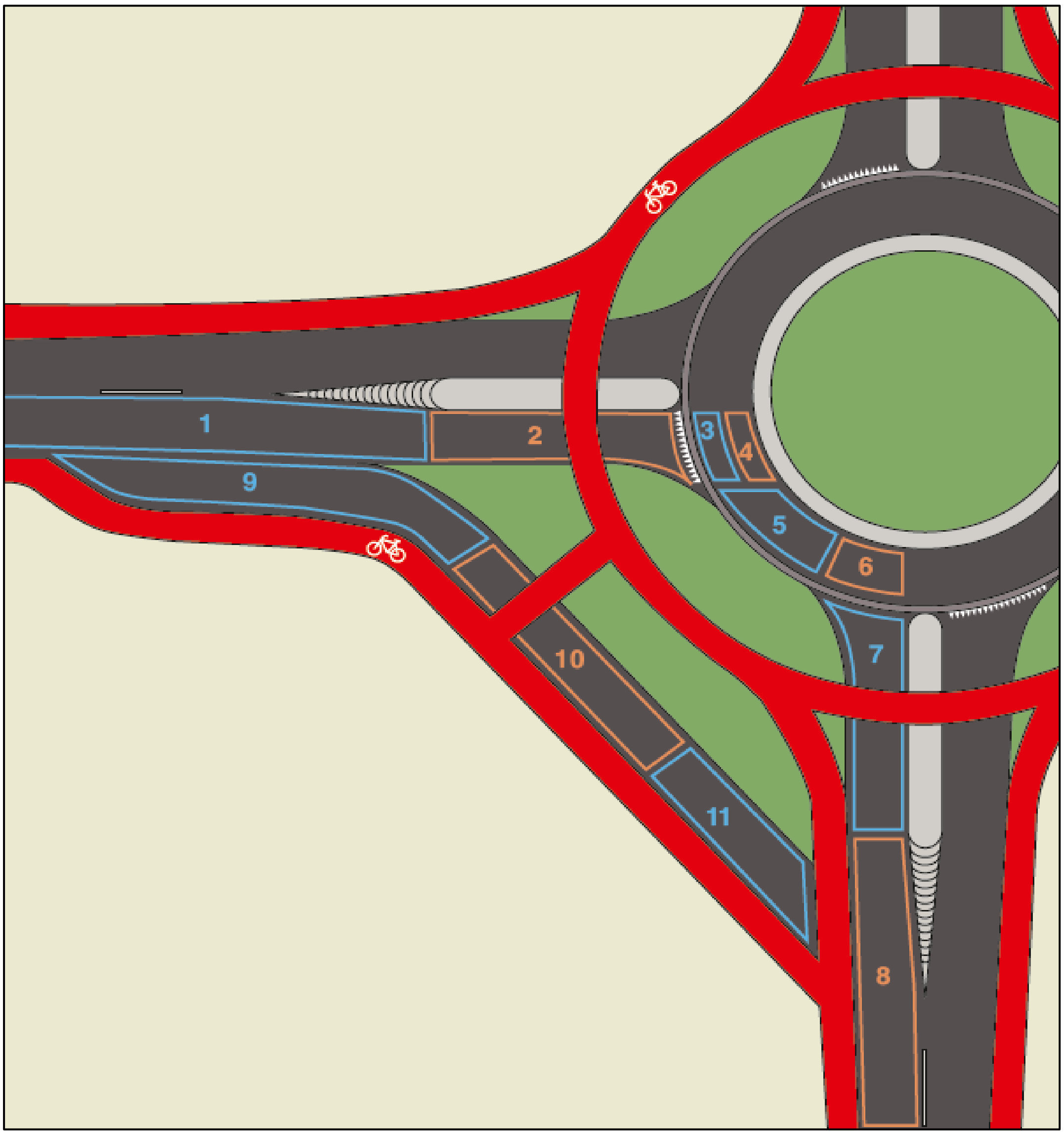

Figure 1 Roundabout segments

The figure is a representation of a typical roundabout quadrant. The segments are defined in such a way that the variety of real-world designs is represented by the figure and meaningful analyses based on the defined standard segments are possible. To capture all possible designs, a sort of a 'maximal design' is used, representing a typical roundabout lay-out with some extra features that are not necessarily always present. For example, a bypass lane is added in order to include also crashes that happen on bypass lanes at certain roundabouts. Nevertheless, bypass lanes are in reality rather infrequent at roundabout locations (e.g. for Flanders, Belgium 22 roundabouts with at least one bypass lane were present in a stratified random sample of 148 roundabouts (Daniels et al., 2011)). This means that only crashes at segments 9, 10 or 11 must be registered in case of a roundabout with such a bypass lane. The same goes for the cycle facilities (cycle paths and cycle crossings): pedestrian or bicyclist crossings are not necessarily present at real-world roundabouts and even if so, they might occur in a number of varieties, e.g. closer or further from the circulatory roadway, with or without priority for bicyclists/pedestrians versus motorised traffic. This means that, whereas the figure is representing a cycle path on some distance of the circulatory roadway, the real distance between the cycle facility and the roadway may vary between 0 and about 10 meter. However, the principle of the current approach is that all crashes happening on the pedestrian/cyclist crossing are assigned to segments 2 and 7, regardless of the design of the pedestrian/bicyclist facility, in particular regardless of the distance between the crossing and the circulatory roadway. This principle applies also to the number of lanes at the circulatory roadway and/or the entries and exits: both one lane and two lane roundabouts are represented by figure 1.

2.3 Analysis of the Crash Data

The collision diagrams were used to assign every crash to the corresponding segment. Pearson's chi-square tests, which can be used to measure whether a statistical significant relation exists between two variables, are used to analyse the data. The null hypothesis of the chi-square test always assumes that both variables are statically independent of each other; implying that no relation exists between both variables. This study uses a confidence interval of 95%.

3 Results

3.1 Crash Distribution over Segments

The registered crashes at the study locations were mostly property-damage-only (64%). Most crashes occurred before and on the entering lanes of the roundabouts. Table 2 indicates that 69% of the registered crashes took place in segment 1 to 4, with segment 4 responsible for 21% of the crashes. The exiting lanes seem to be less prone to crashes. No crashes were registered for segments 9 and 11. This may be due to the low number of crashes on the bypass and also to the small share of roundabouts with bypass (N=3) in the police data. The crash severity seems to differ according to the roundabout segment. The majority of injury crashes occurred in segment 4 and 7 (44% and 48%) while only 13% of the injury crashes took place in segment 5. Furthermore, chi-square tests revealed that significantly more injury crashes occurred in segment 4 (X^2 (1, N = 83) = 4,751, p = 0.029) compared to the other segments while segment 5 (X^2 (1, N = 32) = 8,091, p = 0.004) is identified as the segment with significantly fewer injury crashes. In general, the most severe crashes occurred in segments 2, 3 and 4 with segment 4 as the segment with the highest number of slightly, seriously and fatally injured victims (Table 2).

Table 2 Distribution of roundabout crashes by roundabout segment and crash severity

Roundabout segment	Total crashes N=399	Property damage only crashes	Injury crashes	Slightly injured*	Severely injured*	Fatally injured*
Segment 1	65 *(16)*	48	17	17	0	0
Segment 2	52 *(13)*	31	21	19	2	0
Segment 3	75 *(19)*	48	27	25	2	0
Segment 4	83 *(21)*	45	38	32	5	1
Segment 5	32 *(8)*	28	4	4	0	0
Segment 6	53 *(13)*	33	20	18	1	1
Segment 7	27 *(7)*	14	13	13	0	0
Segment 8	8 *(2)*	7	1	1	0	0
Segment 9	0	0	0	0	0	0
Segment 10	4 *(1)*	3	1	1	0	0
Segment 11	0	0	0	0	0	0

Values between *()* represent percent values of the column total

* The severity of the injury crashes is determined by the injury severity of the road user who endured the most serious injury during the crash

3.2 Crash Types

The crashes were categorised into eight different crash types. These crash types are described in table 3 and figure 2. Four main crash types – rear-end, collision with central island, entering-circulating and vulnerable road user – accounted for 75% of roundabout crashes.

At single-lane roundabouts, rear-end crashes were the most common crash type (32%), followed by vulnerable road users (17%) and collision with central island crashes (16%). The remaining crash types at single-lane roundabouts – run-off-road and loss-of-control – accounted for 12% and 8% of all crashes, respectively. Common crash types at double-lane roundabouts were collision with central island (29%), rear-end (20%) and loss-of-control crashes (17%). At double-lane roundabouts, run-off-road and entering-circulating crashes accounted for 8 and 13% of crashes, respectively. Sideswipe crashes were only registered at double-lane roundabouts and accounted for 13% of all crashes at two-lane roundabouts. In the sample, collisions with vulnerable road users occurred only at single-lane roundabouts. Some wrong-way crashes were noticed at both single-lane and double-lane roundabouts but only accounted for 1%.

Table 3 Roundabout crash types

Crash Type	Description
Run-off-road (1)	Single-vehicle crash in which a vehicle leaves the road and collides with an off-road object such as a traffic sign or splitter island
Collision with central island[1] (2)	Single-vehicle crash in which a vehicle leaves the circulatory road and collides with the central island
Wrong-way (3)	Road user enters the roundabout in the non-permitted direction
Rear-end (4)	Second vehicle collides with the rear of the lead vehicle
Loss-of-control (5)	Collision between two road users due to loss of control
Vulnerable road user (6)	Collisions between a vehicle and vulnerable road users such as pedestrians, bicyclists or mopeds
Entering-circulating (7)	Collisions between two road users in which the entering vehicle fails to yield and collides with the circulating vehicle
Sideswipe (8)	Collisions at double-lane roundabouts caused by lane-changing on the circulatory road and by exiting the roundabout

[1]Collisions with the central island can be regarded as a form of loss-of-control crashes or run-off-road crashes. Due to the high number of collisions with the central island it was decided to define it as a separate crash type.

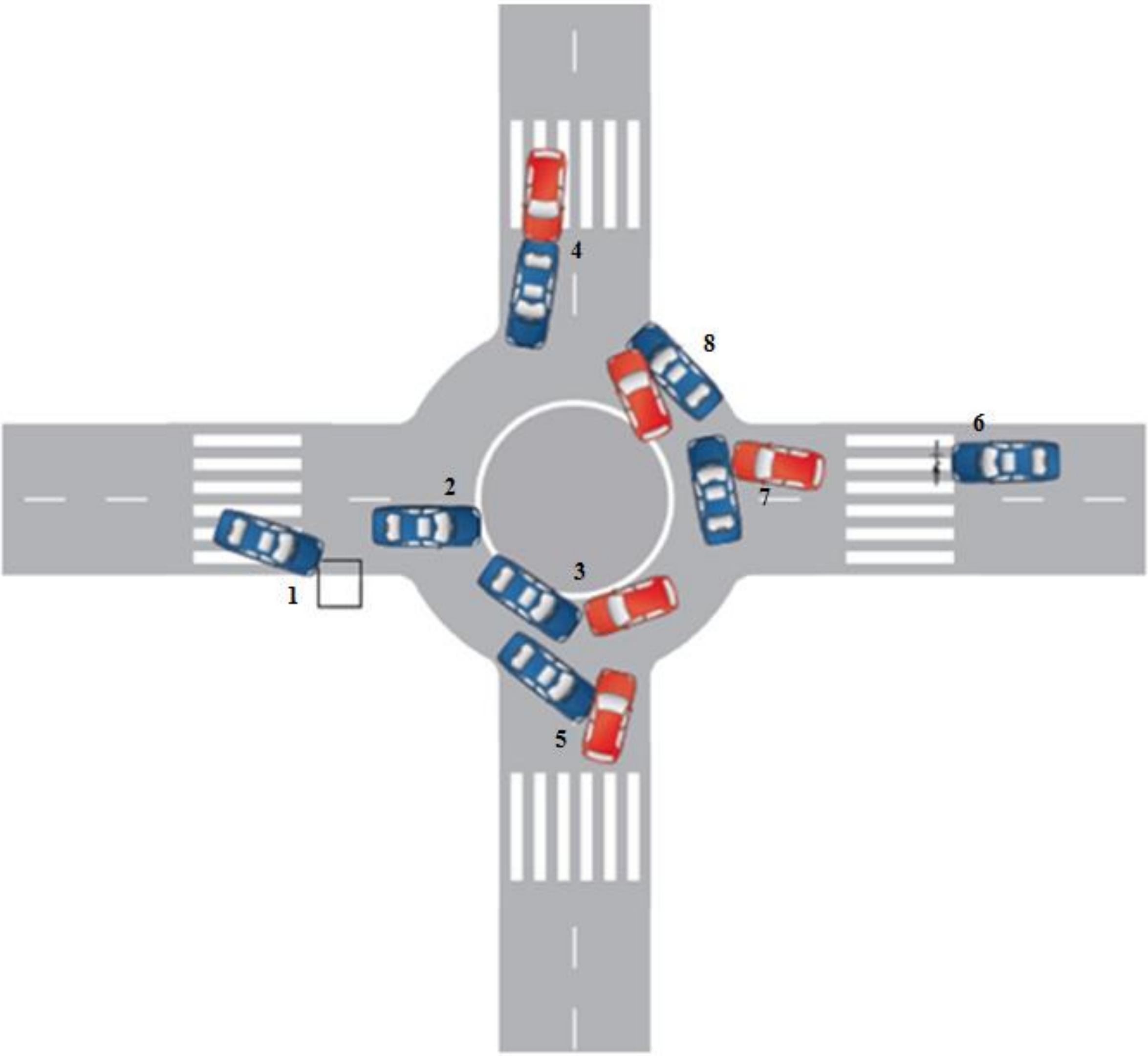

Figure 2 Roundabout crash types

3.3 Relation between Crash Type and Location

The crash types were allocated to the roundabout segments according to their crash location (Table 4). The results in table 5 indicate that significantly more rear-end crashes take place in segment 1 and 2. Entering-circulating crashes were the dominant crash type for segment 3. Furthermore, significantly less run-off-road X^2 (1, N = 75) = 8.556, p = 0.003) and rear-end crashes (X^2 (1, N = 75) = 27,739 p = 0.000) occurred in segment 3. In segment 4 significantly more collisions occurred with the central island. However, this segment is also characterised by significantly less loss-of-control crashes. Significantly more wrong-way, loss-of-control and rear-end crashes occurred in segment 5. However, loss-of-control crashes can be regarded as the most dominant crash type for this roundabout segment since they are more significant (X^2 (1, N = 32) = 11,441 p = 0.003) at the 95% CI than the other two crash types. Crashes that result from a collision with the central island appeared significantly less in segment 5. Segment 6 is characterised by a large variety of crash types. Significantly fewer rear-end and entering-circulating crashes took place in segment 6 while significantly more vulnerable road user, sideswipe and loss-of-control crashes occurred in this roundabout segment. Vulnerable road user and run-off-road crashes occurred significantly more in segment 7 and can therefore be considered as the two dominant crash types for this location. For segments 8 and 10, it is impossible to draw sound conclusions due to the small sample size. To summarize, the crash types are related to the roundabout design and are therefore mostly related to specific locations.

Table 4 Roundabout crash types by crash location

Segments[a]	Crashes (%)	X²	p[b]
Segment 1	N= 65		
Rear-end	94	160,036	**<0,001**
Loss-of-control	5	2,881	0,090
Sideswipe	1	0,729	0,703
Segment 2	N= 52		
Run-off-road	19	1,836	0,175
Wrong-way	2	0,511	0,429
Rear-end	52	15,554	**<0,001**
Loss-of-control	6	1,437	0,231
Vulnerable road user	17	1,244	0,368
Sideswipe	4	0,066	0,681
Segment 3	N= 75		
Run-off-road	1	8,556	**0,003**
Rear-end	3	27,739	**<0,001**
Loss-of-control	8	0,626	0,429
Entering-circulating	68	240,062	**<0,001**
Vulnerable road user	19	3,172	0,075
Segment 4	N= 83		
Run-off-road	6	2,576	0,109
Collision with central island	93	357,636	**<0,001**
Loss-of-control	1	9,846	**0,002**
Segment 5	N= 32		
Run-off-road	16	0,850	0,369
Collision with central island	3	6,092	**0,014**
Wrong-way	6	9,653	**0,034**
Rear-end	47	5,527	**0,019**
Loss-of-control	28	11,441	**0,003**

Segment 6	N= 53		
Run-off-road	9	0,115	0,735
Rear-end	9	11,199	**0,001**
Loss-of-control	26	16,383	**<0,001**
Entering-circulating	4	4,798	**0,028**
Vulnerable road user	33	21,299	**0,000**
Sideswipe	19	47,248	**0,000**
Segment 7	N= 27		
Run-off-road	36	20,769	**<0,001**
Wrong-way	7	2,129	0,245
Loss-of-control	21	4,206	0,052
Vulnerable road user	36	15,866	**0,001**
Segment 8	N= 8		
Run-off-road	75	35,018	**<0,001**
Rear-end	25	0,058	1,000
Segment 10	N= 4		
Run-off-road	33	1,599	0,290
Rear-end	67	2,110	0,201

[a] Not every crash type occurred in each segment

[b] $p \leq 0.05$ (significant at 95% CI)

X^2-test: each crash type is per segment compared to the combined average of all other segments

3.4 Relation between Crash Type and Crash Severity

In general, approximately one third of the investigated roundabout crashes were injury crashes. The proportion of injury crashes was the highest in crashes involving vulnerable road users (76%). Approximately 47% of the collisions with the central island of the roundabout resulted in road user casualties. The chi-square tests indicated that these two crash types result in significantly more injury crashes compared to the other crash types (Table 5). Run-off-road and sideswipe crashes are characterised by significantly fewer injury crashes, indicating that these roundabout crash types result in lower crash severities. A separate chi-square test revealed that collision with central island crashes were more likely than other crash types to result in serious and fatal injuries (X^2 (1, N = 399) = 11.781, p = 0.008). Although vulnerable road user crashes were characterised by significantly more injury crashes, the separate chi-square test (X^2 (1, N = 399) = 0.793, p = 0.416) was unable to determine whether this crash type resulted in significantly more minor or severe injuries.

Table 5 Crash severity according to crash type

Crash type	Number of crashes	Property damage only crashes	Injury crashes	X^2	p[a]
All crash types	399	254 *(64)*	145 *(36)*		
Run-off-road	43 (11)	35 *(81)*	8 *(19)*	7,332	**0,007**
Collision with central island	79 (20)	42 *(53)*	37 *(47)*	5,435	**0,020**
Wrong-way	4 (1)	4 *(100)*	0	2,232	0,135
Rear-end	115 (29)	81 *(70)*	34 *(30)*	2,557	0,110
Loss-of-control	41 (10)	28 *(68)*	13 *(32)*	1,809	0,179
Entering-circulating	54 (13)	40 *(74)*	14 *(26)*	3,262	0,071
Vulnerable road user	50 (13)	12 *(24)*	38 *(76)*	42,633	**<0,001**
Sideswipe	13 (3)	12 *(92)*	1 *(8)*	4,562	**0,033**

Values between *()* represent percent values of the row total

Values between () represent percent values of the column total

[a] $p \leq 0.05$ (significant at 95% CI)

X^2-test: each crash type is per crash severity compared to the combined average of the crash severity of all other crash types

3.5 Relation between Crash Type and Weather/Light Conditions

Table 6 shows the distribution of roundabout crashes per segment according to weather and light conditions. The weather appeared to be a significant factor for the crashes at the entering and exiting lane since significantly more crashes occurred on wet pavement in segment 1 (X^2 (1, N = 60) = 10,527, p = 0.001) and segment 7 (X^2 (1, N = 18) = 3,925, p = 0.048) compared to all other segments. Segments 5 (X^2 (1, N = 26) = 4,361, p = 0.037) and 6 (X^2 (1, N = 47) = 7,395, p = 0.007) at the circulatory road are characterised by significantly more crashes on dry pavement. The light conditions are an important contributory factor regarding the crash occurrence at the entering lane and circulatory road. Daytime crashes occurred significantly more in segment 1 (X^2 (1, N = 63) = 4,988, p = 0.026) and segment 3 (X^2 (1, N = 64) = 10,683, p = 0.001). Night time crashes occurred more likely in segment 4 (X^2 (1, N = 74) = 52,232, p < 0.001) while dawn/dusk time crashes more likely took place in segment 6 (X^2 (1, N = 49) = 8,856, p = 0.009).

Table 6 Distribution of roundabout crashes by roundabout segment, weather and light conditions

Roundabout segment	Weather[a]				Light conditions[b]		
	Dry	Wet	Fog	Snow/glazed frost	Day	Night	Dusk/Dawn
Segment 1	33 *(55)*	26 *(43)*	0	1 *(2)*	39 *(62)*	19 *(30)*	5 *(8)*
Segment 2	26 *(67)*	13 *(33)*	0	0	25 *(52)*	21 *(44)*	2 *(4)*
Segment 3	32 *(73)*	10 *(23)*	0	2 *(4)*	45 *(70)*	17 *(27)*	2 *(3)*
Segment 4	43 *(72)*	14 *(23)*	1 *(2)*	2 *(3)*	13 *(18)*	59 *(79)*	2 *(3)*
Segment 5	23 *(88)*	3 *(12)*	0	0	15 *(56)*	12 *(44)*	0
Segment 6	41 *(87)*	5 *(11)*	0	1 *(2)*	31 *(63)*	11 *(23)*	7 *(14)*
Segment 7	9 *(50)*	8 *(44)*	0	1 *(6)*	8 *(42)*	10 *(53)*	1 *(5)*
Segment 8	6 *(100)*	0	0	0	4 *(67)*	2 *(33)*	0
Segment 9	0	0	0	0	0	0	0
Segment 10	2 *(50)*	2 *(50)*	0	0	4 *(100)*	0	0
Segment 11	0	0	0	0	0	0	0

Values between *()* represent percent values of the row total

[a] Information not available for 95 crashes

[b] Information not available for 27 crashes

The crash types were also examined with regard to the weather and light conditions at the time of the crash (table 7). Significantly more run-off-road crashes occurred on wet pavement X^2 (1, N = 26) = 5,545, p = 0.019). Rear-end crashes (1, N = 103) = 3,231, p = 0.072) also appear to be more likely when the pavement is wet. The result is statistically significant at a confidence interval of 90%. Since the p-value of 0.072 falls just outside the 95% confidence interval, it can be assumed that a relation exists between wet pavement and the occurrence of rear-end crashes. The only other crash type that differs significantly are the sideswipe crashes (1, N = 12) = 5,131, p = 0.021), since nearly all crashes took place on dry pavement.

The occurrence of five crash types is related to the light conditions or time of day. Significantly more collisions with the central island occurred during night time (1, N = 75) = 52,911, p <0.001) while significantly more loss-of-control crashes took place at dusk/dawn. Daytime crashes were more likely than night time crashes to be rear-end crashes (1, N = 115) = 11,881, p = 0.001), vulnerable road user crashes (1, N = 42) =6,301, p = 0.012) and entering-circulating crashes (1, N = 50) = 6,528, p = 0.011).

Table 7 Distribution of crash types by weather and light conditions

Crash types	Weather[a]				Light conditions[b]		
	Dry	Wet	Fog	Snow/glazed frost	Day	Night	Dusk/Dawn
Run-off-road	13 (50)	12 (46)	0	1 (4)	14 (44)	18 (56)	0
Collision with central island	44 (72)	14 (23)	1(2)	2 (3)	14 (19)	59 (79)	2 (2)
Wrong-way	2 (100)	0	0	0	2 (50)	2 (50)	0
Rear-end	68 (66)	34 (33)	0	1 (1)	77 (67)	32 (28)	6 (5)
Loss-of-control	29 (83)	5 (14)	0	1 (3)	20 (49)	16 (39)	5 (12)
Entering-circulating	27 (79)	6 (18)	0	1 (3)	35 (70)	15 (30)	0
Vulnerable road user	24 (67)	11 (30)	0	1 (3)	30 (71)	7 (17)	5 (12)
Sideswipe	12 (100)	0	0	0	6 (46)	6 (46)	1 (8)

Values between *()* represent percent values of the row total

[a] Information not available for 95 crashes

[b] Information not available for 27 crashes

3.6 Single-lane and Double-lane Roundabouts

One roundabout design characteristic which is studied is the impact of the number of lanes on the crash type and the location of the crashes. Table 8 shows a distribution of the crashes by crash type according to number of roundabout lanes. Five of the eight crash types seem to be related with the number of roundabout lanes. At single-lane roundabouts significantly more rear-end and vulnerable road user crashes occurred than at roundabouts with two lanes. Double-lane or two-lane roundabouts are characterised by significantly more loss-of-control, collision with the central island and sideswipe crashes compared to single-lane roundabouts. These three crash types are possibly related to the larger size of double-lane roundabouts. Furthermore, two lanes make weaving manoeuvres possible, which can lead to sideswipe crashes.

Table 8 Distribution of crashes at single-lane and double-lane roundabouts per crash type

Crash types	Number of crashes	Single-lane roundabout	Double-lane roundabout	X²	p[a]
All crashes	399	290 *(73)*	109 *(27)*		
Run-off-road	43 (11)	34 *(79)*	*9* (21)	0,990	0,320
Collision with central island	79 (20)	47 *(59)*	*32* (40)	8,105	**0,004**
Wrong-way	4 (1)	3 *(75)*	*1* (25)	0,011	0,917
Rear-end	115 (29)	93 *(81)*	*22* (19)	5,455	**0,020**
Loss-of-control	41 (10)	22 *(54)*	*19* (46)	8,328	**0,004**
Entering-circulating	54 (13)	40 *(74)*	*14* (26)	0,061	0,805
Vulnerable road user	50 (13)	50 *(100)*	*0*	21,486	**<0,001**
Sideswipe	13 (3)	1 (8)	*12* (92)	32,917	**<0,001**

Values between *()* represent percent values of the row total

Values between () represent percent values of the column total

[a] $p \leq 0.05$ (significant at 95% CI)

The crashes were distributed over the segments and assigned to the number of roundabout lanes according to their location (table 9). Segments 1 and 7 on single-lane roundabouts are characterized by significantly more crashes than double-lane roundabouts. The registered number of crashes in segment 8 (N=8) is too small to draw sound conclusions. Therefore, this finding can only be regarded as a first indication that significantly more crashes occur in segment 8 on single-lane roundabouts. On double-lane roundabouts significantly more crashes took place in segments 4 and 6 compared to single-lane roundabouts. A separate chi-square test revealed that the crash severity was also higher in segment 4 on double-lane roundabouts (X^2 (1, N = 145) = 18.834; p = 0.000) since more injury crashes occurred in this segment at roundabouts with two lanes. Although more crashes occurred in segment 6 on double-lane roundabouts, significantly more injury crashes took place in this segment on single-lane roundabouts (X^2(1, N = 145) = 6.951, p = 0.008). These two results are consistent with the results from table 5 and 6 indicating that segment 4 is characterised by crashes resulting from collisions with the central island while vulnerable road user crashes are the dominant crash type for segment 6. Table 6 already indicated that these two crash types mostly result in injury crashes.

Table 9 Distribution of crashes at single-lane and double-lane roundabouts per segment

Segment	Number of crashes	Single-lane roundabout	Double-lane roundabouts	X²	p[a]
All segments	399	290 *(73)*	109 *(27)*		
Segment 1	65 (16)	63 *(97)*	*2* (3)	22,981	**<0,001**
Segment 2	52 (13)	34 *(65)*	*18* (35)	1,603	0,205
Segment 3	75 (19)	59 *(79)*	*16* (21)	1,666	0,197
Segment 4	83 (21)	53 *(64)*	*30* (36)	4,112	**0,043**
Segment 5	32 (8)	24 *(75)*	*8* (25)	0,094	0,759
Segment 6	53 (13)	26 *(49)*	*27* (51)	17,181	**<0,001**
Segment 7	27 (7)	24 *(89)*	*3* (11)	3,831	**0,050**
Segment 8	8 (2)	3 *(37)*	*5* (63)	5,089	**0,024**
Segment 10	4 (1)	4 *(100)*	*0*	1,519	0,218

Values between *()* represent percent values of the row total

Values between () represent percent values of the column total

[a] $p \leq 0.05$ (significant at 95% CI)

X²-test: the crash number for each segment is per roundabout type compared to the combined average crash number of all other segments

3.7 Cycle Facilities at Roundabouts

The second design characteristic that is studied is the effect of the type of cycle facility at the roundabout on crashes with vulnerable road users (cyclists and mopeds). Four different types of cycle paths are distinguished (see also Daniels et al., 2009 for a more detailed explanation):

- Mixed traffic: bicyclists are mixed with motorised traffic and they use the same entry/exit lane and carriageway.
- Cycle lanes within the roundabout: cycle lanes next to the carriageway within the roundabout.
- Separate cycle paths: the distance between the carriageway and the cycle facility increases and the cycle path no longer belongs to the roundabout. In this study, separate cycle path with and without priority to cyclists are combined due to the relatively low number of roundabouts with separate cycle paths with priority (N=2).
- Grade separated cycle paths: bicyclists operate independently from motorised traffic.

The sample of crashes with cyclists and mopeds is rather small for all the different cycle facilities, hence it is not possible to draw hard conclusions. The presented results in this section can only be regarded as indicative. Table 10 compares the crashes with cyclists and mopeds for the four types of cycle facilities. Significantly more crashes with cyclists and mopeds occurred at roundabouts with cycle lanes. Significantly fewer crashes occurred at roundabouts with separate and grade separated cycle paths. However, these differences in crash susceptibility may also be related with different cyclist volumes at the cycle facilities. Due to the lack of traffic volume data, we were unable to test this hypothesis.

Table 10 Distribution of cyclists' and mopeds' crashes according to type of cycle facility

Cycle facilities	Total crashes	Crashes (only cyclists and mopeds)	X^2	p^a
All cycle facilities	399	46		
Mixed traffic	21 (5)			
Cyclists and mopeds		3 (6)	2,572	0,109
Cycle lanes within roundabout	131 (33)		36,913	**<0,001**
Cyclists and mopeds		36 (79)		
Separated cycle paths	138 (35)		12,585	**<0,001**
Cyclists and mopeds		6 (13)		
Grade separated cycle paths	109 (27)		23,103	**<0,001**
Cyclists and mopeds		1 (2)		

Values between () represent percentages of the column total

[a] $p \leq 0.05$ (significant at 95% CI)

X^2-test: the crash number for each cycle facility is compared to the combined average crash number of all types of cycle facilities

The design of the cycle facilities has an influence on the crash location (table 11). Significantly more crashes with cyclists and mopeds occurred in segment 6 on roundabouts with cycle lanes within the roundabout. On roundabouts with separate cycle paths, significantly more crashes took place in segment 7 while significant less crashes occurred in segment 6. To summarize, the type of cycle facility influences the crash location of crashes with cyclists and mopeds since this location appears to be intertwined with the location where the cycle path interacts with the infrastructure for other (motorised) road users.

Table 11 Distribution of cyclists' and mopeds' crashes according to type of cycle facility and roundabout segment

Cycle facilities	Total crashes[a]	Crashes (only cyclists and mopeds)	X²	p[b]
Mixed traffic	21	3		
Segment 2	3 (14)	0	0,010	1,000
Segment 3	9 (42)	2 (67)	0,397	0,611
Segment 6	2 (9)	1 (33)	0,485	0,650
Segment 7	0	0	0,000	1,000
Cycle lanes within roundabout	131	36		
Segment 2	7 (5)	5 (14)	1,427	0,245
Segment 3	26 (20)	10 (28)	0,003	1,000
Segment 6	17 (13)	16 (44)	6,250	**0,012**
Segment 7	7 (5)	5 (14)	3,001	0,118
Separate cycle paths	138	6		
Segment 2	9 (7)	2 (33)	2,454	0,144
Segment 3	2 (1)	1 (17)	1,135	0,414
Segment 6	4 (3)	0	4,906	**0,039**
Segment 7	4 (3)	3 (50)	5,375	**0,041**
Grade separated cycle paths	109	1		
Segment 2	18 (17)	0	0,224	1,000
Segment 3	13 (12)	1 (100)	2,624	0,280
Segment 6	27 (25)	0	0,526	1,000
Segment 7	2 (2)	0	0,255	1,000

Values between () represent percentages of the column total

[a] Only the crashes that occurred in these 4 segments are mentioned in this column

[b] $p \leq 0.05$ (significant at 95% CI)

X²-test: the crash number for each segment is per type of cycle facility compared to the combined average crash number of all other segments

3.8 Involved Road Users

Crashes with vulnerable road users are often more severe than crashes between motorised vehicles. This was also the case for the studied roundabouts (table 12). Significantly more car-cyclist, car-moped and single-vehicle crashes with cyclists resulted in a crash with injured vulnerable road users. In general, motorcyclists are a risk group and are often involved in traffic crashes. At roundabouts, crashes in which at least one motorcyclist was involved resulted significantly in a higher number of injury crashes. Table 11 shows that significantly less injury crashes occurred between two cars while the number of injury crashes was not significantly higher for single-vehicle crashes. No injury crashes occurred between cars and trucks. This result is very significant according to table 12.

Table 12 Distribution of injury crashes according to involved road users

Crashes and road user type	Number of crashes	Property damage only crashes	Injury crashes	X^2	p[a]
All crashes	399	252 *(63)*	147 *(34)*		
Car (single-vehicle)	118 (30)	78 *(66)*	40 *(34)*	0,624	0,430
Car-car	179 (45)	133 *(74)*	46 *(25)*	17,326	**<0,001**
Car-cyclist	41 (10)	9 *(22)*	32 *(78)*	33,345	**<0,001**
Car-moped	12 (3)	4 *(33)*	8 *(67)*	4,730	**0,037**
Car-pedestrian	6 (1)	2 *(33)*	4 *(67)*	2,329	0,199
Car-truck	18 (5)	18 *(100)*	0	10,996	**0,001**
Truck (single-vehicle)	6 (1)	5 *(83)*	1*(17)*	1,066	0,420
Cyclist (single-vehicle)	8 (2)	0	8 *(100)*	13,995	**<0,001**
At least one motorcycle	11 (3)	3 *(27)*	8 *(73)*	6,260	**0,022**

Values between () represent percentages of the column total

Values between *()* represent percent values of the row total

[a] $p \leq 0.05$ (significant at 95% CI)

X^2-test: the crash number for each road user type is per crash severity compared to the combined average crash severity number of all other collision opponents

The crash type mostly reflects the type of involved road user (table 13). Run-off-road and collision with central island crashes were dominated by single-car crashes. Cars were significantly more involved in rear-end and wrong-way crashes while loss-of-control crashes occurred mostly between cars and cyclists (single-vehicle). Crashes between cars, trucks and mopeds occurred significantly more when one road user enters the roundabout and the other drives on the circulatory road. Vulnerable road user crashes were characterised by significantly more adverse encounters between cars, cyclists, mopeds and pedestrians than all other crash types. Finally, cars and trucks were mostly involved in sideswipe crashes.

Table 13 Roundabout crash types and involved road users

	Crashes (%)	X^2	p[a]
Run-off-road	N=43		
Car (single-vehicle)	90	79,997	<0,001
Truck (single-vehicle)	2	0,220	0,498
Cyclist (single-vehicle)	4	1,718	0,209
At least one motorcycle	2	1,366	0,617
Collision with central island	N=79		
Car (single-vehicle)	94	182,752	<0,001
Truck (single-vehicle)	4	3,409	0,098
At least one motorcycle	2	0,025	1,000
Wrong-way	N=4		
Car-car	100	4,966	0,040
Loss-of-control	N=41		
Car (single-vehicle)	18	3,112	0,078
Car-car	60	4,118	0,042
Car-truck	5	0,025	0,699
Cyclist (single-vehicle)	10	14,463	0,005
At least one motorcycle	7	3,731	0,087
Rear-end	N=115		
Car-car	95	149,403	<0,001
Car-truck	4	0,372	0,542
At least one motorcycle	1	2,103	0,190
Entering-circulating	N=54		
Car-car	61	5,948	0,015
Car-cyclist	4	2,803	0,094
Car-moped	10	8,653	0,013
Car-truck	17	22,062	<0,001
At least one motorcycle	8	5,231	0,045

Vulnerable road user	N=50		
Car-cyclist	76	255,777	<0,001
Car-moped	12	14,917	0,002
Car-pedestrian	8	40,650	0,000
Cyclist (single-vehicle)	2	0,002	1,000
At least one motorcycle	2	0,155	1,000
Sideswipe	N=13		
Car-car	77	5,584	0,018
Car-truck	23	10,752	0,017

[a] $p \leq 0.05$ (significant at 95% CI)

X^2-test: the crash number for each road user type is per crash type compared to the combined average crash number of all other collision opponents

The type of involved road user is related to the crash location of the roundabout crash (table 14). Roundabout segment 1 is dominated by significantly more car-car crashes. According to table 4, rear-end crashes were the most dominant crash type for this segment and table 13 confirms that significantly more crashes between cars result in rear-end crashes. Significantly more cars and pedestrians appear to be involved in the crashes that took place in segment 2. Segment 3 is characterised by significantly more car-truck, car-moped and cyclist (single-vehicle) crashes. Entering-circulating crashes were the dominant crash type for segment 3 (table 4). Table 12 shows that crashes between cars-mopeds and cars-trucks mostly resulted in entering-circulating crashes. Significantly less car-car crashes took place in segment 4 while significantly more single-car crashes took place in this segment. The dominant crash type for this segment were collision with the roundabout crashes (table 4) in which single-cars were mostly involved (table 13). Significantly more crashes between cars and cyclists took place in segment 6. This is consistent with the findings in table 6 and 13 indicating that vulnerable road user crashes between cars and cyclists were the dominant crash type for this segment. Single-vehicle crashes occurred significantly less. Car-car crashes occurred significantly less in segment 7. However, segment 7 is characterised by significantly more crashes between cars and pedestrians. Table 4 and 13 already mentioned that vulnerable road crashes between cars and pedestrians were one of the dominant crash types of this segment. The sample sizes of segments 8 and 10 are too small to produce meaningful significant results.

Table 14 Roundabout crash location and involved road users

Segment	**Crashes (%)**	**X²**	**p[a]**
Segment 1	N=65		
Car-car	95	78,034	**<0,001**
At least one motorcycle	5	0,955	0,400
Segment 2	N=52		
Car (single-vehicle)	20	2,451	0,117
Car-car	48	0,364	0,546
Car-cyclist	12	0,089	0,765
Car-moped	2	0,163	1,000
Car-pedestrian	6	7,251	**0,032**
Car-truck	8	1,362	0,275
Cyclist (single-vehicle)	2	0,003	1,000
At least one motorcycle	2	0,163	1,000
Segment 3	N=75		
Car-car	48	0,293	0,588
Car-cyclist	15	1,928	0,165
Car-moped	12	21,662	**<0,001**
Car-truck	14	16,682	**<0,001**
Truck (single-vehicle)	3	0,841	0,315
Cyclist (single-vehicle)	5	5,201	**0,044**
At least one motorcycle	4	0,530	0,440
Segment 4	N=83		
Car (single-vehicle)	89	190,064	**<0,001**
Car-car	4	74,686	**<0,001**
Truck (single-vehicle)	4	2,888	0,119
At least one motorcycle	3	0,211	0,710
Segment 5	N=32		
Car (single-vehicle)	32	0,158	0,691

Car-car	57	1,767	0,184
Car-cyclist	4	1,563	0,339
Car-truck	4	0,094	1,000
Cyclist (single-vehicle)	3	0,341	0,454
Segment 6	N=53		
Car (single-vehicle)	8	12,683	**<0,001**
Car-car	51	0,819	0,370
Car-cyclist	31	26,896	**<0,001**
Car-moped	4	0,252	0,644
Car-truck	6	0,205	0,717
Segment 7	N=27		
Car (single-vehicle)	27	0,131	0,718
Car-car	19	7,534	**0,006**
Car-cyclist	22	2,597	0,164
Car-pedestrian	12	18,275	**0,005**
Truck (single-vehicle)	4	0,968	0,342
Cyclist (single-vehicle)	8	4,375	0,094
At least one motorcycle	4	0,103	1,000
Segment 8	N=8		
Car (single-vehicle)	75	8,467	**0,009**
Car-car	25	1,333	0,303
Segment 10	N=4		
Car (single-vehicle)	33	0,029	1,000
Car-car	67	0,568	0,591

[a] $p \le 0.05$ (significant at 95% CI)

X^2-test: the crash number for each road user type is per segment compared to the combined average crash number of all other segments

Finally, the relation between the number of roundabout lanes and the involved road users was studied. The number of lanes appeared to have an influence on three types of road users: cars, cyclists and trucks. Significantly less crashes between cars and cyclists occurred on double-lane compared to single-lane roundabouts (X^2 (1, N = 399) = 124.981; p = 0.000). Double-lane roundabouts also lead to significantly more crashes between cars and trucks (X^2 (1, N = 399) = 14.430; p = 0

4 Discussion

This study aimed to describe crash patterns at roundabouts. The number of included roundabouts was relatively low (N= 28) and could be a somewhat biased representation of a larger (e.g. countrywide) roundabout population in the sense that only roundabouts were included where at least one crash was registered and where detailed crash data were available for. A possible bias associated herewith is a slight overrepresentation of roundabouts with higher numbers of crashes. However, the objective of the study was not to make inferences about the performance of roundabouts compared to each other, but to identify crash types, locations and factors that are associated with roundabout crashes. The collected sample of 399 crashes can considered to be valid for that purpose.

The present study reveals four crash types to be the most common at roundabouts: rear-end crashes (29%), collisions with the central island (20%), entering-circulating crashes (13%) and crashes with vulnerable road users (13%). Crashes with vulnerable road users and collisions with the central island are characterised by significantly higher proportions of injury crashes. Daniels et al. (2010) already found the crash severity at roundabouts to be strongly dependent on the involved road user type resulting in higher injury severities - compared to crashes with cars or trucks – for crashes with pedestrians, bicyclists, moped riders and motorcyclists. The high crash severity rate of collisions with the central island might by determined by relative high approach speeds associated with these crashes in combination with the rigidness of the central island making it incapable of softening the impact. High approach speeds might be an indicator of road users' non-awareness of approaching a roundabout, perhaps as a consequence of a reduced visibility of the roundabout or as a form of risk-taking behaviour (e.g. trying to cross the roundabout at high speeds).

The crash location appears to be an important factor for the crash occurrence. About 80% of the crashes occurred on the entry lanes and the circulatory road (segment 1- 4 and 6). Two earlier studies also pointed out that the crash frequency is very high in these two roundabout locations (Mandavilli et al., 2009; Montella, 2011). As a result the crash frequency is higher when entering than exiting the roundabout. The location of the four dominant crash types is also related to certain roundabout segments. Rear-end collisions mostly occurred on the entry lanes (segment 1 and 2) indicating differences in decelerations between drivers before entering the roundabout. Most of the collisions with the central island (segment 4) took place in the evening or at night. Possibly, roundabouts are less visible in dusky light conditions or at night. Another plausible explanation for these crashes, is that road users tend to adopt higher approach speeds due to the lower traffic volumes at night. The combination of higher approach speeds and a bad visibility of the roundabout in dusky light conditions or at night can eventually lead to a collision with the central island. Mandavilli et al. (2009) also found that night-time crashes are more likely crashes where vehicles leave the roadway and collide with the central island or other objects. Vulnerable road user crashes predominated the exit lanes (segments 6 and 7) where vehicles can conflict with vulnerable road users indicating that crossing the roundabout at the exit lane is more dangerous for vulnerable road users. Most likely, the lower speeds when exiting roundabouts are offset by the higher degree of complexity that drivers of exiting vehicles experience after interacting with other vehicles in the roundabout. Drivers and vulnerable road users might feel more comfortable with the entering interaction because there are no other competing demands (Sakshaug, Laureshyn, Svensson, & Hydén, 2010). Because drivers experience almost no complexity or high task demands when entering the roundabout, they may also be convinced that exiting the roundabout is a quite easy task. This conviction might lead to less alertness from drivers for vulnerable road users when exiting the roundabout which in turn increases the probability to be involved in vulnerable road user crashes. Entering-circulating crashes primarily dominated the location where the entry lane is connected to the circulatory road (segment 3). A plausible cause for most of these crashes were entering drivers who failed to yield to circulating drivers (Flannery and Elefteriadou, 1999; Robinson et al., 2000) or circulating drivers who used their direction indicators to early.

The influence of the roundabout design was examined by taking into account the number of lanes. The number of lanes appeared to determine the crash type and location since the results indicated a significant difference between single-lane and double-lane roundabouts. Single-lane roundabouts were characterised by rear-end crashes in segment 1 and vulnerable road user crashes in segment 7. Mandavilli et al. (2009) confirm that more rear-end crashes occur at the entry lane of single-lane roundabouts. The finding that significantly more vulnerable road user crashes occur at this roundabout type is inconsistent with the existing literature but might be biased by the too small sample size for double-lane roundabout locations (N=3). The crashes at double-lane roundabouts were more clustered at the location where vehicles leave the roundabout (segment 6) on account of weaving movements and loss-of-control. The sideswipe or weaving movement crashes are primarily caused by drivers on the inner lane who want to leave the roundabout but collide with circulating vehicles on the outer lane while the loss-of-control crashes are possibly the result of drivers who fail to keep their vehicle under control due to the centripetal force. Mandavilli et al. (2009) and Montella (2011) also found that crashes at the entry and exit lanes dominated single-lane roundabouts whereas crashes at the exit-location were more present at double-lane roundabouts. Furthermore, significantly more collisions with the central island occurred in segment 4 on double-lane roundabouts. According to Robinson et al. (2000) double-lane roundabouts are more dangerous due to a lower speed reduction compared to single-lane roundabouts which results in more single-vehicle crashes with the central island. Other studies confirmed this finding (Mandavilli et al., 2009; Montella, 2011).

Finally, the type of cycle facility turns out to determine the number and the nature of the observed crashes. Cycle lanes within the roundabout were previously found to be in general more dangerous for vulnerable road users than the other types (mixed traffic, separate cycle paths) (Daniels et al., 2009). The results of our study confirm this finding since significantly more vulnerable road user crashes occurred on the exit lanes of roundabouts with this type of cycle facility. Jörgensen and Jörgensen (1994, cited in Hydén and Várhelyi, 2000) found that drivers who enter the roundabout primarily focus on other vehicles and less on bicyclists. This looked-but-failed-to-see error is a primary concern at roundabouts with integrated cycle lanes because this design requires almost no action of the involved road users in most vulnerable road user-vehicle interactions (Sakshaug et al., 2010) which gives rise to the phenomenon that drivers not notice the vulnerable road users but in first instance direct their attention and visual scanning strategy to other vehicles. As a consequence, bicyclists cycling on a cycle lane within the roundabout (along the outer edge of the circulatory road) are not detected by drivers who enter/exit the roundabout which leads to many conflict situations. Furthermore, Sakshaug et al (2010) found that interacting vulnerable road users and motorists to a larger extent continue with unadjusted speeds when cycle lanes are integrated in the roundabout which probably leads to less attentiveness towards each other and higher crash risks for cyclists.

5 Conclusions

Roundabouts are characterised by four dominant crash types: rear-end crashes, single-vehicle collisions with the central island, entering-circulating crashes and crashes with vulnerable road users. The crash severity appeared to be related with the crash type since crashes with vulnerable road users and single-vehicle crashes often lead to more severe injuries.

Another interesting finding is the fact that the crash occurrence is dependent of the roundabout segment. Rear-end crashes predominantly occur in the zones before entering the roundabout (segment 1 and 2) while nearly all crashes in the zones close to the central island (segment 4) are single-vehicle collisions with this island. Vulnerable road user crashes mostly take place in the zone where drivers start to leave the roundabout and cross the path of circulating cyclists (segments 6 and 7). Entering-circulating crashes are dominant in the merging zone for entering and circulating traffic (segment 3).

There is also an indication that certain design characteristics give rise to the dominant crash types. Significantly more crashes with vulnerable road users and rear-end crashes occur at single-lane roundabouts while double-lane roundabouts lead to more collisions with the central island. Moreover,

cycle lanes within the roundabout are associated with more crashes with cycles and mopeds, especially at the location were cyclists and moped riders interact with vehicles exiting the roundabout (segment 6).

Future studies of crashes occurring at roundabouts should further examine the relationship between dominant crash types and roundabout characteristics such as the speed limit, type of cycle facility, location (urban or rural) and geometric aspects (radius of deflection, entry angle, exit radius, entry radius,…). These studies should also include the study of more complex double-lane roundabouts and roundabouts with bypasses since these two roundabout types were under represented in our sample. Finally, it is also worthwhile to examine which crash contributory factors cause the four dominant crash types at roundabout locations.

6 Recommendations

This study should be regarded as an exploratory study that identifies and analyses the dominant crash types and their crash locations at typical roundabouts. Based on the results, the following policy recommendations can be formulated.

With regard to the vulnerable road user crashes, it is preferable that future roundabouts will not be constructed with cycle lanes close to the roadway. This recommendation does not imply that already implemented roundabouts with integrated cycle lanes need to be redesigned to roundabouts with separate or grade-separated cycle paths. Merely converting the cycle facility to another one without adjusting the geometric variables will not improve the safety for vulnerable road users and drivers of motorised vehicles. For example, removing integrated cycle lanes by renovating the circulatory road, makes the roadway wider which results in higher vehicle speeds that could lead to an increased occurrence of other crash types such as single-vehicle collisions with the central island or other fixed objects.

Furthermore, the roundabout should be more conspicuous at night and for motorists who are unfamiliar with the roundabout. At night the entire roundabout and especially the central island should be well-illuminated or clearly visible with the headlights of the vehicle. Ground-level lighting of the central island, reflective pavement markings and reflective paint on curbs may increase the visibility. Landscaping the central island increases the conspicuity by reducing the sight distance and making the intersection a focal point.

From the safety point of view, it is also crucial that roundabouts are constructed in such a way that the speeds of the approaching road users are reduced. Therefore, entry lanes and entry deflection should be narrow and tight enough to promote slow speeds.

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