

EXPLAINING DIFFERENCES IN SAFETY PERFORMANCE OF ROUNDABOUTS

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ABSTRACT

The conversion of an intersection into a roundabout has been proven to reduce in general the number of accidents with injuries or fatalities. However, evaluation studies frequently showed considerable individual differences in safety performance of roundabouts or particular groups of roundabouts. The main purpose in the present study was to explain the variance in safety performance of roundabouts through the use of risk models based on accident data, traffic data and geometric data of a sample of 90 roundabouts in Flanders-Belgium. The results show that the variation in accident counts is relatively small and mainly driven by the traffic exposure. Bicyclists and moped riders are more frequently than expected involved in accidents at roundabouts. Roundabouts with cycle lanes close to the roadway are clearly performing worse than roundabouts with separate cycle paths. Confirmation is found for the existence of a "safety in numbers"-effect for bicyclists, moped riders and – more uncertain – for pedestrians at roundabouts.

1. INTRODUCTION

Roundabouts have become a common type of intersection design in many countries, although they are not yet used to the same extent everywhere. The number of roundabouts seems to increase steadily in countries and regions where they are already common while they are gaining popularity in regions where they were not applied in the past (Brilon & Vandehey, 1998; Brown, 1995; Pellecuer & St-Jacques, 2008; Rodegerdts et al., 2007; Thai Van & Balmeffrezol, 2000). In a number of circumstances, roundabouts are assumed to be more beneficial than other intersection types, both in terms of traffic operations and traffic safety (Bird, 2001; Ogden, 1996; PIARC, 2003).

With respect to traffic safety, the conversion of an intersection into a roundabout has been proven to reduce the number of crashes with injuries or fatalities (e.g. in Elvik, 2003; Persaud et al., 2001). However, research has also shown that effects for particular user groups, such as bicyclists, are less favourable or even unfavourable (Daniels et al., 2009; Daniels et al., 2008; Schoon & van Minnen, 1993).

Those general effects have typically been established by observational before- and after-studies and meta-analyses on the resulting estimates. Nevertheless, before- and after-studies frequently showed considerable differences in safety performance of particular roundabouts or particular groups of roundabouts. Obviously, chance factors might explain a part of the heterogeneity in the results. Crashes are rare events and from an analytical point of view, the number of crashes on the disaggregate level of particular locations is low and easily affected by pure chance elements. However, heterogeneity in the safety performance of intersections such as roundabouts might also be explained, at least partly, by some structural differences between locations.

The main purpose in the present study was to explain the variance in safety performance of roundabouts through the use of state-of-the-art cross-sectional risk models based on crash data, traffic data and geometric data of a sample of 90 roundabouts in Flanders-Belgium. The main target was to investigate which variables might explain a structural part of the variation in crash rates at roundabouts and to which extent the stated effects would correspond with earlier research results elsewhere. Moreover, an attempt was also made to add some variables that were not or not always included in prior analyses and that potentially could influence the safety level of roundabouts. In particular, this last element refers to some design characteristics of cycle facilities that are commonly used in a few European countries.

The paper is organized as follows. The next section describes the data that were collected and the way it was done. Subsequently, the analysis method is described and the results are provided. Finally the results are discussed and conclusions are drawn.

2. DATA COLLECTION

90 roundabouts on regional roads in Flanders-Belgium were selected through a stratified random sample procedure (three or four roundabouts for each of the 28 administrative road districts) out of a database of the Roads and Traffic Agency. The included roundabouts were the same as in a previous study (Daniels et al., 2009). For the purpose of the present study, each roundabout in the sample was revisited and photographed, traffic counts were executed and additional geometric data were collected on the spot. Information on the construction year of the roundabout was available from the database. All investigated roundabouts were constructed between 1994 and 2000. Collected data were a number of variables, expressed as dummies and describing some particular features of the roundabouts: a raised central island, a traversable truck apron (with, if present, the width of the apron), an oval shape of the central island, a gated roadway through the central island to accommodate oversized trucks, a bypass for right-turning traffic in one or more directions, and whether the roundabout was located inside or outside built-up area. Geometric data consisted also of the number of lanes on the roundabout, the road width, the central island diameter, the inscribed circle diameter (distance across the circle inscribed by the outer edge of the circulatory roadway) and the number of legs.

Furthermore some variables were collected in order to describe the present facilities for bicyclists and pedestrians. Four types of cycle facilities were distinguished: roundabouts with mixed traffic (motor vehicles and bicyclists use the same roadway), cycle lanes (lanes reserved for bicyclists close to the roadway), cycle paths (dedicated paths for bicyclists on a distance of more than one meter from the roadway) and grade-separated roundabouts (with tunnels for bicyclists). The reader is referred to Daniels et al. (2009) for a detailed description of the different types of cycle facilities and some illustrations. The collected variables are listed in table 1. No particular data were collected that enabled to determine the actual speeds at the roundabouts. Worth mentioning is that roundabouts in Flanders are generally constructed with perpendicular approaches in combination with central islands that are large enough to impose considerable lateral movements (deflections) on entering vehicles. Consequently, speeds of any types of vehicles at roundabouts are reduced considerably.

Traffic data were collected as follows: at each examined roundabout all entering traffic was counted by one or two observers during one hour by day (between 8:00 and 18:00). Traffic modes were classified in light vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Light vehicles comprised mainly private cars, but also minibuses and all kinds of vans. Heavy vehicles were trucks, trailers, busses and tractors. A particular reason for the distinction between motorcycles and mopeds is their different driving path through a roundabout. Mopeds are often allowed to use cycle facilities when these are present, while this is not the case for motorcycles. Furthermore, the engine power of mopeds is legally limited in such a way that no speeds higher

than 45 km/h can be reached on level roads. Calibration counts were held on two roundabouts during one day (08:00-18:00).

Table 1 Explanatory variable description

Variable (ABBREVIATION)	Observations	Descriptive statistics
Annual average number of injury accidents on the roundabout	90	Mean: 1.37; VAR: 1.39
Annual average number of accidents with private cars on the roundabout	90	Mean: 1.14; VAR: 1.05
Annual average number of accidents with bicyclists	90	Mean: 0.42; VAR: 0.21
Annual average number of accidents with moped riders on the roundabout	90	Mean: 0.29; VAR: 0.19
Annual average number of accidents with bicyclists or moped riders on the roundabout	90	Mean: 0.68; VAR: 0.60
Annual average number of accidents with heavy vehicles on the roundabout	90	Mean: 0.10; VAR: 0.02
Annual average number of accidents with motorcycles on the roundabout	90	Mean: 0.08; VAR: 0.02
Annual average number of accidents with pedestrians on the roundabout	90	Mean: 0.07; VAR: 0.02
Annual average number of single-vehicle accidents	90	Mean: 0.28; VAR: 0.13
Annual average number of multiple-vehicle accidents	90	Mean: 1.09; VAR: 1.06
Inside built-up area? (INSIDE) (1 = Yes; 0 = No, thus outside)	90	Yes: 39; No: 51
Central island min. 0.5 m raised? (ELEV) (1 = Yes; 0 = No)	90	Yes: 70; No: 20
Traversable truck apron present? (APRON) (1 = Yes; 0 = No)	90	Yes: 83; No: 7
Apron width (in meters) (APRONWIDTH)	83	Mean: 1.85; S.D.: 0.55
Central island diameter (in meters) (CENTRDIAM)	90	Mean: 25.29; S.D.: 12.72
Inscribed circle diameter (in meters) (OUTDIAM)	90	Mean: 40.46; S.D.: 13.52
Number of legs (3LEG, 4LEG, 5LEG) (1 = Yes; 0 = No)	90	3-leg: 20; 4-leg: 60; 5-or 6-leg: 10
Gated roadway through the central island? (EXCEPT) (1 = Yes; 0 = No)	90	Yes: 4; No: 86
Bypass present in some directions? (BYPASS) (1 = Yes; 0 = No)	90	Yes: 15; No: 75
Oval roundabout? (OVAL) (1 = Yes; 0 = No)	90	Yes: 4; No: 86
Two-lane roundabout? (TWOLANE) (1 = Yes; 0 = No, thus single-lane)	90	Yes: 7; No: 83
Road width on the roundabout (all lanes together, in meters) (ROADWIDTH)	90	Mean: 6.46 ; S.D.: 1.10 (single-lanes) Mean: 8.21 ; S.D.: 0.80 (two-lanes)
Construction year of the roundabout (YEAR)	90	Median: 1996; range [1994;2000]
Traffic signals present before roundabout construction? (SIGNALS) (1 = Yes; 0 = No)	90	Yes: 21; No: 69
Mixed Traffic? (MIXED) (1 = Yes; 0 = No)	90	Yes: 9; No: 81
Cycle lanes? (CYCLANE) (1 = Yes; 0 = No)	90	Yes: 40; No: 50
Cycle paths? (CYCLPATH) (1 = Yes; 0 = No)	90	Yes: 38; No: 52
Grade-separated? (GRADESEP) (1 = Yes; 0 = No)	90	Yes: 3; No: 87
Cycle lane width (in meters) (CYLANEWIDTH) (only in case of cycle lanes)	40	Mean: 1.73; S.D.: 0.28
Cycle path width (in meters) (CYPATHWIDTH) (only in case of cycle paths)	38	Mean: 1.86; S.D.: 0.38
Priority for cyclists when crossing entry/exit lanes? (PRIOR) (only in case of cycle paths) (1 = Yes; 0 = No)	38	Yes: 18; No: 20
Distance between roundabout roadway and cycle path (in meters) (DISTRoadCYCLSEGM) (only in case of cycle paths)	38	Mean: 2.91; S.D.: 2.61
Distance between roadway and cycle path at crossings (in meters) (DISTRoadCYCLCROSS) (only in case of cycle paths)	38	Mean: 5.68; S.D.: 7.65

Variable (ABBREVIATION)	Observations	Descriptive statistics
Cycle facility coloured red? (RED) (not applicable in case of mixed traffic) (1 = Yes; 0 = No)	81	Yes: 74; No: 7
Pavement of cycle facility different from roadway? (PAVEMENT) (not applicable in case of mixed traffic) (1 = Yes; 0 = No)	81	Yes: 28; No: 53
Interrupted line marking present between roadway and cycle lane? (only in case of cycle lanes) (MARKING) (1 = Yes; 0 = No)	40	Yes: 37; No: 3
Physical elements between roadway and cycle lane? (only in case of cycle lanes) (PHYS) (1 = Yes; 0 = No)	40	Yes: 17; No: 23
Width of physical elements (in meters) (only if CYCLANE=1 and PHYS=1) (PHYSWIDTH)	17	Mean: 0.63; S.D.: 0.35
Sidewalk present around the roundabout? (SIDEWALK) (1 = Yes; 0 = No)	90	Yes: 55; No: 35
Zebra markings present on exit/entry lanes? (ZEBRA) (1 = Yes; 0 = No)	90	Yes: 57; No: 33
Distance between roadway and zebra markings (in meters) (ZEBRADIST)	57	Mean: 6.67; S.D.: 8.65
Nr. of entering motor-vehicles 8:00-18:00 (ADT) (corrected for yearly ADT-evolution)	90	Mean: 13416; S.D.: 6266
Nr. of pedestrians 8:00-18:00 (PED)	90	Mean: 292; S.D.: 765
Nr. of bicyclists 8:00-18:00 (BIC)	90	Mean: 526; S.D.: 842
Nr. of mopeds 8:00-18:00 (MOP)	90	Mean: 100; S.D.: 128
Nr. of motorcycles 8:00-18:00 (MCY)	90	Mean: 129; S.D.: 326
Nr. of light vehicles 8:00-18:00 (LGT)	90	Mean: 12139; S.D.: 5765
Nr. of heavy vehicles 8:00-18:00 (HMY)	90	Mean: 1176; S.D.: 979

The results of the calibration counts were used to calculate adjustment factors that brought all the hourly traffic counts to a common 10 hour (08:00-18:00) level. Subsequently, the counts for private cars, heavy vehicles and motorcycles were added up in order to estimate a value for the Average Daily Traffic (ADT), representing the motorised, fast traffic. This approach enabled to obtain a useful classification of the sample of roundabouts according to their traffic volume. As a result, traffic volume data were available for six different traffic modes.

Data from all registered injury crashes (Statistics Belgium) were available for the investigated period. The ministry of Mobility and Public Works routinely geo-codes (i.e. assigns spatial XY-coordinates) all crash data since 1996. The 90 roundabout locations were localised and geo-coded by the researchers through the use of Google Earth. Subsequently the roundabout data were linked in a GIS-system (ArcMap) with the geo-referenced crash data for the period 1996-2004. All crashes within a distance of 100 meters of the centre of the roundabout were included in the dataset. After subtraction of the crashes that occurred before the roundabouts were constructed, the dataset consisted of 932 injury crashes.

Table 2 shows some frequency statistics of the crash data and the involvement of different types of road users. The crashes were classified according to the same six road user groups as the traffic counts: light vehicles, heavy vehicles, motorcycle, mopeds, bicycles and pedestrians. Light vehicles were involved in 82.9% of all registered injury crashes at the investigated roundabouts. Bicyclists were present in 30% of the crashes and mopeds in 21.5%. No other user group occurred in more than 10% of the crashes. Since usually more than one road user is involved in a crash, the sums of the frequency counts and the percentages in Table 2 exceed the totals in the first row. In comparison with their average share in traffic on the observed locations moped riders ($\chi^2 = 1962$, $p < 0.01$), bicyclists ($\chi^2 = 1220$, $p < 0.01$), motorcyclists ($\chi^2 = 206$, $p < 0.01$) and pedestrians ($\chi^2 = 29$, $p < 0.01$) were more frequently involved in crashes. Light ($\chi^2 = 1.67$, ns) and heavy vehicles ($\chi^2 = 0.54$, ns) were less frequently involved, but these differences are not significant.

Table 2 Frequency statistics of crashes in the roundabout dataset according to type of involved road user

	Counts	% of total	Avg/year/roundbt.	Variance
Injury crashes at the 90 roundabouts	932	100	1.37	1.39
Injury crashes with at least one				
light vehicle	773	82.9	1.14	1.05
bicycle	280	30.0	0.42	0.21
moped	200	21.5	0.29	0.19
bicycle or moped	463	49.7	0.68	0.60
heavy vehicle	70	7.5	0.10	0.02
motorcycle	58	6.2	0.08	0.02
pedestrian	44	4.7	0.07	0.02

Table 3 Frequency statistics of crashes in the roundabout dataset according to crash type

	Counts ¹	% of total	Avg/year/roundbt.	Variance
Single-vehicle crashes	189	20.3	0.27	0.13
Multiple-vehicle crashes	737	79.1	1.09	1.06

¹ For 6 crashes the type is unknown

Since they can be believed to show different patterns, information was also sought for single-vehicle crashes and multiple-vehicle crashes separately. About eight in ten crashes at the investigated roundabouts were multiple-vehicle crashes (Table 3).

3. METHODOLOGY

Regression models were fitted using the available geometric and traffic variables. The dependent variable was the average annual number of crashes per roundabout (N=90). Crash data are usually modelled by Poisson or negative binomial regression models. Generally it is concluded that negative binomial modelling should be preferred above Poisson-modelling when the data are overdispersed, i.e. when the variance is significantly larger than the mean (Lord et al., 2005; Washington et al., 2003). In our dataset however, no overdispersion in the data seemed to be present. On the contrary, the variance of the average annual number of crashes turned out to be more or less equal to the mean, at least when all crashes were considered (see Table 2). However, mainly when subgroups of crashes were considered, the data appeared even to be underdispersed.

In a first step Poisson loglinear models were fit to explain crash rates at roundabouts. All exposure variables were transformed to their natural logarithm. Since underdispersion was found in the crash data, some additional models were fit by using gamma probability models like proposed earlier by Oh et al. (2006). The reader is referred to Daniels et al (n.d.) for some more technical details about the modelling procedure.

4. RESULTS

The results are provided in Table 4. For reasons of brevity, only the results for the Poisson models are provided and some differences between the Poisson models and the gamma models are explained in the text hereunder.

The model for all crashes shows two significant exposure variables: ADT and bicyclist volume. Furthermore the presence of a cycle lane affects the number of crashes positively. The variables SIGNALS (roundabouts replacing signal-controlled intersections) and 3LEG (roundabouts with three legs) are significant at the 9%-level in the gamma model, but do not occur in the Poisson model. The coefficient for the exposure variables is close to one, suggesting an almost proportional increase of the yearly crash rate with higher traffic volumes.

Specific models were fit for crashes with particular road users: bicycles, mopeds, motorcycles, heavy vehicles, light vehicles and pedestrians. The model for crashes with light vehicles is similar to the models for all crashes, which is not unexpected due to the dominance of crashes with private cars in the entire dataset. Crashes with bicyclists are explained by the ADT and the volume of bicyclists. The number of crashes with mopeds is, apart from the exposure variables, dependent from the construction year of the roundabout. The parameter sign is negative, meaning that fewer crashes with mopeds seem to occur at more recently constructed roundabouts. Higher numbers of crashes with mopeds seem to occur at 3-leg roundabouts. Roundabouts that replaced signal-controlled intersections (SIGNALS) correlate with a higher number of crashes for different road user types, although not strongly significant.

The best fitting models for both the crashes with motorcycles and with heavy vehicles were ADT-only models. In the model for crashes with pedestrians no variable was significant at the 5%-level.

Furthermore separate models were fit for single-vehicle crashes and for multiple-vehicle crashes. The number of single-vehicle crashes turns out to be explained by the ADT. Multiple-vehicle crashes are affected by the ADT, by the presence of two-wheelers (bicyclists and mopeds together) and furthermore by the variables CYCLPATH, 3LEGS and, SIGNALS.

The reader should note that some variables show strong correlations which makes that they are to some extent mutually exchangeable. Examples of strongly correlating variables were the duo's CYCLPATH / CYCLLANE and LN(BIC) / LN(BICMOP). In the case of the multiple-vehicle crashes the Poisson model delivered the variable CYCLPATH as an explanatory variable whereas the gamma model delivered a correlating variable, CYCLLANE. Some trials revealed that those variables could be substituted by each other without losing too much of the goodness-of-fit.

Table 4 Parameter estimates for the Poisson-regression models

Variables	All crashes	Crashes with light vehicles	Crashes with bicyclists	Crashes with mopeds	Crashes with motorcycles	Crashes with heavy vehicles	Crashes with pedestrians	Multiple-vehicle crashes	Single-vehicle crashes
Intercept	-9.20 (<0.01)	-9.41 (<0.01)	-10.06 (<0.01)	-9.15 (0.06)	-15.68 (0.06)	-14.05 (0.06)	-22.68 (0.04)	-10.72 (<0.01)	-8.09 (0.05)
LN(ADT)	0.89 (<0.01)	0.88 (<0.01)	0.78 (0.03)	0.73 (0.16)	1.38 (0.11)	1.23 (0.11)	1.99 (0.08)	0.98 (<0.01)	0.72 (0.10)
LN(BIC)	0.14 (0.04)	0.15 (0.05)	0.27 (0.04)						
LN(BICMOP)								0.23 (0.01)	
LN(MOP)				0.29 (0.07)					
CYCLPATH								-0.42 (0.05)	
CYCLLANE	0.40 (0.03)	0.40 (0.04)							
SIGNALS		0.40 (0.10)		0.94 (0.07)				0.50 (0.05)	
YEAR				-0.23 (0.05)					
3 LEGS				0.90 (0.07)				0.48 (0.06)	
INSIDE							1.71 (0.07)		

() = p-values; explanatory variables only included if pq0.10

5. DISCUSSION

Influencing risk variables

Traffic volume (ADT) was a significant predictor in most of the fitted models. It was only less significant in those models where the number of observations was low such as in the models for pedestrians or heavy vehicles. When traffic volume was poorly significant, no other variables came into the model. Therefore it can be concluded that the ADT was technically by far the most important variable in the models, which corresponds with many earlier findings in traffic safety research.

Less straightforward to interpret is the parameter estimate of the ADT. In most cases of the Poisson-models the estimate was below 1 which suggest a positive, but less than proportional relationship between the ADT and the crash rate. However, all but one of the gamma probability models show parameter estimates above 1 which would suggest that the number of crashes would increase at an increasing rate with an increasing ADT. Existing research seems to show a comparable ambiguity since parameters were found below as well as above 1 for crashes at roundabouts (Brüde & Larsson, 2000; Maycock & Hall, 1984).

Apart from the ADT, the volume of bicyclists and/or mopeds turned out be a significant predictor as well. Surprisingly this is not only true for the specific models for bicyclists or mopeds but also for the crashes with light vehicles (mostly private cars) and the multiple-vehicle crashes. This highlights the important role of encounters between light vehicles on the one hand and bicycles and mopeds on the other hand.

The parameter estimate of the cyclist/moped volume is consistently below 1 which supports the notion of a 'safety in numbers' effect for crashes with two-wheelers like it was reported elsewhere (Brüde & Larsson, 1993; Jacobsen, 2003; Turner et al., 2006).

Roundabouts with cycle lanes (N=40) are clearly performing worse than roundabouts with cycle paths (N=38). The other two design types, mixed traffic (N=9) and grade-separated (N=3) showed no particular effect but their limited presence in the dataset could explain this. The limited numbers of mixed traffic and grade-separated roundabouts in the sample explains equally the correlation between the two most dominant groups, cycle lanes and cycle paths. This correlation causes some troubles in order to interpret whether roundabouts with cycle lanes are performing worse than the other types, or conversely, whether roundabouts with cycle paths are doing better than the other three types. Although CYCLLANE is more dominantly present in the models, this study stays inconclusive on this matter. More explicit results were found in the before-and-after study of crashes at the same roundabouts (Daniels et al., 2009), where was found that roundabouts with cycle lanes performed worse compared to the three other design types. It should be mentioned that the present data enabled to correct for differences in exposure which excludes one still existing and important possible confounding variable for being responsible for the differences in safety performance of the different cycle facilities. It might therefore be concluded that the present results are confirming the findings in the before-after study of Daniels et al. (2009) with respect to the role of the different types of cycle facilities, i.e. mainly the elevated risk level at roundabouts with cycle lanes. Together with the findings in the previous study, the present results seem to confirm the theses about the doubtfulness of cycle lanes at roundabouts like suggested in previous work (Brilon, 1997; Brüde & Larsson, 1996; van Minnen, 1995).

However, it should be noticed as well that this study, like every observational study, could be affected by some possible confounding elements. The existence of unknown but relevant variables for which variables in the model act as unexpected proxies, could provide an alternative explanation for the relevance of the variables CYCLLANE or CYCLPATH. Since locations are not randomly selected to be converted into a roundabout with cycle lanes or cycle paths, some

response-relevant differences might have been present already from the before-situation (Hauer, 2005). In other words, particular reasons might exist why road authorities decide to construct roundabouts with a particular design instead of some alternatives and those reasons are not always well-known. The existing formal guidelines do not give conclusive guidance on this and too little is known about the informal decision rules that might be applied when the conversion of intersections into roundabouts is considered. Future research could reveal more about these implicit criteria. A possible hypothesis is that in a number of cases, cycle lanes are preferred above cycle paths due to lack of available public space and/or due to excessive expropriation costs. But in those cases some other features like smaller roadways, more parking manoeuvres, less optimal entry or exit radii or non-orthogonal roundabout legs could also be structurally more present and be responsible for an unknown part of the found effect.

The variable SIGNALS is significant in different models which suggest that roundabouts replacing traffic signals perform worse than other roundabouts. Again this result is consistent with the previous study where was found that roundabouts that were replacing signal-controlled intersections have had a worse evolution compared with roundabouts on other types of intersections. Elvik (2003) came to the same conclusion based on a meta-analysis of 28 studies. Nevertheless, the interpretation of this variable should still be interpreted cautiously since the variable SIGNALS refers to a previously (before the roundabout construction) existing difference that was not observable anymore in the examined situation after the roundabout construction. One possible explanation might be related to the violation of one of the basic rules of an experimental design, i.e. the randomness of the assignment of study subjects to the treatment or control group. Engineers are not randomly selecting intersections neither to place traffic signals, nor to convert them afterwards to roundabouts. This could mean that there were particular reasons to equip the concerned intersections once with traffic signals and afterwards to convert the signal-controlled intersections into roundabouts. Those particular reasons could be related to traffic safety, but also to other elements, such as smoother traffic operations. Consequently this could mean that the SIGNAL-variable in our dataset acts as a proxy for other, influencing but unknown variables. Traffic volume is included in our models and its influence is therefore accounted for. A remaining candidate relevant, but unknown parameter could be the degree of 'complexity' of a certain intersection since it could explain why the number of crashes on some locations is higher than expected on the basis of the ADT. Further research on this topic is recommended.

Worth to mention is the distinct role of three-leg roundabouts (3LEG) that was found in some models, in all but one cases with a positive sign, suggesting that three-leg roundabouts perform worse than roundabouts with four or more legs. This finding corresponds with the finding by Elvik (2003) that converting intersections to roundabouts had a greater decreasing effect on injury crashes in four-leg intersections than in three-leg intersections.

The variables EXCEPT and OVAL occur only in one model. In practice they relate only to very small subgroups of roundabouts since both features are each only present in four cases. Therefore their presence in this model has a considerable likelihood to be influenced by chance elements and is not further discussed.

The variable YEAR (construction year of the roundabout) showed a significant contribution in the models for crashes with moped riders and had a negative sign, suggesting a lower number of crashes, at more recently constructed roundabouts. An important comment should be made here: our models are fitting the average annual number of crashes after the roundabout construction which means that, since the roundabouts were constructed in different years, the annual crash data for each roundabout are not reflecting exactly the same time period. Crash data from more recently constructed roundabouts are thus on average more recent than crash data from older roundabouts. Consequently, an alternative explanation for the negative sign of YEAR in the model for mopeds could also be the existence of a general downward trend in the number of crashes with mopeds at roundabouts and is not necessarily related with a better performance of more

recently constructed roundabouts. However, a check of the average yearly crash count at the 35 roundabouts that were constructed before 1996 revealed no downward trend in the number of moped crashes for this subgroup, which supports rather the assumption of the better performance of more recently constructed roundabouts.

Note also that the exposure variable for the volume of pedestrians was not present in the Poisson-model for pedestrian crashes, which might explain why some other, correlating variables like INSIDE were significant in that model. The parameter estimate for the pedestrian volume in the gamma model is below 1, which again corresponds with the "safety in numbers" – thesis for crashes with vulnerable road users. 3LEG had only a negative parameter sign in the model for the crashes with pedestrians.

Variables that were NOT found to be important

It may be relevant to have a look at variables that were not meaningful in any of the presented models, in some cases maybe unexpected. Perhaps the most important among those variables are the ones that describe geometric features, in particular the roundabout dimensions: inscribed circle diameter, central island diameter, the road width or the number of lanes. Particularly the number of lanes was in previous research reported to be a relevant variable (Brüde & Larsson, 2000), but the present results do not confirm the earlier findings on this point. In the before-after studies by Daniels et al. (2009) and in Persaud et al. (2001), roundabouts with two lanes tended equally to perform worse, but also in those cases the number of lanes could act as a proxy for traffic volume and has therefore not necessarily an impact on the crash risk. Further research on this topic is recommended and is of importance.

6. CONCLUSIONS

The main conclusions of this study can be summarized as follows:

- Vulnerable road users (moped riders, motorcyclists, bicyclists, pedestrians) are more often involved in injury crashes at roundabouts than could be expected based on their presence in traffic.
- Variations in crash rates at roundabouts are relatively small and mainly driven by the traffic exposure.
- In the investigated dataset, roundabouts with cycle lanes are clearly performing worse than roundabouts with cycle paths.
- Confirmation is found for the existence of a "safety in numbers"-effect for bicyclists, moped riders and, with less certainty, for pedestrians at roundabouts.
- Some variables turned out to be no meaningful predictors for the number of crashes in the studied sample, in particular the ones that describe the roundabout dimensions: inscribed circle diameter, central island diameter, road width or the number of lanes.
- Due to the nature of a cross-sectional study it cannot be excluded that significant variables in the dataset act as a proxy for other, influencing but unknown variables. This might be particularly the case for the variables SIGNALS (roundabouts replacing signal-controlled intersections) and 3LEG (roundabouts with three legs). This might even not be excluded for the revealed differences between cycle lanes and cycle paths but is less likely in that case due to the better theoretical appeal of the influence of the design types and due to the consistency of this finding with the results of the previous before-and-after-study.
- Continued research on safety effects of different roundabout types and in different countries is recommended.

7. REFERENCES

- Bird, R. N. (2001). Junction Design. In K. J. Button (Ed.), *Handbook of Transport Systems and Traffic Control* (pp. 399-412). Oxford: Elsevier.
- Brilon, W. (1997). Sicherheit von Kreisverkehrplätzen. *Zeitschrift für Verkehrssicherheit*, 43(1), 22-28.
- Brilon, W., Vandehey, M. (1998). Roundabouts - The State of the Art in Germany. *ITE Journal*, (November), 48-54.
- Brown, M. (1995). *The Design of Roundabouts*. London: Transport Research Laboratory.
- Brüde, U., Larsson, J. (1993). Models for predicting accidents at junctions where pedestrians and cyclists are involved. How well do they fit? *Accident Analysis & Prevention*, 25(5), 499-509.
- Brüde, U., Larsson, J. (1996). *The safety of cyclists at roundabouts: a comparison between Swedish, Danish and Dutch results*. Swedish National Road and Transport Research Institute (VTI).
- Brüde, U., Larsson, J. (2000). What roundabout design provides the highest possible safety? *Nordic Road and Transport Research*, 2000(2), 17-21.
- Daniels, S., Brijs, T., Nuyts, E., & Wets, G. (n.d.). Explaining variation in safety performance of roundabouts. *Forthcoming in Accident Analysis & Prevention*. doi: 10.1016/j.aap.2009.08.019.
- Daniels, S., Brijs, T., Nuyts, E., Wets, G. (2009). Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities. *Journal of Safety Research*, 40(2), 141-148.
- Daniels, S., Nuyts, E., Wets, G. (2008). The effects of roundabouts on traffic safety for bicyclists: an observational study. *Accident Analysis & Prevention*, 40(2), 518-526.
- Elvik, R. (2003). Effects on Road Safety of Converting Intersections to Roundabouts: Review of Evidence from Non-U.S. Studies. *Transportation Research Record: journal of the Transportation Research Board*, 1847, 1-10.
- Hauer, E. (2005). Cause and effect in observational cross-section studies on road safety. . Unpublished manuscript, 106 pp., . Retrieved January 27, 2009, from www.roadsafetyresearch.com.
- Jacobsen, P. L. (2003). Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Inj Prev*, 9(3), 205-209.
- Lord, D., Washington, S., & Ivan, J. (2005). Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory. *Accident Analysis & Prevention*, 37(1), 35-46.
- van Minnen, J. (1995). *Rotondes en voorrangsregelingen*. Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.
- Ogden, K. W. (1996). *Safer Roads: A Guide to Road Safety Engineering*. Melbourne, Australia: Ashgate Publishing Ltd.
- Oh, J., Washington, S., & Nam, D. (2006). Accident prediction model for railway-highway interfaces. *Accident Analysis & Prevention*, 38(2), 346-356.
- Pellecuer, L., & St-Jacques, M. (2008). Dernières avancées sur les carrefours giratoires. *Rev. can. génie civ.*, 35, 542-553.
- Persaud, B., Retting, R., Garder, P., & Lord, D. (2001). Safety Effects of Roundabout Conversions in the United States: Empirical Bayes Observational Before-and-after Study. *Transportation Research Record: Journal of the Transportation research Board*, 1751, 1-8.

PIARC (2003). *Road Safety Manual*. Paris: World Roads Association.

Rodegerdts, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., et al. (2007). *Roundabouts in the United States. Report 572*. Washington DC, USA: Transportation Research Board - National Cooperative Highway Research Program.

Schoon, C., van Minnen, J. (1993). *Ongevallen op rotondes II*. Leidschendam, the Netherlands: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.

Statistics Belgium. Road accident data. Brussels, Federal Public Service Economy, SMEs, Self-employed and Energy.

Thai Van, M., Balmeffrezol, P. (2000). Design of Roundabouts in France. *Transportation Research Record, 1737*, 92-97.

Turner, S. A., Roozenburg, A., Francis, T. (2006). *Predicting Accident Rates for Cyclists and Pedestrians*. Land Transport New Zealand.

Washington, S., Karlaftis, M., Mannering, F. (2003). *Statistical and Econometric Methods for Transportation Data Analysis*. Boca Raton, Florida, USA: Chapman & Hall/CRC.