Title: Explaining variation in safety performance of roundabouts.

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ABSTRACT

The conversion of an intersection into a roundabout has been proven to reduce generally the number of crashes 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 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. Poisson and gamma modelling techniques were used, the latter one since underdispersion in the crash data was observed. The results show that the variation in crash rates is relatively small and mainly driven by the traffic exposure. Vulnerable road users are more frequently than expected involved in crashes at roundabouts and 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.

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 & Balmefrezol, 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. Several authors have suggested structural differences in roundabout safety performance according to exposure elements (traffic volume), but also according to some geometric features of roundabouts. Examples of explanatory models for crash counts at roundabouts are described in Brüde & Larsson (2000), Kennedy (2007) and Rodegerdts et al. (2007).

Some other authors attempted to fit models for particular user groups. Most of these models were related to bicyclists, probably since a weaker safety record for bicyclists at roundabouts has often been suggested (Brüde & Larsson, 1996, 2000; Hels & Orozova-Bekkevold, 2007; Layfield & Maycock, 1986; Turner et al., 2006).

The common purpose of all those attempts was to reveal some structural relationships between particular design or traffic characteristics on the one hand and the level of safety of roundabouts on the other hand. In most models, the investigated parameters were traffic volume and some geometric data, such as number of lanes, curvature, number of legs and the central island size. Generally, clear relationships were found between traffic volume (AADT) and crash frequencies. However, within the group of geometric data, few variables showed a more or less structural relationship with the crash frequency.

Three reasons justify a renewed attempt to investigate explaining factors for safety at roundabouts. Firstly, the amount of research in this domain is all in all rather limited. Secondly, design guidelines for roundabouts differ from one country to another, which makes that research results from one country are not necessarily valid for another country and still some efforts are needed to gradually establish better universal knowledge on this topic. Thirdly, design guidelines have evolved over time and the newest roundabouts can be supposed to be designed according to more recent guidelines. Since design guidelines should have benefited from research results that have been found during the past decades, the design of modern roundabouts should therefore reflect improved insights in some elements that affect safety performance. Consequently, explaining factors for the crashes at roundabouts could have evolved over time as well.

The influence of design elements on safety is typically investigated by the fitting of cross-sectional risk models, i.e. models in which the variation in safety performance of a study sample is explained through the use of regression modelling techniques, nowadays most often Poisson regression and negative binomial regression.

The main purpose in the present study is 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 is 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 is 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 remainder of 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 Daniels et al. (2009). For the purpose of the present study, each roundabout in the sample was visited 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. For each roundabout the type of cycle facilities was recorded as well as the presence of line markings or small barriers between the roundabout and the cycle facility (in case of cycle lanes), the priority rules for bicyclists when crossing the exit/entry lanes (in case of separate cycle paths) and the pavement colour. Moreover, the width of the cycle facility – when present - was measured as well as its distance from the roadway. Finally, pedestrian facilities like the presence of a sidewalk around the roundabout, the presence of a zebra marking on the entry or exit lanes and – when present - the distance between the zebra marking and the outer edge of the circulatory roadway were measured. 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)	Number of 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, 56LEG) (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 with 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? (CYCLLANE) (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
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 CYCLLANE=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 (HVY)	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, although this approach has obviously its limitations, see the discussion part. As a result, traffic volume data were available for six different traffic modes. Figure 1 shows box-plots of the frequency of different traffic modes and the variability of the observed values.

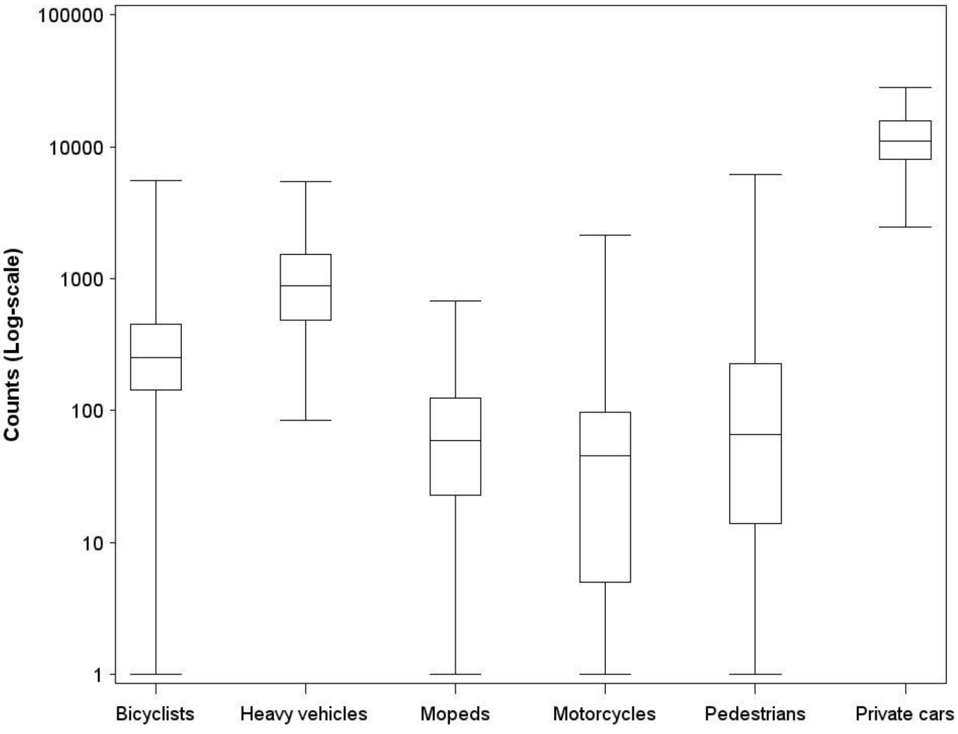

Figure 1 Box plot of average daytime traffic volume counts on the examined roundabouts (presented: largest observation, upper quartile, median, lower quartile, smallest observation)

The traffic counts were done during spring 2008 whereas the crash data for the examined roundabouts were spread over the period from the year after the construction year of the roundabout up to and including 2004, the last year of available data. In order to match the periods of the crash counts with the periods of the traffic counts another calibration procedure was followed. Firstly, the ‘average roundabout year’ was calculated per individual roundabout by considering the, rounded off, median year of available crash data per roundabout. For example, the ‘average roundabout year’ of a roundabout constructed in 1999 was 2002 (median of 2000 till 2004). Subsequently the calculated ADT per roundabout was divided by the mean evolution index of traffic on comparable roads in Flanders (AWV, 2008) for the period from the ‘average roundabout year’ till 2007 (2007 representing the volumes that match best with the traffic counts held during spring 2008). Since similar time series data were only available for aggregate ADT-values and not for particular traffic modes, the correction was only done for the aggregate values. Consequently, the value ADT10H in table 1 was corrected for trend evolutions in traffic volume, but the traffic volumes for the particular traffic modes (values BIC, PED, MOP...) were not.

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 sum 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 roundabouts were multiple-vehicle crashes (Table 3).

Table 4 shows the frequencies of single-vehicle crashes for each road user type and compares the shares of the different traffic modes in the crash counts with their share in traffic. The two most frequent single-vehicle crash types were those with light vehicles and motorcycles. A small p-value for the chi-square test of homogeneity of the two populations indicates strong evidence of heterogeneity: mopeds, bicycles and motorcycles were more frequently involved in single-vehicle crashes than expected on the basis of their traffic share, whereas light vehicles were involved less. The odds-ratios are provided as well in order to get more information about the strength of the association, showing that mainly motorcyclists (OR 19.2) and moped riders (OR 13.2) are overrepresented in single-vehicle crashes.

The collision matrix for multiple-vehicle crashes is shown in Table 5. Light vehicles are involved in more than eight in ten (656 on 737) multiple-vehicle crashes. In 60% of the multiple vehicle crashes either a bicyclist or a moped rider was involved. The three dominant collision types were those between light vehicles mutually, light vehicles against bicyclists and light vehicles against mopeds. No other collision type is found in more than 5% of the multiple-vehicle crashes. The chi-square tests and odds-ratios show that mainly mopeds (OR 47.1) and bicyclists (OR 14.5) are overrepresented in multiple-vehicle crashes.

Table 4 Frequency of single-vehicle crashes per user group

	Light vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Other/ unknown	TOTAL
Single-vehicle crashes	118	10	28	16	16	1	189
%	62.4	5.3	14.8	8.5	8.5	0.5	100
Traffic volume	12139	1176	129	100	526	292	14362
Share in roundabout traffic (in %)	84.5	8.2	0.9	0.7	3.7	2	100
OR[1] (p-value[2])	0.3 (<0.01)	0.6 (0.15)	19.2 (<0.01)	13.2 (<0.01)	2.4 (<0.01)	0.3 (0.14)	

[1] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 single-vehicle crashes for the road user type divided by single-vehicle crashes of all the other road users and Ω_2 volume of road users at the roundabouts divided by volume of all the other road users

[2] p-value of the chi-square test with null hypothesis H_0: proportion of single-vehicle crashes per road user type homogeneous with share in roundabout traffic. H_0 rejected if $p \leq 0.05$

Table 5 Collision matrix for multiple-vehicle crashes (N= 737)

	Light vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Pedes-trian	Other/ unknown	∑
Light vehicle	217	24	21	143	207	23	16	651
Heavy vehicle	24	2	2	10	19	3	1	61
Motorcycle	21	2	0	2	2	0	0	27
Moped	143	10	2	3	17	6	2	183
Bicycle	207	19	2	17	8	7	2	262
Pedestrian	23	3	0	6	7	0	0	39
Other/ unknown	16	1	0	2	2	0	0	21
∑	651	61	27	183	262	39	21	
% of crashes	88.3	8.3	3.7	24.8	35.5	5.3	2.8	100
Traffic volume	12139	1176	129	100	526	292		14362
Share in roundabout traffic (in %)	84.5	8.2	0.9	0.7	3.7	2		100
OR[1] (p-value²)	1.4 (0.01)	1.0 (0.93)	4.2 (<0.01)	47.1 (<0.01)	14.5 (<0.01)	2.7 (<0.01)		

[1] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 single-vehicle crashes for the road user type divided by single-vehicle crashes of all the other road users and Ω_2 volume of road users at the roundabouts divided by volume of all the other road users

² p-value of the chi-square test with null hypothesis H_0: proportion of single-vehicle crashes per road user type homogeneous with share in roundabout traffic. H_0 rejected if $p \leq 0.05$

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 have in the last decade most often been modelled by Poisson or negative binomial regression models. Much literature dealt with the phenomenon of overdispersion that is often found in crash data. 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. Some models were also fit without transforming the exposure variables, but the transformed data delivered a better fit. The relative shares of the different traffic modes (percentage of motorcycles, pedestrians...) were initially considered as explanatory variables as well, but they were omitted later since they turned out to correlate often strongly with the absolute exposure values and to yield no improvements in the models.

As a result, the functional form of the chosen models was the following:

$$E(\lambda) = e^{\alpha}.\,{Q_1}^{\beta_1}.\,{Q_2}^{\beta_2}.\,e^{\sum_{i=1}^{n}\gamma_i.x_i} \qquad (1)$$

with E(λ) = expected annual number of crashes

Q_1 = ADT (motor vehicles)

Q_2 = traffic volume for particular vehicle types (bicyclists, mopeds,...)

x_i = other explanatory variables

α, β_1, β_2, γ_i = model parameters

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). Gamma models allow for variances that are not constant or equal to the mean, but rather proportional to the square of the mean (Myers et al., 2002). Gamma probability models allow for both overdispersion and underdispersion in the data.

The gamma model makes use of the gamma probability distribution that for a given λ

$$f(\lambda;\varphi;\mu) = \frac{(\varphi/\mu)^{\varphi}.e^{(-\varphi.\lambda/\mu)}.\lambda^{\varphi-1}}{\Gamma(\varphi)};\ \lambda \geq 0 \qquad (2)$$

with E(λ) = μ and VAR(λ) $= \frac{\mu^2}{\varphi}$

φ is the dispersion parameter. Underdispersion exists if $\varphi > 1$, overdispersion if $\varphi < 1$, equidispersion if $\varphi = 1$ (Agresti, 2002).

All models were fitted by using the GENMOD-procedure in SAS and made use of the log link function. The following modelling procedure was followed: initially, all possible explanatory variables were included in the models. Next, variables were removed step by step according to the following criteria:

- Inspection of the correlation matrix. In case of strong correlation ($\rho \geq 0.6$) one of the two correlating variables was eliminated, in principle the variable with the highest p-value and under the condition that the model fit did not deteriorate strongly (checked by the Akaike Information Criterion). If the remaining variable was eliminated in a further step in the modelling process, the correlating variable was re-introduced in the model and subsequently checked for its significance. In case of strong correlations between geometric variables and exposure variables the last ones were kept in the models since there are well established grounds (e.g. Fridstrøm et al., 1995; Greibe, 2003) to consider them as important predictors .
- Non – significant variables, each time with a more severe criterion. In none of the final models variables were left with an individual significance value above 0.2.
- Goodness of fit of the models was evaluated by the Akaike Information Criterion (AIC). The best fitting model was the model with the lowest value for the AIC.

The list of available explanatory variables consisted of 40 possible covariates. Interaction terms were constructed in order to model variables that were only relevant in specific cases, e.g. the variable PHYS (physical elements between roadway and cycle facility) that was only recorded in case of a cycle lane roundabout (CYCLLANE=1).

The variable YEAR (construction year of the roundabout) was initially modelled as a categorical variable, delivering individual parameter estimates for all years but one (compared with the reference year). Since it appeared that in most models the relationship between the annual average of crashes and the construction year showed a more or less linear shape, the variable YEAR was scaled into a series with the first year (1994) =1, the second year = 2 etc. and subsequently included in the models as a continuous variable. This enabled a single parameter estimate for the variable YEAR which did in practice not affect the model fits and which enabled a more straightforward interpretation of the results.

Furthermore, models were checked on their stability and the comprehensibility of the estimated effects. Variables were assessed in terms of their correlations with some other candidate variables and in terms of their theoretical appeal (Maher & Summersgill, 1996).

4. RESULTS

The results are provided in Table 6 and Table 7. The results for the Poisson models and the gamma models are both provided. 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 less than one in the Poisson model, suggesting an increase with higher traffic volumes at a decreasing rate. However, the gamma model shows a different result with an estimate for β_1 above 1. The parameter estimates for the bicyclist volumes are similar for the Poisson models and the gamma models.

Specific models were fit for crashes with particular road users: bicycles, mopeds, motorcycles, heavy vehicles, light vehicles and pedestrians. The models for crashes with light vehicles are very similar to the models for all crashes, which was not unexpected due to the dominancy of crashes with private cars in the entire dataset. Crashes with bicyclists are explained by the ADT and the volume of bicyclists, both in the Poisson and gamma models. Two additional variables turned out to be significant in the gamma models, LN(MOP) and CYCLLANE, both with positive parameter estimates. 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 always consistently for the Poisson and the gamma models, and not always strongly significant.

A number of similarities relating to vehicle dimensions, speed properties, use of cycle facilities and position on the road can be assumed to exist between bicyclists and moped riders. An extra model was therefore fitted for all crashes where at least one bicyclist or moped rider was involved. Besides the two exposure variables (ADT and BICMOP, the joint volume of bicycles and mopeds), three geometric variables appeared to be relevant in this model: the presence of a cycle path (with a negative parameter sign), SIGNALS (only in the Poisson model) and 3LEG.

The best fitting models for both the crashes with motorcycles and with heavy vehicles were ADT-only models. In the Poisson model for crashes with pedestrians no variable was significant at the 5%-level. In the gamma model the variables CYCLLANE, SIGNALS, 3LEG (with, on the contrary of some other models, a negative parameter) and INSIDE (roundabout inside built-up area) were significant.

Furthermore separate models were fit for single-vehicle crashes and for multiple-vehicle crashes. The results are provided in Table 7. The number of single-vehicle crashes turns out to be explained by the ADT, by the presence of a pass-through for exceptional transport (EXCEPT) and in cases of oval roundabouts (OVAL), the latter two only in the gamma model. Multiple-vehicle crashes are affected by the ADT, by the presence of two-wheelers (bicyclists in the gamma model, bicyclists and mopeds together in the Poisson model) and furthermore by the variables CYCLPATH (Poisson model) / CYCLLANE (gamma model), 3LEG and, only in the Poisson model, SIGNALS.

Table 6 Parameter estimates for Poisson and gamma-models with particular road users

Variables[1]	All crashes	Crashes with light vehicles	Crashes with bicyclists	Crashes with mopeds	Crashes with mopeds or bicyclists	Crashes with motor-cycles	Crashes with heavy vehicles	Crashes with pedestrians
Intercept	-9.20 (<0.01) *-11.68 (<0.01)*	-9.41 (<0.01) *-11.72 (<0.01)*	-10.06 (<0.01) *-14.85 (<0.01)*	-9.15 (0.06) *-15.35 (<0.01)*	-9.53 (<0.01) *-13.84 (<0.01)*	-15.68 (0.06) *-25.70 (<0.01)*	-14.05 (0.06) *-15.55 (<0.01)*	-22.68 (0.04) *-31.07 (<0.01)*
LN(ADT)	0.89 (<0.01) *1.16 (<0.01)*	0.88 (<0.01) *1.13 (<0.01)*	0.78 (0.03) *1.19 (<0.01)*	0.73 (0.16) *1.38 (<0.01)*	0.74 (0.02) *1.20 (<0.01)*	1.38 (0.11) *2.44 (<0.01)*	1.23 (0.11) *1.39 (<0.01)*	1.99 (0.08) *2.77 (<0.01)*
LN(BIC)	0.14 (0.04) *0.11 (0.03)*	0.15 (0.05) *0.13 (0.02)*	0.27 (0.04) *0.24 (0.05)*					
LN(BICMOP)					0.33 (<0.01) *0.33 (<0.01)*			
LN(MOP)			*0.21 (0.05)*	0.29 (0.07) *0.24 (0.01)*				
LN(PED)								*0.27 (<0.01)*
CYCLPATH					-0.65 (0.02) *-0.65 (0.01)*			
CYCLLANE	0.40 (0.03) *0.38 (0.02)*	0.40 (0.04) *0.38 (0.02)*	*0.58 (0.05)*					*1.57 (<0.01)*
SIGNALS	*0.35 (0.09)*	0.40 (0.10) *0.37 (0.08)*		0.94 (0.07)	0.63 (0.05)			
YEAR				-0.23 (0.05) *-0.19 (0.02)*				
3 LEGS	*0.32 (0.09)*	*0.33 (0.09)*		0.90 (0.07) *1.06 (0.01)*	0.63 (0.05) *0.62 (0.05)*			*-1.28 (0.01)*
INSIDE								1.71 (0.07)
AIC	228.36 *198.10*	211.28 *167.63*	129.91 *-42.67*	106.42 *-167.52*	166.74 *63.08*	47.86 *-496.63*	53.61 *-448.91*	41.15 *-590.48*
Dispersion parameter[2] (φ)	*0.52*	*0.57*	*1.80*	*2.38*	*1.44*	*3.57*	*3.65*	*3.14*

[1] values in normal typeface are results from the Poisson-models, values in italics are from the gamma models; ( ) p-values; explanatory variables only included if $p \leq 0.10$, except for LN(ADT) that is always included.

[2] for the gamma models: overdispersion if $\varphi<1$, underdispersion if $\varphi j>1$, equidispersion if $\varphi=1$

Table 7 Parameter estimates for Poisson and gamma-models with single/multiple-vehicle crashes

Variables[1]	**Multiple-vehicle crashes**	**Single-vehicle crashes**
Intercept	-10.72 (<0.01) *-14.52 (<0.01)*	-8.09 (0.05) *-10.18 (<0.01)*
LN(ADT)	0.98 (<0.01) *1.37 (<0.01)*	0.72 (0.10) *0.93 (<0.01)*
LN(BICMOP)	0.23 (0.01)	
LN (BIC)	*0.19 (0.01)*	
CYCLPATH	-0.42 (0.05)	
CYCLLANE	*0.47 (0.03)*	
3 LEGS	0.48 (0.06) *0.53 (0.03)*	
SIGNALS	0.50 (0.05)	
EXCEPT		*2.78 (0.03)*
OVAL		*-4.44 (<0.01)*
AIC	204.35 *160.24*	106.53 *-123.33*
Dispersion parameter[2] (φ)	*0.90*	*2.09*

[1] values in normal typeface = Poisson-models, values in italics = gamma models; ( ) = p-values; explanatory variables only included if $p \leq 0.10$

[2] for the gamma models. Overdispersion if $\varphi<1$, underdispersion if $\varphi>1$, equidispersion if $\varphi=1$

For those response variables that showed an overdispersion some negative binomial models were also fit. The results were very similar to the Poisson models and are not presented for reasons of brevity. 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, but it was preferred to present the best fitting models and to comment upon some interpretations hereunder.

5. DISCUSSION

5.1. Modelling approach

The gamma probability models show systematically better fits than the Poisson models in terms of their AIC-values. Also when models with exactly the same covariates were compared, the gamma models appeared to perform systematically better. The gamma models tend to include more variables than the Poisson-models.

Theoretically, underdispersion and even equidispersion are not expected in crash data and one might question whether the observed underdispersion is an artefact of the data or reveals a high structural homogeneity of the examined locations. Although the gamma probability models seemed to be able to fit the observed data in this particular dataset better, it was useful as well to fit Poisson models in order to show the effects of different assumptions for the random structure of the data and to avoid a tendency toward overfitting the data. As a conclusion it seems that the identified relevant variables throughout the different models are rather consistent for both types of regression models. Figure 2 shows the predicted yearly crash numbers for the 90 roundabouts for the three possible model approaches (Poisson, negative binomial and gamma). The used model is each time the model for all crashes, but limited to one explanatory variable (ADT). The figure shows similar results for the three models in the observed range of ADT-values, although it seems as well that the curves of the Poisson and the negative binomial models resemble each other, while the gamma model is yielding higher predictions in case of higher ADT-values and somewhat lower predictions in the lower range of ADT’s.

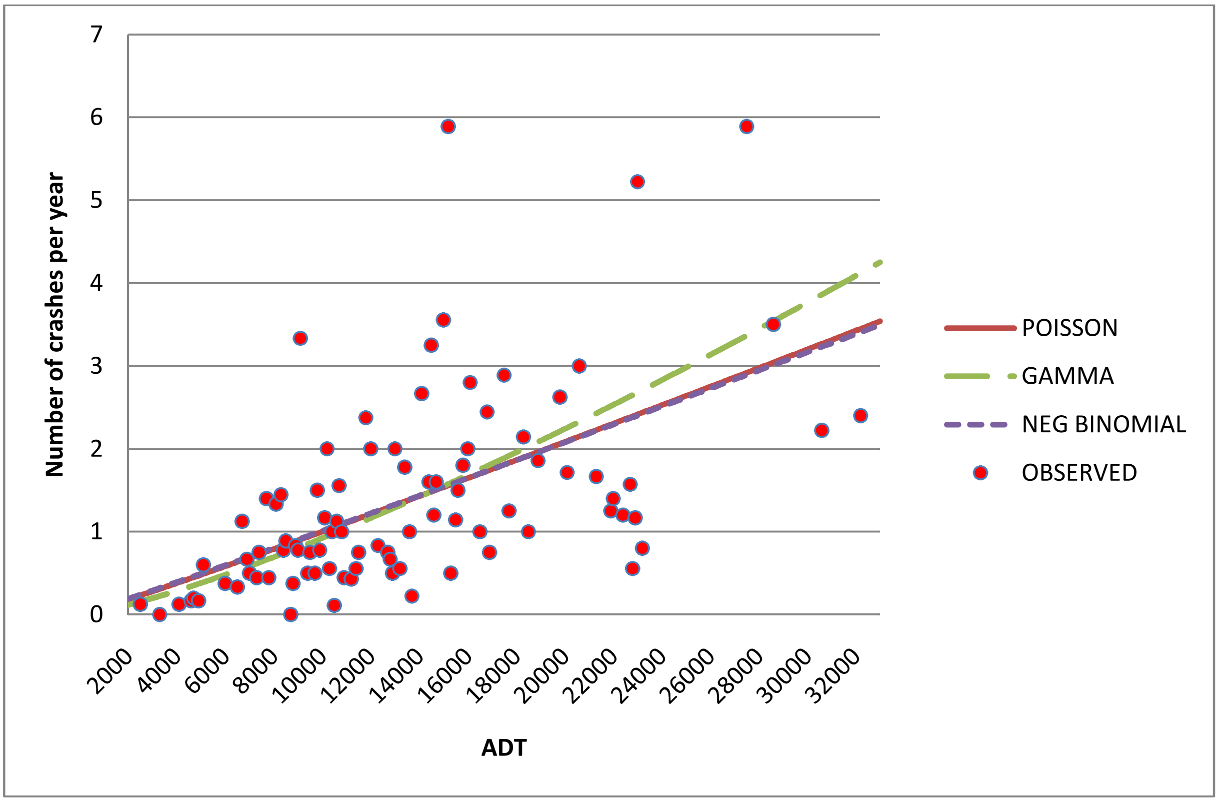

Figure 2 Predicted yearly crash numbers related to ADT (exposure-only model for all crashes)

Attempts were made to deal with multicollinearity which was an expected phenomenon in this dataset. Especially some variables that turned out to be significant predictors for some models were checked on their correlations with other variables in the dataset. For instance the variable SIDEWALK (presence of a footpath alongside the roundabout) turned out to be significant in some models. A logistic regression of the odds of SIDEWALK =1 upon a series of explanatory variables showed the variables LN_ADT (-), LN_PEDESTRIANS (+) and ZEBRA (+) to be significant. This raised the question to which degree the presence of a sidewalk was measuring another concept, most likely merely exposure variables like ADT and the presence of pedestrians. It was therefore decided to replace SIDEWALK by an exposure variable in cases when this had only a minor influence on the model fit.

5.2. 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 is 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 like it was already shown in the collision matrix in Table 5.

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 few 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.

5.3. Variables that were NOT found to be important

Subsequently, it is important 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.

5.4. Study limitations

It is clear that a study based on a relatively small sample of locations in one particular country should not pretend to be valid for all possible roundabout designs wherever applied. Nevertheless, we believe that the results confirm some earlier findings but also shed a new light on some others. In that sense this study should be considered as one in a series of efforts, made and to be made by many in different countries, which should gradually enable to develop consistent theories and guidelines about safety issues at roundabouts.

The registered variables were based partly on those that were used in similar studies and for another part derived from and limited to the practical possibilities to collect information about them. This means as well that information could not be collected about all possible useful variables. Mainly some parameters to reflect actual or potential vehicle speeds at roundabouts were not present in the used dataset and were earlier reported to be important (Hels & Orozova-Bekkevold, 2007; Layfield & Maycock, 1986; Maycock & Hall, 1984). However, Rodegerdts et al. (2007) found no reliable relationship between speeds and the crash frequency at roundabouts where actual speeds were measured.

Another limitation relates to the traffic counts that were derived from the one hour – measurements at the roundabout locations. Undoubtedly, the inference of ADT-values from one hour-counts brings some extra uncertainty in the results. Moreover, no night-time traffic counts were available. The assumption in the study was that daytime traffic is a valid indicator for the relative 24h traffic volume for each location, i.e. for the locations compared with each other. This assumption is supported by the fact that the share of daytime traffic between 8:00 and 18:00 in the total 24 hour traffic on comparable regional N-roads is 61.35%, with a standard deviation of only 2.33% (AWV, 2008). Since the obtained traffic data were believed to be valid predictors for 24h traffic, it was preferred to include all the crashes, thus also night-time crashes, in the study sample. None of the included geometric variables were believed to exert a specific effect on night-time crashes.

A further restriction lies in the poor knowledge of some changes in the roundabout design that may have been made after the initial construction of the roundabout. Although major changes are not common, adaptations at a certain moment after the roundabout construction such as changes in road markings (e.g. to create an extra lane on the roundabout), improved road lighting or signposting are sometimes made. No information on this was available which meant that this could not be accounted for. It can be assumed that some of the treatments that were done after the roundabout construction were – intentionally or not – affecting road safety.

A last issue deals with the underlying quality of the used crash data. The official reporting of crash data has been proved to be incomplete and possibly biased. Incomplete reporting would have no further consequences, if it was not biased by other variables like the type of crash (single-vehicle/multiple-vehicle) or the type of involved road user. Research has shown that the reporting rate is dependent from the road user type. Elvik & Mysen (1999) found in a meta-analysis the highest reporting rates for car occupants, generally slightly lower rates for pedestrians, still lower for motorcyclists and the lowest for bicyclists. Obviously, such a biased reporting rate might be influential to our data in that sense that the odds-ratios like shown in Table 4 and in Table 5 for bicyclists and, to a lesser extent for moped riders, motorcyclists and pedestrians, might still be underestimations, although they are already well above 1.

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 then could be expected based on their presence in traffic. Moped riders and motorcyclists are overrepresented in single-vehicle crashes whereas moped riders and bicyclists are overrepresented in multiple-vehicle crashes.
- 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.

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