Title: Extended prediction models for crashes at roundabouts.

Authors: Stijn Daniels[1°], Tom Brijs[1], Erik Nuyts[2], Geert Wets[1]

[1] Hasselt University - Transportation Research Institute
Wetenschapspark 5 bus 6 3590 Diepenbeek
Belgium
Tel. +32 11 26 91 11 Fax +32 11 26 91 99 e-mail {stijn.daniels; tom.brijs; geert.wets}@uhasselt.be

[2] PHL University College - Architecture, Art and Design Research Institute
Universitaire Campus Building E 3590 Diepenbeek
Belgium
Tel. +32 11 24 92 13 e-mail erik.nuyts@phl.be

° Corresponding author

Manuscript published in *Safety Science*

Please cite as follows:

Daniels, S., Brijs, T., Nuyts, E., Wets, G., 2011. Extended prediction models for crashes at roundabouts. Safety Science 49, 198–207.

https://doi.org/10.1016/j.ssci.2010.07.016

Key words: roundabout, Poisson, gamma, model, regression, crash, safety

ABSTRACT

This paper builds upon the results of previously developed crash prediction models for roundabouts. The originally investigated sample was extended from 90 to 148 roundabouts. Poisson and gamma modelling techniques were used, the latter ones since underdispersion in the crash data was observed. Separate models were fit for crashes with six different types of road users: bicyclists, motorcyclists, passenger and heavy four-wheel vehicles, moped riders and pedestrians. A further distinction was made between single-vehicle and multiple-vehicle crashes.

The results show that the overall number of crashes is more or less proportional to the number of motorized vehicles. The mean number of single-vehicle crashes per passing vehicle is lower on busier roundabouts. Confirmation is found for the existence of a ‘safety in numbers’ effect for different types of road users. Three-leg roundabouts tend to perform worse than roundabouts with four or more legs. More crashes seem to occur at roundabouts with bypasses for traffic in some direction. Larger central islands correlate with more single-vehicle crashes. Moped riders and motorcyclists are strongly overrepresented in both single-vehicle and multiple-vehicle crashes whereas bicyclists are clearly overrepresented in multiple-vehicle crashes. Roundabouts with cycle paths perform better than roundabouts with other types of cycle facilities, particularly in comparison with roundabouts with cycle lanes close to the roadway.

1. INTRODUCTION

Compared with other types of intersections, roundabouts have some intrinsic properties favouring traffic safety: they reduce speeds considerably and they decrease the number of possible conflict points between road users. With respect to traffic safety, the conversion of an intersection into a roundabout has consistently 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 some user groups, in particular bicyclists, are less favourable or even unfavourable (Daniels et al., 2009, 2008; Schoon and van Minnen, 1993).

In a previous study (S. Daniels, T. Brijs, E. Nuyts, & G. Wets, 2010) the same authors elaborated crash prediction models, based on a sample of 90 roundabouts in Flanders-Belgium. The results showed that the variation in crash rates was relatively small and was mainly driven by the traffic exposure. Vulnerable road users turned out to be involved more frequently than expected in crashes at roundabouts and roundabouts with cycle lanes close to the roadway were clearly performing worse than roundabouts with cycle paths on some distance from the roadway. Furthermore confirmation was found for the existence of a 'safety in numbers' effect for bicyclists, moped riders and –with less certainty– for pedestrians at roundabouts.

We acquired information on an additional set of 58 roundabouts. As a result, a dataset of 148 roundabouts including geometric information, crash data and exposure data was available. Moreover one additional year of crash data could be incorporated. Since the additional data enabled to extend the models substantially, it was felt useful to incorporate these extra data into the existing models. This enabled to check the robustness of the previously stated results and to reveal structures in the dataset that were not or insignificantly present in the previous dataset. Moreover, the applied methods were somewhat refined. This work is presented in the current paper.

Elements that correspond strongly to the information presented in the previous paper will only be repeated very briefly in order to put the focus on modified or added elements and to avoid needless repetition. Nevertheless, the provided information in the present paper should be sufficiently complete to stand on itself and to allow a comprehensive understanding of the performed analyses and the resulting conclusions.

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

The dataset was based on a previously composed dataset of 90 roundabouts (S. Daniels et al., 2010), that was extended. The dataset consisted of three categories: geometric data, traffic counts and crash data. Extra data for the three categories could be collected for an extra sample of 58 roundabouts. The nature of the available data on geometry and traffic volume was identical to that of the previous dataset and is explained below. Apart from the extension of the number of objects in the dataset, crash information from one extra year (2005) was included. In the remainder of this paper we will use the terms 'existing' and 'additional' data to refer respectively to the previously composed dataset of 90 roundabouts and the additional data on 58 roundabouts. With 'extended dataset' we will refer to the full dataset of 148 roundabouts.

Each roundabout in the sample was visited and photographed, traffic counts were executed and geometric data were collected on the spot. Information on the construction year of the roundabout was available from the Roads and Traffic Agency's database. All investigated roundabouts were constructed between 1990 and 2002. The collected variables are listed in Table **1**.

Values for the variable SIGNALS (traffic signals present in the before-situation) were not available for the additional roundabout sample. This variable was therefore excluded for further analysis in this paper.

Average daily traffic data (08:00-18:00) were estimated for each roundabout based on a traffic count of all entering traffic during one hour. Traffic modes were classified into passenger vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Passenger vehicles comprised mainly private cars, but also minibuses and all kinds of vans. Heavy vehicles were trucks, trailers, busses and tractors. The followed procedure was identical to the one that was previously adopted (Daniels et al., 2010).

The 148 roundabout locations were localised and geo-coded in Google Earth. Subsequently the roundabout data were linked in a geographical information system (ESRI ArcMap) with the geo-referenced crash data (available from Statistics Belgium) for the period 1996-2005. 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 extended dataset consisted of 1491 injury crashes.

Table 2 shows elementary descriptive statistics of the previously existing versus the extended dataset. The mean (μ) number of crashes dropped in the extended dataset from 1.37 to 1.22, while the variance (σ^2) decreased somewhat from 1.39 to 1.33. A comparison between the two columns in Table 2 shows that the addition of one year extra crash data does not explain the differences.

These differences could be related to the applied selection criteria. The existing dataset of 90 roundabouts was randomly selected from a dataset of all existing roundabouts on regional roads in Flanders that were constructed between 1994 and 2000. The additional dataset was selected from the same original dataset and consisted of the remaining roundabouts in the dataset on regional roads in three of the five Flemish provinces (Antwerp, Flemish Brabant and Limburg). Additionally, 9 roundabouts were included that were constructed in 2001 or 2002.

Table 1 Explanatory variable description

Variable (ABBREVIATION)	Number of observations	Descriptive statistics
Inside built-up area? (INSIDE) (1 = Yes; 0 = No, thus outside)	148	Yes: 55; No: 93
Central island min. 0.5 m raised? (ELEV) (1 = Yes; 0 = No)	148	Yes: 115; No: 33
Traversable truck apron present? (APRON) (1 = Yes; 0 = No)	148	Yes: 141; No: 7
Central island diameter (in meters) (CENTRDIAM)	148	Mean: 25.22; S.D.: 12.30
Inscribed circle diameter (in meters) (OUTDIAM)	148	Mean: 40.29; S.D.: 12.85
Number of legs (3LEGS, 4LEGS, 56LEGS) (1 = Yes; 0 = No)	148	3-leg: 32; 4-leg:100; 5-or 6-leg: 16
Gated roadway through the central island? (EXCEPT) (1 = Yes; 0 = No)	148	Yes: 4; No: 144
Bypass present in some directions? (BYPASS) (1 = Yes; 0 = No)	148	Yes: 22; No: 126
Oval roundabout? (OVAL) (1 = Yes; 0 = No)	148	Yes: 8; No: 140
Two-lane roundabout? (TWOLANE) (1 = Yes; 0 = No, thus single-lane)	148	Yes: 15; No: 133
Road width on the roundabout (all lanes together, in meters) (ROADWIDTH)	133	Mean: 6.38 ; S.D.: 1.26 (single-lanes)
	15	Mean: 7.78 ; S.D.: 1.41 (two-lanes)
Construction year of the roundabout (YEAR)	148	Median: 1996; range [1990;2002]
Mixed Traffic? (MIXED) (1 = Yes; 0 = No)	148	Yes: 13; No: 135
Cycle lanes? (CYCLLANE) (1 = Yes; 0 = No)	148	Yes: 64; No: 84
Cycle paths? (CYCLPATH) (1 = Yes; 0 = No)	148	Yes: 66; No: 82
Grade-separated cycle facilities? (GRADESEP) (1 = Yes; 0 = No)	148	Yes: 4; No: 144
Sidewalk present around the roundabout? (SIDEWALK) (1 = Yes; 0 = No)	148	Yes: 71; No: 77
Zebra markings present on exit/entry lanes? (ZEBRA) (1 = Yes; 0 = No)	148	Yes: 75; No: 73
Nr. of pedestrians 8:00-18:00 (PED)	148	Mean: 246; S.D.: 645
Nr. of bicyclists 8:00-18:00 (BIC)	148	Mean: 470; S.D.: 765
Nr. of mopeds 8:00-18:00 (MOP)	148	Mean: 76; S.D.: 108
Nr. of motorcycles 8:00-18:00 (MCY)	148	Mean: 98; S.D.: 260
Nr. of passenger vehicles 8:00-18:00 (LIGHT)	148	Mean: 11627; S.D.: 5818
Nr. of heavy vehicles 8:00-18:00 (HEAVY)	148	Mean: 1155; S.D.:1237
Nr. of entering motor-vehicles 8:00-18:00 (ADT)	148	Mean: 12881; S.D.: 6491

Table 2 Average annual number of crashes per roundabout

	1996-2004	1996-2005
N=90 (existing data)	$\mu = 1.37$, $\sigma^2 = 1.39$	$\mu = 1.35$, $\sigma^2 = 1.31$
N=58 (extra data)	$\mu = 1.03$, $\sigma^2 = 1.46$	$\mu = 1.01$, $\sigma^2 = 1.33$
N=148 (full dataset)	$\mu = 1.23$, $\sigma^2 = 1.44$	$\mu = 1.22$, $\sigma^2 = 1.33$

The descriptive statistics like reflected in Table 1were compared between the two samples by means of significance tests for the difference between two proportions (z-tests). Compared to the original 90 roundabout dataset, the 58 added locations turned out to be more often located outside built-up areas (72% of the cases instead of 57% before, z=1.93, p 0.05). However, when the 9 roundabouts that were constructed after 2000 were excluded from the added sample of 58, the proportions of roundabouts outside built-up areas became almost equal (72% versus 69%, z= 0.34, p 0.73). This could indicate that road authorities started to convert more often intersections outside built-up areas into roundabouts more recently. A difference was also found for the average daily traffic (ADT) that was lower in the additional dataset (12004) then in the existing dataset (13416). This difference appears not to be related to the higher proportion of roundabouts outside the built-up area in the new dataset. On the contrary, roundabouts outside built-up areas have throughout the extended dataset higher average ADT's then roundabouts inside built-up areas (13566 and 11674 respectively). Furthermore, it should be noticed that identical calculation and calibration procedures for the traffic volume in both datasets were applied (see Daniels et al., 2010).

A conclusion based on these elements is that the new dataset differs to some extent from the existing dataset in the sense that the added roundabouts were on average less busy and more often located outside built-up areas. It will be checked further in this paper to what extent the conclusions derived from the analyses of the existing data will remain valid for the extended dataset. All analyses in the remainder of this paper will be made for the entire extended dataset of 148 roundabouts.

Table 3 shows the average annual number of crashes per roundabout in the extended dataset, for each different road user type separately. The crashes were classified according to the same six road user groups as the traffic counts: passenger vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Passenger vehicles were involved in 85% of all registered injury crashes at the investigated roundabouts. Bicyclists were present in 28% of the crashes and mopeds in 18%. 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 crash counts (column 1) and the percentages (column 2) in Table 3 exceed the totals in the first row.

Moped riders, bicyclists, motorcyclists and pedestrians were more frequently involved in crashes than would be expected based on their average share in traffic on the observed locations. Passenger and heavy vehicles were almost as frequently involved as expected.

Table 3 Frequency statistics of crashes in the roundabout dataset according to type of involved road user

	Crash counts	**Proportion of total crashes**	**Avg/year/ roundbt.**	**Variance**	**Proportion of traffic volume**	**χ^2**	**p[1]**
Injury crashes at the 148 roundabouts	1491	100	1.22	1.33			
Injury crashes with at least one							
pass. vehicle	1261	0.846	1.04	1.08	0.850	0.23	0.63
bicycle	410	0.275	0.33	0.17	0.034	1423.66	<0.01
moped	270	0.181	0.21	0.13	0.006	1857.59	<0.01
heavy vehicle	111	0.074	0.09	0.02	0.084	1.77	0.18
motorcycle	97	0.065	0.08	0.01	0.007	354.89	<0.01
pedestrian	61	0.041	0.05	0.01	0.018	35.60	<0.01

[1] significance of the chi-square test with null hypothesis H_0: proportion of crashes per road user type equals share in roundabout traffic. H_0 rejected if $p \leq 0.05$

Table 4 Frequency statistics of crashes in the roundabout dataset according to crash type

	Counts[1]	% of total	Avg/year/ roundbt.	Variance
Single-vehicle crashes	329	22.1	0.29	0.26
Multiple-vehicle crashes	1151	77.2	0.92	0.94

[1] For 11 crashes the type is unknown

Crashes were subdivided according to the number of involved road users. Almost eight in ten of the reported crashes at the roundabouts were multiple-vehicle crashes (Table 4).

Table 5 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 important single-vehicle crash types were those with passenger vehicles and motorcycles. A small p-value for the chi-square test of homogeneity of the two populations indicates strong evidence of heterogeneity. Mopeds and motorcycles were more frequently involved in single-vehicle crashes than expected on the basis of their traffic share, whereas the four-wheeled vehicles (passenger and heavy) were less involved. The magnitude of the odds ratios for motorcyclists (OR 23.1) and moped riders (OR

13.4) show that the revealed effects were not only significant but substantial as well. Compared to the existing dataset, two results changed: firstly, the result for the heavy vehicles became significant at the 5%-level and secondly, the odds ratio for the bicyclists decreased and is not longer significant at the 5%-level. A clearer distinction seems therefore possible between road user groups that show (strong) over-involvement in single-vehicle crashes (mopeds and motorcycles) and groups showing under-involvement (four-wheel vehicles) relative to their traffic participation.

The collision matrix for multiple-vehicle crashes is shown in Table 6. Passenger vehicles are involved in 90% of all multiple-vehicle crashes, bicyclists in 34% and mopeds in 21%. The most dominant collision types were those between passenger vehicles mutually, passenger vehicles against bicyclists and passenger vehicles against mopeds. No other collision type is found in more than 5% of the multiple-vehicle crashes.

Also in Table 6, odds ratios were calculated for the relative occurrence of crashes in comparison with the traffic participation for each road user type. In order to estimate the probability of occurrence of road user types in crashes, it was assumed that exactly two road users or vehicles were involved in every multiple-vehicle crash. The calculated odds ratios show that mainly moped riders, bicyclists and motorcyclists are overrepresented in multiple-vehicle crashes when compared with their traffic participation.

Table 5 Frequency of single-vehicle crashes per user group (N=329)

	Pass. vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Other/ unknown	TOTAL
Number of single-vehicle crashes	223	17	47	23	17	2	329
% of all single-vehicle crashes	67.8	5.2	14.3	7	5.2	0.6	100
Average volume	11627	1155	98	76	470	246	13672
Share in roundabout traffic (in %)	85	8.4	0.7	0.6	3.4	1.8	100
OR[1] (p-value[2])	0.4 (<0.01)	0.6 (0.03)	23.1 (<0.01)	13.4 (<0.01)	1.6 (0.08)	0.33 (0.11)	

[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 6 Collision matrix for multiple-vehicle crashes (N= 1138)[1]

	Pass. vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Pedes-trian	∑
Passenger vehicle	407	41	35	189	316	38	1026
Heavy vehicle	41	4	3	11	29	4	92
Motorcycle	35	3	0	3	3	1	45
Moped	189	11	3	7	21	9	240
Bicycle	316	29	3	21	10	7	386
Pedestrian	38	4	1	9	7	0	59
∑	1026	92	45	240	386	59	
% of crashes[2]	90.2	8.1	4	21.1	33.9	5.2	
Traffic volume	11627	1155	98	76	470	246	13672
Share in roundabout traffic (in %)	85.0	8.4	0.7	0.6	3.4	1.8	100
Probability (in %) of at least one road user of this type in a random selection of 2 road users[3]	97.8	16.2	1.4	1.1	6.8	3.6	
Odds ratio[4]	0.9	0.5	2.9	19.2	5	1.4	

[1] One or both road user types were not known for 13 crashes. These were not included

[2] to read as “involved in x % of the total number of crashes. Since two or more different types of road users are involved in many crashes, the sum of the percentages in this row exceeds 100.

[3] Calculated by applying the probability rule P(A or B) = P(A) + P(B) – P(A and B) for non-mutually exclusive events A and B

[4] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 % of crashes with this road user type and Ω_2 probability of at least one road user of this type in a random selection of two road users

An interesting subsequent step was to assess whether the real crash involvement for the different combinations of road user types corresponded with the expected involvement based on the traffic participation of each road user type. This was done by evaluating the frequency of collisions for each possible combination of road user types in comparison with the frequency of encounters between those vehicle types. Therefore we adopted the following procedure:

In a first step, the number of encounters between at least 2 road users was theoretically derived from the available exposure data. To this end, the assumptions made by Elvik et al. (2009) were adopted and slightly modified:

1. Multiple-vehicle collisions are not possible without encounters of at least two vehicles. An encounter is defined as a quasi-simultaneous arrival at the roundabout, i.e. within an interval of 1s. Opposite to the approach by Elvik et al., conflicts (e.g. those leading to rear-end crashes) were assumed to be also possible in case of 2 vehicles coming from the same direction.
2. Traffic volumes are not time-dependent.
3. Individual arrivals are independent and the arrivals per unit of time follow a Poisson-process.
4. The proportions of the different road user types in traffic in the period 08:00-18:00 are reflecting the real daily proportions on a 24 hour basis.

Given the average daily (10 hours) number of entering vehicles at the roundabouts of 13672 (all directions and all road user types together), the mean number of arrivals λ per second equals $\lambda = \frac{13672}{10*60*60\ s} = 0.38$

Then, the probability of x arrivals per second can be written as $P(x) = \frac{\lambda^{x}.e^{-\lambda}}{x!}$

Consequently, the probability of an encounter of at least 2 road users in the considered period of 1 second is given by P(x>1) = 1 - P(x=0) - P(x=1) = 1-0.6841-0.2597 = 0.0562

The resulting expected number of encounters per day (10h) then equals 0.0562 * 13672 = 768.

Subsequently, the expected proportion of encounters between two different road user types (e.g. passenger vehicle X heavy vehicle, bicycle X bicycle) to the total number of encounters is calculated. This is done by multiplying the respective shares in roundabout traffic (Table 6) and then relating them to the calculated total number of encounters. For instance, to get the estimated probability of encounters between mopeds and passenger vehicles, multiply 0.006 with 0.85 and 2 = 0.0102 (multiply by 2 to incorporate one possible permutation). Then, the estimated number of encounters for each road user combination is easily estimated by multiplying the estimated probability with the estimated total number of encounters (N=768). For instance the estimated number of encounters between mopeds and passenger vehicles is 0.0102*768 ≈ 8. The results are provided in Table 7.

In a second step, odds ratios are estimated for the crash frequency of each possible combination of road user types compared with the relative involvement in encounters. The results are shown as well in Table 7. For instance, the odds ratio of 10.31 for the combination mopeds and heavy vehicles means that 10 times more crashes are count than would be expected based on the estimated number of encounters of both vehicle types in traffic. The results in Table 7 show that the count number of crashes is lower than expected for three combinations of vehicle types: passenger vehicle * passenger vehicle (0.21), heavy vehicle *passenger vehicle (0.22) and heavy vehicle * heavy vehicle (0.49). All other collision types occur more frequently than expected.

It can be noticed that these estimations might be biased since the number of crashes is in reality measured over a period of 24 hours per day whereas the traffic volume estimations and proportions that are used in the present study are only valid for a period of 10 hours per day. Particularly, it is likely that the proportion of pedestrians and two-wheeled road users is lower during night than during daytime. In that case, the stated figures for the relative crash involvement for those user types are still an underestimation of the real distortions.

Table 7 Estimated frequency of encounters and relative crash involvement for each possible combination of road user types[1]

	Passenger vehicle	Heavy vehicle	Motorcycle	Moped	Bicycle	∑
Passenger vehicle	555 (0.21)					555
Heavy vehicle	110 (0.22)	6 (0.49)				116
Motorcycle	9 (2.56)	1 (2.17)	0			10
Moped	8 (20.71)	1 (10.31)	0 (32.21)	0 (192.77)		9
Bicycle	45 (6.19)	4 (4.47)	0.5 (5.33)	0.5 (48.78)	1 (7.48)	51
Pedestrian	24 (1.09)	2 (1.16)	0 (3.38)	0 (39.2)	1 (4.99)	27
∑	751	14	0.5	0.5	2	768

[1] Reflected values = a (b) with
a = Estimated daily number of encounters between represented road user types
b = (Odds) ratios of the odds of multiple-vehicle crashes for collisions between the represented road user type divided by all other collisions and the odds of the expected daily number of encounters for the represented road user types divided by all other encounters

3. REGRESSION MODELING

Regression models were fitted using the available geometric and traffic variables. The dependent variable was the average annual number of crashes per roundabout (N=148). In a first step, Poisson loglinear models were fit to explain crash rates at roundabouts. Since underdispersion was found in the crash data, additional models were fit by using gamma probability models that are able to account for underdispersion (Oh, Washington, & Nam, 2006).

The functional form of the chosen models was the following:

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

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

The gamma model makes use of the gamma probability distribution (Agresti, 2002) 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 φ > 1, overdispersion if φ <1, equidispersion if φ = 1.

All models were fitted by using the GENMOD-procedure in SAS and made use of the log link function. In Daniels et al. (2010), the adopted modelling approach was a stepwise backward elimination procedure starting from initial models with all possible variables. In the resulting models only variables were reflected that showed a significance value below or equal to 0.10, except for the ADT that was always included. The best fitting models (in terms of their AIC-value) were represented, which resulted in the fact that the Poisson and gamma models contained not necessarily the same variables and were therefore not always easy mutually comparable.

The current models were somewhat differently fitted: a forward selection procedure was followed like proposed by Hauer (2004). Initially, only the variables ADT (motorized vehicle traffic) and the exposure variable for the specific vehicle category (e.g. motorcyclist volume for the model predicting the crashes with motorcyclists) were included. The exposure variables were transformed to their natural logarithm, which meant they were incorporated in the multiplicative part of the model as shown in equation (1). Subsequently, the “spreadsheet” approach (E. Hauer, 2004) was followed in order to check any candidate variable for entering the models. This approach started from the exposure-only model. The predicted crash rates and the observed crash rates for each observation in the model were subsequently listed in a spreadsheet, together with all the values of the different variables. Then, each relevant possible value was evaluated for entering in the model. This was done as follows: firstly, ‘bins’ were created for each possible value (in case of dummies or discrete variables with a small number of possible values) or group of values (in other cases). Then, the sum of all the observed crashes in the bins was compared with the sum of all predicted crashes and it was evaluated whether this showed a systematic difference for all the evaluated bins. If so, this indicated that the candidate variable could be meaningful in the model. Subsequently, the variable was introduced in the model, together with all the other variables that were selected this way.

Subsequently, the Poisson and gamma models were fitted with the resulting list of variables. In case of strong correlation ($\rho \geq 0.6$) one of the two correlating variables was eliminated, in principle the variable with the smallest individual significance. 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. in (Fridstrøm et al., 1995; Greibe, 2003) to consider them as important predictors.

Variables that were neither significant at the 10% level in the Poisson nor in the gamma-model were eliminated, except for the exposure variables who were always included. If a variable was significant in either the Poisson model or the gamma model, it was included in both models in order to maintain comparability between the two models. The goodness of fit of the subsequent models was evaluated by the Akaike Information Criterion (AIC). The best fitting model was in principle the model with the lowest value for the AIC. However, due to the abovementioned constraints, the final models were not necessarily those with exactly the lowest AIC-value.

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 approach was also followed in Daniels et al. (2010) and yielded better results than using YEAR as a categorical variable. The followed procedure enabled a single parameter estimate for the variable YEAR which enabled a more straightforward interpretation of the results.

Table 8 and Table 9 show the results. The results for the Poisson models and the gamma models are both provided. It was considered to include all variables that were at least significant in one of the fitted models in all the other models as well. This would offer the advantage that the values for some variables could, even if not significant, easily be compared between different models. However, we decided not to do so because including all the variables listed in Table 8 and Table 9 deteriorated the individual significance level of some variables severely and deteriorated the model fit. Moreover the theoretical basis for including some variables in some models was very unclear: for instance including a variable like the presence of cycle paths in the models for motorcyclists would not correspond with common sense.

The first column of Table 8 presents the most general model, the one for all crashes. The crash rate appears to be influenced by two exposure variables: the motor vehicle exposure ADT and the bicyclist exposure (BIC), although not significantly by the latter one. Furthermore, the presence of a cycle path influences the number of crashes negatively and more crashes occur at roundabouts with three legs. These findings are very consistent with the findings in the previous study.

Specific models were fit for crashes with particular road users: bicycles, mopeds, motorcycles, heavy vehicles, passenger vehicles and pedestrians. The models for crashes with passenger vehicles showed strong similarities with the models for all crashes, which was not unexpected due to the dominancy of crashes with passenger vehicles in the entire dataset. However, one extra variable enters the model for crashes with passenger vehicles: the presence of a bypass, which correlates with a higher number of crashes.

Crashes with bicyclists are explained by the ADT and the volume of bicyclists, both in the Poisson and gamma models. Furthermore, the number of crashes with bicyclists turns out to be lower on roundabouts with separate cycle paths. See the discussion part for some comments on this result. The number of crashes with mopeds is, apart from the exposure variables, dependent on the construction year of the roundabout (YEAR) and is higher on roundabouts with 3 legs (3LEGS). Furthermore, fewer crashes with mopeds occur at roundabouts where the central island is raised than those where this is not the case (ELEV). Apart from the exposure variables (ADT and MCY), the crash rate for motorcyclists was dependent on the shape of the central island: fewer crashes seemed to occur at oval roundabouts (OVAL).

Only exposure and the year of construction seemed to have an effect on the crash rate for trucks. Crashes with pedestrians seem to be influenced by the ADT and by the pedestrian volume (PED). Furthermore the number of crashes with pedestrians seems to be higher at roundabouts inside built-up areas (INSIDE) then on roundabouts outside the built-up area.

Furthermore separate models were fit for single-vehicle crashes and for multiple-vehicle crashes. The results are provided in Table 9. The number of single-vehicle crashes turns not longer out to be only explained by the ADT. A larger diameter of the central island (CENTRDIAM) is correlated with a higher single-vehicle crash rate. The presence of a cycle path (CYCLPATH), the presence of an oval central island (OVAL) and roundabouts that were located inside built-up area (INSIDE) were correlated with fewer single-vehicle crashes. Multiple-vehicle crashes are affected by the ADT, by the presence of bicyclists and furthermore by the variables CYCLPATH, 3LEGS, YEAR, BYPASS and ZEBRA which are the same variables as in the existing dataset.

Table 8 Parameter estimates for Poisson and gamma-models with particular road users (N=148)

Variables[1]	All crashes	Crashes with passenger vehicles	Crashes with bicyclists	Crashes with mopeds	Crashes with motor-cycles	Crashes with heavy vehicles	Crashes with pedestrians
Intercept	-10.05 (<0.01) *-10.64 (<0.01)*	-9.27 (<0.01) *-9.91 (<0.01)*	-11.01 (<0.01) *-14.23 (<0.01)*	-15.47 (<0.01) *-15.40 (<0.01)*	-12.61 (0.03) *-22.79 (<0.01)*	-10.97 (0.06) *-9.48 (<0.01)*	-19.90 (0.02) *-28.69 (<0.01)*
LN(ADT)	1.06 (<0.01) *1.10 (<0.01)*	0.99 (<0.01) *1.04 (<0.01)*	0.91 (<0.01) *1.22 (<0.01)*	1.46 (<0.01) *1.49 (<0.01)*	1.10 (0.07) *2.22 (<0.01)*	0.70 (0.35) *0.39 (029)*	1.62 (0.07) *2.50 (<0.01)*
LN(BIC)	0.05 (0.18) *0.08 (0.12)*		0.26 (0.01) *0.32 (<0.01)*				
LN(MOP)				0.23 (0.07) *0.21 (0.01)*			
LN(MCY)					-0.10 (0.48) *-0.23 (0.02)*		
LN(HEAVY)						0.36 (0.35) *0.58 (0.03)*	
LN(PED)							0.20 (0.37) *0.25 (<0.01)*
CYCLPATH	-0.45 (<0.01) *-0.33 (0.06)*	-0.52 (<0.01) *-0.33 (0.07)*	-0.54 (0.09) *-0.59 (0.04)*				
YEAR				-0.15 (0.09) *-0.21 (0.01)*		-0.17 (0.22) *-0.17 (0.01)*	
3 LEGS	0.37 (0.04) *0.59 (0.01)*	0.42 (0.03) *0.58 (0.01)*		0.47 (0.29) *0.70 (0.07)*			
INSIDE							1.15 (0.29) *1.39 (<0.01)*
BYPASS		0.43 (0.04) *0.36 (0.17)*					
ELEV				-0.58 (0.17) *-0.74 (0.08)*			
OVAL					-1.72 (0.57) *-2.06 (<0.01)*		
AIC	369.10 *315.11*	340.79 *262.68*	179.18 *--305.16*	140.11 *-575.52*	76.14 *-978.17*	81.21 *-953.34*	52.68 *-1306.19*
Dispersion parameter[2] (φ)	*1.12*	*1.22*	*2.93*	*3.53*	*4.35*	*4.55*	*4.43*

[1] values in normal typeface = Poisson-models, values in italics = gamma models; ( ) = p-values
[2] for the gamma models. Overdispersion if φ<1, underdispersion if φ>1, equidispersion if φ=1

Table 9 Parameter estimates for Poisson and gamma-models with single/multiple-vehicle crashes

Variables[1]	**Multiple-vehicle crashes**	**Single-vehicle crashes**
Intercept	-10.50 (<0.01) *-12.33 (<0.01)*	-5.84 (0.06) *-6.99 (<0.01)*
LN(ADT)	1.04 (<0.01) *1.21 (<0.01)*	0.44 (0.18) *0.62 (0.02)*
LN (BIC)	0.12(0.05) *0.15 (0.02)*	
CYCLPATH	-0.32 (0.08) *-0.25 (0.22)*	-0.66 (0.05) *-0.51 (0.08)*
3 LEGS	0.45 (0.03) *0.60 (0.02)*	
YEAR	-0.09 (0.04) *-0.08 (0.05)*	
BYPASS	0.41 (0.06) *0.43 (0.14)*	
OVAL		-2.24 (0.15) *-1.56 (0.01)*
ZEBRA	0.37 (0.05) *0.22 (0.32)*	
CENTRDIAM		0.03 (0.01) *0.01 (0.27)*
INSIDE		-0.63 (0.15) *-0.72 (0.03)*
AIC	311.13 *190.68*	176.93 *-304.39*
Dispersion parameter[2] (φ)	*1.48*	*2.87*

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

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

4. DISCUSSION

4.1. Modelling approach

Like in the analyses of the existing dataset, both Poisson and gamma models were fit. The modelling procedure was somewhat modified in order to obtain as much as possible information from the data. However, the adaptations did not substantially influence the results. The underdispersion that was found in the existing dataset persisted. The observed underdispersion indicates that the variation of the crash rates at the investigated roundabouts is low. It appears that the parameter estimates of the variables in the Poisson and the gamma models are generally close to each other. However, the significance values of the parameters differ sometimes considerably between the both models. In essence, it might be concluded that the modelling procedure and the results were quite consistent for the extended dataset compared with the existing dataset.

4.2. Multicollinearity

Attempts were made to deal with multicollinearity which was an expected phenomenon in this dataset. Principally, multicollinearity is a though issue and one can theoretically not be certain about which variables to include in a model when two or more variables correlate strongly (Verbeek, 2004). A first type of expected multicollinearity in our models relates to the correlation of infrastructure variables with traffic exposure. For instance, larger roundabouts (larger values for OUTDIAM) are related to higher traffic volumes (ADT) and more pedestrians (PED) are present at roundabouts inside built-up areas (INSIDE). Due to the well established importance of exposure in crash prediction modelling, we decided to include at least one exposure variable in each model before looking at any infrastructure variable. In case of a strong correlation, the infrastructure variable would have been removed. A second type of multicollinearity relates to correlations between different exposure variables. In principle, each model comprised two exposure variables. However, the addition of a second road user type was not possible in the model for passenger vehicles and the model for single-vehicle crashes due to the fact that the suitable candidate second covariate (the number of passenger vehicles LIGHT) correlated strongly with the ADT and its inclusion deteriorated the individual significance values severely. A third type of multicollinearity is found between the infrastructure variables. For instance the size of the central island (CENTRDIAM) appears to correlate to a large extent with the size of the entire roundabout (OUTDIAM) which made it impossible to include both variables together in the models in a reliable way. However, CENTRDIAM an OUTDIAM are not *by definition* dependent on each other and thus not substitutable. In these cases, we chose to include that variable in the particular models that was believed to be the principally most relevant. Another example is the duo CYCLPATH / CYCLLANE. It was preferred to include CYCLPATH consistently in all models since this was found to be the best explaining variable in most of the different cases. Some more comments on this are given below.

4.3. Influencing exposure 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. 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.

The coefficient for the motorized vehicle exposure (ADT) is not consistently above or below 1 in most of the models. A coefficient of 1 would suggest an increase in crash rate (crashes per year) that is proportional to the traffic volume, whereas a coefficient of above respectively below 1 would equal an increase that is respectively higher or lower than proportional to the traffic volume increase. For the single-vehicle crashes, however, the coefficient for the ADT is well below 1, suggesting that the average number of single-vehicle crashes per passing vehicle is lower on busier roundabouts. In existing research, ADT-parameters below as well as above 1 for crashes at roundabouts were found (Brüde & Larsson, 2000; Maycock & Hall, 1984).

Also the exposure variables for the specific road user types appeared to contribute significantly to the models. This was the case for the bicyclist volume, the number of moped riders and the number of pedestrians (only significant in the gamma model), each time in the model for the respective group of road users. These results are roughly the same as in the previous dataset. Additionally to the previous dataset, the volume of trucks and the volume of motorcyclists entered the respective models, although far from significant in the case of the Poisson model. It can be noticed that all the parameter estimates for the specific road user types are considerably below 1, which could support the "law of rare events" (Elvik, 2006), stating that the more rarely a certain traffic hazard is encountered, the greater its effect is on the crash rate. This law implies as well that the rarer some types of road users are encountered in traffic, the higher the risk of a collision with those road users per encounter. Jacobsen (2003) expressed this phenomenon as the 'safety-in-numbers effect'. This effect makes that, although the total number of crashes is higher in case of higher traffic volumes on a certain location, the individual risk for each road user decreases. The results in the present study confirm the presence of a ‘safety in numbers effect’ for different road user categories at the investigated roundabouts.

The exposure variable for the volume of bicyclists entered also the models for all crashes and for multiple-vehicle crashes. This highlights the important role of the most dominant type of encounters in the crash statistics, being the collisions between passenger vehicles mutually and those between passenger vehicles and bicycles as it appears from the collision matrix in Table 6.

4.4. Are cycle paths better or cycle lanes worse?

In the previous study, we stated that roundabouts with cycle lanes were clearly performing worse than roundabouts with cycle paths. But we added that, although the variable CYCLLANE was more dominantly present in the models, the study stayed inconclusive on the question whether roundabouts with cycle lanes were performing worse (i.e. had more crashes) than other types or roundabouts with cycle paths were performing better than other types. In the present study, it seems that the variable CYCLPATH has gained importance and contributes better to the model fit. Again, the other two design types, mixed traffic (N=13) and grade-separated (N=4) showed no particular effect but their limited presence in the dataset could still be a major explanation. The limited numbers of mixed traffic and grade-separated roundabouts in the sample explain equally the correlation between the two most dominant groups, cycle lanes and cycle paths. This correlation obscures the interpretation of the revealed effects. More explicit and – due to the quasi-experimental study design - better controlled results were found in the before-and-after study of crashes at roundabouts (Daniels et al., 2009), where was found that roundabouts with cycle lanes performed worse compared to the three other design types.

4.5. Other risk variables

Three-leg roundabouts appear to perform worse than roundabouts with four or more legs. This finding corroborates the findings in the previous study since the variable 3LEGS showed very comparable parameter estimates and smaller significance values. It corresponds also with a previous finding (Elvik, 2003) that converting intersections to roundabouts had a greater decreasing effect on injury crashes in four-leg intersections than in three-leg intersections. A possible explanation for the worse results of 3-leg roundabouts is that speeds at 3-leg roundabouts are likely to be somewhat higher since approach and exit angles are in principle somewhat wider (on average on 120°) than in case of a four leg roundabout (on average on 90°).

Again, some variables appeared only in one of the models for subgroups. An interesting result is that fewer crashes with motorcyclists and less single-vehicle crashes seem to occur at oval roundabouts (OVAL). A straightforward explanation for this result seems not to be available. Human errors are expected to occur more often on roundabouts with non-circulatory central islands since more manoeuvring actions are required (FHWA, 2000; Kennedy, 2007). Therefore, central island shapes that deviate from a strictly circulatory shape are generally not recommended. Particularly motorcyclists might have more difficulties in negotiating roundabouts with non-circulatory central islands. Consequently, a lower crash rate at roundabouts with oval central islands is not really expected. Possibly, it might be the result of risk overcompensation. However, it should be noticed that this result was far from significant in the Poisson models and therefore seems to be considerably influenced by the modelling assumptions. At least it needs some further research.

More multiple-vehicle crashes seem to occur at roundabouts with zebra markings (ZEBRA) on the entries and the exits. Roughly the same comments apply to this result. It is counterintuitive and might be explained by overcompensation, but at the same time the result is too unsure (since insignificant for the gamma model) to allow drawing many conclusions.

More crashes with passenger vehicles and more multiple-vehicle crashes (which are to a certain extent overlapping groups) appear to occur at roundabouts with bypasses for traffic in some direction (BYPASS). A possible explanation for this is related to higher speeds and some extra – perhaps less expected – conflict points that are met at such a roundabout. This finding seems to support the statement in different design guidelines for roundabouts that bypass lanes should be avoided since the entries and the exits bypass lanes can increase the number of conflicts (FHWA, 2000).

The variable YEAR (construction year of the roundabout) showed a significant contribution in different models. Like it was discussed in the previous paper, the most likely explanation for this is that fewer crashes (of certain types) occur at more recently constructed roundabouts.

An interesting result is the higher number of single-vehicle crashes on roundabouts with larger central islands (1 to 3% extra single-vehicle crashes per meter central island diameter extra) (CENTRDIAM). A larger central island necessitates - ceteris paribus and when radial approaches are used like it is the case in Flanders-Belgium - a stronger lateral vehicle deflection when entering a roundabout and is therefore expected to reduce speeds more strongly. However, it may lead as well to a higher number of collisions with the central island, which seems to be supported here. However, since it was only significant in the Poisson model and not in the gamma model, this result should be interpreted carefully. Furthermore, the reader should keep in mind that the overall number of crashes was not affected by the size of the central island, which suggests that, although the number of single-vehicle crashes might increase somewhat, the total number of crashes is not demonstrably affected by the size of the central island.

More crashes with pedestrians seem to occur at roundabouts inside the built-up area (INSIDE), even if there is accounted for the pedestrian volume. There seems to be no simple explanation for this. Again, the significance of this result is strongly dependent on the adopted distributional assumptions. Furthermore, fewer single-vehicle crashes occur inside built-up areas. This might be related to lower speeds that can be expected to be present inside built-up areas compared with locations outside built-up areas.

Apart from the variable SIGNAL where no information was available for in the additional dataset, only the variable EXCEPT (gated roadway for exceptional transport through the central island) was present in the existing models and did not longer appear in one of the models for the extended dataset. However, the removal of EXCEPT was not unexpected since this result was highly unsure in the previous model wherein it appeared.

4.6. Two-lane roundabouts

The variable TWOLANES (two-lane roundabouts) did not enter any of the models, neither in the existing dataset nor in the extended dataset. However, the mere fact that a certain variable is not *significant* must not directly lead to the conclusion that this variable could not be *important*. In statistical terms, the fact that the zero-hypothesis is not rejected should not lead to the conclusion that the zero-hypothesis has to be accepted (Hauer, 2004). Nevertheless, the modelling practice revealed that the variable TWOLANES was never coming close to significance, which makes it less likely that a further extension of the used dataset would suddenly show some effect of this variable.

In the previous paper, we mentioned that the number of lanes in existing research showed some tendencies to be relevant (Brüde & Larsson, 2000; Stijn Daniels et al., 2009; Bhagwant Persaud, Retting, Garder, & Lord, 2001). But we argued as well that the number of lanes could act as a proxy for traffic volume in those studies. Based on all those elements, we stated that at least no confirmation was found for higher crash rates at double-lane roundabouts and that further research would be needed. Based on the present analyses, we believe that this conclusion should be maintained.

4.7. Underreporting

The used crash data were the police recorded crash data on the investigated locations. Previous research indicated that crash data are in general likely to show a level of underreporting. The main predictor for the level of underreporting has consistently turned out to be the severity of the outcome of the crash. However, research has indicated also that underreporting might be selective according to crash types (lower degree of reporting for single-vehicle crashes) (Alsop & Langley, 2001; Amoros, Martin, & Laumon, 2006; Elvik & Mysen, 1999) or road user types (lower reporting for vulnerable road users) (Alsop & Langley, 2001; Elvik & Mysen, 1999; James, H., 1991). If underreporting is assumed to be selective across road user types, the overrepresentation of vulnerable road users in crashes in Table 3 would even be an underestimation. Similarly, if a lower reporting of single-vehicle crashes is assumed, the share of single-vehicle crashes in the total number of crashes (see Table 4) is an underestimation. However, it should be noticed that, as long as underreporting is assumed to be not selective across locations, this phenomenon will not affect the parameter estimates (except for the intercept) of the fitted risk models (Table 8 and Table 9) due to their cross-sectional nature.

4.8. Study limitations

Finally, some limitations of this study should be taken into account. Although we tried to overcome them in a best possible way, they might have affected the stated results also in the extended models. Firstly, it is clear that a study based on a relatively small (even if extended) sample of locations in one particular country should not pretend to be valid for all possible roundabout designs wherever applied. Secondly, important concepts might be overlooked since information on a number of circumstances or risk factors was not present in the data. For instance, no information could be collected about actual or potential vehicle speeds at roundabouts, although this might be an important variable (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.

The inference of ADT-values from one hour-counts brings some extra portion of uncertainty in the results, which was already the case in the previous study. Finally, possible changes in the roundabout design that may have been made after the initial construction of the roundabout might act as a confounder.

4.9. Perspectives for further research

Although the assembled dataset enabled to generate meaningful conclusions and new insights, many uncertainties are left. They will need further clarification in the future. Undoubtedly, further extensions should comprise larger samples of roundabouts with a particular geometry such as mini-roundabouts or roundabouts with non-circular central islands. The effects of those particular groups on safety performance might differ from the more common roundabout types and are not yet documented very well.

Ideally, any future research in this domain should be done in a cross-country perspective in order to incorporate better existing differences in roundabout design guidelines and practices. The hope is that such a research would enable not only a better scientific knowledge on contributing factors, but would encourage also more universally accepted design standards.

5. CONCLUSIONS

Based on the research presented in this paper, the following conclusions can be made:

a. 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. Vulnerable road users are generally also overrepresented in crashes at other types of intersections, but the available data did not allow assessing differences between roundabouts and other types of intersections. Moped riders and motorcyclists are strongly overrepresented in single-vehicle crashes whereas moped riders, bicyclists and motorcyclists are overrepresented in multiple-vehicle crashes.

b. Fewer crashes occur at roundabouts with cycle paths than at roundabouts with other types of cycle facilities, particularly in comparison with roundabouts with cycle lanes close to the roadway.

c. Confirmation is found for the existence of a 'safety in numbers' effect for bicyclists, moped riders, motorcyclists, heavy vehicles and for pedestrians at roundabouts

d. The overall number of crashes is more or less proportional to the number of motorized vehicles (ADT). The mean number of single-vehicle crashes per passing vehicle is lower on busier roundabouts.

e. Three-leg roundabouts tend to perform worse than roundabouts with four or more legs.

f. More crashes with passenger vehicles and more multiple-vehicle crashes (which are to a certain extent overlapping groups) seem to occur at roundabouts with bypasses for traffic in some direction.

g. The larger the central island, the more single-vehicle crashes seem to occur. However, the overall number of crashes was not demonstrably affected by the size of the central island.

6. REFERENCES

Agresti, A. (2002). *Categorical Data Analysis*. WILEY SERIES IN PROBABILITY AND STATISTICS (2nd ed.). Hoboken, New Jersey: Wiley-Interscience.

Alsop, J., & Langley, J. (2001). Under-reporting of motor vehicle traffic crash victims in New Zealand. *Accident Analysis & Prevention*, *33*(3), 353-359.

Amoros, E., Martin, J., & Laumon, B. (2006). Under-reporting of road crash casualties in France. *Accident Analysis & Prevention*, *38*(4), 627-635.

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. (2010). Explaining variation in safety performance of roundabouts. *Accident Analysis & Prevention*, *42*, 393-402.

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.

Elvik, R. (2006). Laws of accident causation. *Accident Analysis & Prevention*, *38*(4), 742-747. doi:10.1016/j.aap.2006.01.005

Elvik, R., Erke, A., & Christensen, P. (2009). Elementary Units of Exposure. *Transportation Research Record: Journal of the Transportation Research Board*, *2103*(-1), 25-31. doi:10.3141/2103-04

Elvik, R., & Mysen, A. (1999). Incomplete Accident Reporting: Meta-Analysis of Studies Made in 13 Countries. *Transportation Research Record: Journal of the Transportation Research Board*, *1665*(-1), 133-140. doi:10.3141/1665-18

FHWA. (2000). *Roundabouts: An Informational Guide*. Federal Highway Administration.

Fridstrøm, L., Ifver, J., Ingebrigtsen, S., Kulmala, R., & Thomsen, L. (1995). Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts. *Accident Analysis & Prevention*, *27*(1), 1-20.

Greibe, P. (2003). Accident prediction models for urban roads. *Accident Analysis & Prevention*, *35*(2), 273-285.

Hauer, E. (2004). Statistical Road Safety Modeling. *Transportation Research Record: journal of the Transportation research Board*, *1897*, 81-87.

Hauer, E. (2004). The harm done by tests of significance. *Accident Analysis & Prevention*, *36*(3), 495-500.

Hels, T., & Orozova-Bekkevold, I. (2007). The effect of roundabout design features on cyclist accident rate. *Accident Analysis & Prevention*, *39*, 300-307.

Jacobsen, P. L. (2003). Safety in numbers: more walkers and bicyclists, safer walking and bicycling. Inj Prev, 9(3), 205-209.

James, H. (1991). Under-reporting of accidents. *Traffic engineering and control*, *32*(12), 573-580, 583.

Kennedy, J. (2007). *International comparison of roundabout design guidelines* (p. 98). Transport Research Laboratory.

Layfield, R. E., & Maycock, G. (1986). Pedal-cyclists at roundabouts. *Traffic Engineering and Control*, *June*, 343-349.

Maycock, G., & Hall, R. (1984). *Accidents at 4-arm roundabouts. Report LR 1120.* Transport and Road Research Laboratory.

Oh, J., Washington, S., & Nam, D. (2006). Accident prediction model for railway-highway interfaces. *Accident Analysis & Prevention*, *38*(2), 346-356.

Persaud, B., Retting, R., Garder, P., & Lord, D. (2001). Safety Effect of Roundabout Conversions in the United States: Empirical Bayes Observational Before-After Study. *Transportation Research Record: Journal of the Transportation Research Board*, *1751*(-1), 1-8.

Rodegerdts, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., List, G., et al. (2007). *Roundabouts in the United States. Report 572* (No. NCHRP 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.

Verbeek, M. (2004). *A guide to modern econometrics*. John Wiley and Sons Ltd.