Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities

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Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities.

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ABSTRACT

PROBLEM

Previous research indicated that conversions of intersections into roundabouts appear to increase the number of injury crashes with bicyclists. However, it was assumed that the effectiveness of roundabouts could vary according to some differences in design types of cycle facilities and other geometrical factors.

METHOD

Regression analyses on effectiveness-indices resulting from a before-and-after study of injury crashes with bicyclists at 90 roundabouts in Flanders, Belgium.

RESULTS

Regarding all injury crashes with bicyclists, roundabouts with cycle lanes appear to perform significantly worse compared to three other design types (mixed traffic, separate cycle paths and grade-separated cycle paths). Nevertheless, an increase of he severest crashes was noticed, regardless of the design type of the cycle facilities. Roundabouts that are replacing signal-controlled intersections seem to have had a worse evolution compared to roundabouts on other types of intersections.

IMPACT ON INDUSTRY

The results might affect design guidelines for roundabouts, particularly for the accommodation of bicyclists.

1. PROBLEM

In a previous study, the authors performed a before-and-after analysis of injury crashes with bicyclists at roundabouts (Daniels et al., 2008). Based on a sample of 91 roundabouts on regional roads in Flanders-Belgium, a considerable increase in the number of injury crashes with bicyclists was noticed (best estimate: + 27% with a 95% C.I. of [+0%; +61%] for all injury crashes). For the severest crashes, those with fatal and serious injuries (i.e. a hospitalisation of at least 24 hours) the results were even worse (best estimate of the increase of 41-46%). The results were unexpected, although earlier findings suggested possible specific safety problems for bicyclists at roundabouts (see for example Brilon, 1997; Brüde and Larsson, 2000; Layfield and Maycock, 1986; Schoon and van Minnen, 1993). However, some questions stayed open after the study. A major discussion point has been the influence of different design types of cycle facilities at roundabouts. In practice, considerable differences between countries seem to exist regarding the applied road design in order to conduct bicyclists through roundabouts. It indicates that no commonly accepted solution has been reached so far.

Other remaining research questions had to do with the possible influence of geometrical variables such as the number of lanes at the roundabout and the pavement colour of the cycle facility.

The present article describes the results of analyses based on additionally collected information about the design type of the cycle facilities and some geometrical features of the investigated roundabouts. The main research question in this study was to investigate possible differences between designs for cycle facilities regarding safety for bicyclists.

In the remainder an introductory part is provided about the identification of different types of cycle facilities and about some operational criteria that were used in order to subdivide all roundabouts in four groups. This is followed by a description of the available data and the adopted methodology. Consequently the results are provided and related to existing knowledge and previous research.

2. TYPES OF CYCLE FACILITIES

Although huge differences exist between design practices in different countries, some basic types of designs for bicyclists at roundabouts can be distinguished. They are ordered into four categories:

1. Mixed traffic;
2. Cycle lanes within the roundabout;
3. Separate cycle paths;
4. Grade-separated cycle paths.

The most basic solution is to treat bicyclists the same way as motorised road users, which means that bicycle traffic is mixed with motorised traffic and bicyclists use the same entry lane, carriageway and exit lane as other road users. It is further called the “mixed traffic” solution (see figure 1). In many countries this is the standard design as no specific facilities for bicyclists are provided. In some countries it is common to apply the mixed traffic solution, even when cycle lanes or separate cycle paths are present on approaching roads. In that case, the cycle facilities are bent to the road or truncated about 20-30 meter before the roundabout (CROW, 2007).

A second possible solution are cycle lanes next to the carriageway, but still within the roundabout (figure 2, see also picture 1). Those lanes are constructed on the outer side of the roundabout, around the carriageway. They are visually recognizable for all road users. They may be separated from the roadway by a road marking and/or a small physical element or a slight elevation. They may also be constructed in a different pavement or differently coloured (red, green, blue…). However the cycle lanes are essentially part of the roundabout because they are very close to it and because the manoeuvres bicyclists have to make are basically the same as the manoeuvres for motorised road users. A specific case occurs when the cycle lanes are differently coloured but not separated by a line marking from the carriageway. This solution is called a ‘cycle suggestion lane’. From a legal point of view (at least in Belgium) roundabouts with such a cycle suggestion lane could be considered as roundabouts with mixed traffic since bicyclists are not obliged to use the cycle lane and may use the carriageway. However, in practice the presence of a coloured pavement (which is the case in the 2 instances of suggestion lanes in the sample) is supposed to attract bicyclists to that part of the road. Therefore they are categorised as roundabouts with cycle lanes.

When the distance between the cycle facility and the carriageway becomes somewhat larger (the operational criterion used in this study is: more than 1 meter), the cycle facility cannot be considered anymore as belonging to the roundabout. This is called the separate cycle path-solution. The 1 meter-criterion corresponds with the Flemish guidelines for cycle facilities (MVG, 2006). Since the distance between the separate cycle path and the roadway may mount to some meters (e. g. the Dutch design guidelines recommend 5 meter) (CROW, 2007), specific priority rules have to be established when bicyclists cross, while circulating around the roundabout, the entry or exit lanes.

While it is universally accepted to give traffic circulating on the roundabout priority to traffic approaching the roundabout (offside priority), such is not always the case for bicyclists on separate cycle paths. In some cases, priority is given to the bicyclists when crossing the entry/exit lanes, in other cases bicyclists have to give way. The former is called the "separate cycle paths - priority to bicyclists solution" (figure 3a), the latter the "separate cycle paths - no priority to bicyclists solution" (figure 3b, see also picture 2) (CROW, 1998). When bicyclists have priority, this is supported by a rather circulatory shape of the cycle path around the roundabout allowing smooth riding (figure 3a). When bicyclists have no priority, the bicycle speed is reduced by a more orthogonal shape of the crossing with the exit/entry lane (figure 3b).

Finally, in a limited number of cases grade-separated roundabouts are constructed allowing bicycle traffic to operate independently from motorised traffic (figure 4).

Figure 1 – roundabout with mixed traffic

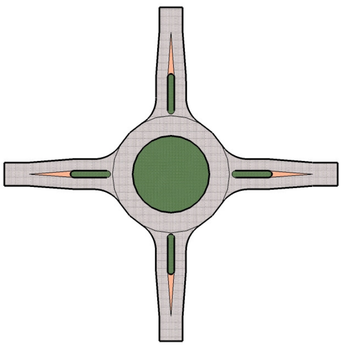


Figure 2 – Roundabout with cycle lanes

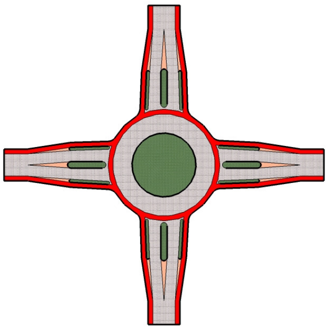


Figure 3a – Roundabout with separate cycle paths – priority to bicyclists

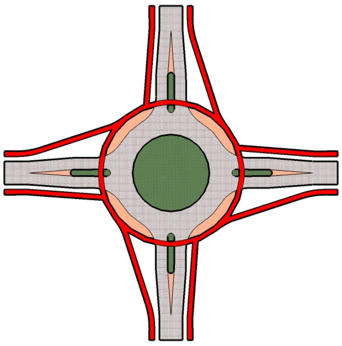


Figure 3b – Roundabout with separate cycle paths – no priority to bicyclists

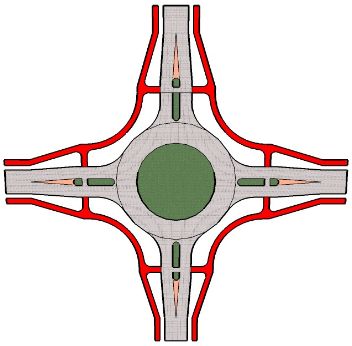
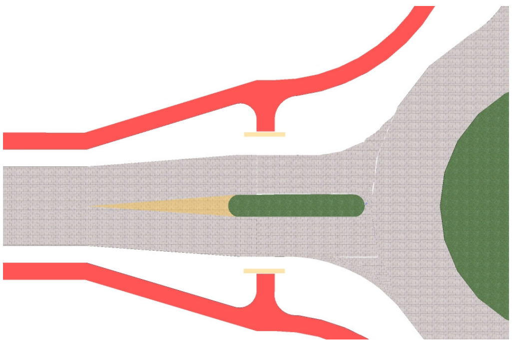


Figure 4 - - Roundabout with grade-separated cycle paths



Picture 1 – Roundabout with cycle lanes

Picture 2 – Roundabout with separate cycle paths (no priority for bicyclists)

3. DATA COLLECTION

A sample of 90 roundabouts in the Flanders region of Belgium was studied. The roundabout data were obtained from the Infrastructure Agency (part of the Ministry of Mobility and Public Works). The used dataset is the same, except for one location, as the dataset that was used in the previous study (Daniels et al., 2008). Additionally acquired data included the presence and the types of cycle facilities, the number of lanes at the roundabout, the presence of lines or barriers between the roundabout and the cycle facility (in case of cycle lanes), the priority rules for bicyclists (in case of separate cycle paths) and the pavement colour.

The data were used to estimate possible differences in the safety performance (effectiveness-indices obtained from a before-after analysis) of roundabouts according to the present accommodation for bicyclists. A second goal was to detect possible explaining factors for the differences in the performance of different roundabouts.

Both single-lane and double-lane roundabouts occur in the sample, although the former type is far more common (table 1).

Table 1 - Number of roundabouts in the study sample

	Number of lanes		
	1	2	TOTAL
Inside built-up area	39	1	40
Outside built-up area	44	6	50
TOTAL	83	7	90

Information was collected about the type of cycle facility that is present at the roundabouts. Pictures were made of each of the 90 roundabouts. According to the type of the cycle facilities, each roundabout was assigned to one of the four before-mentioned categories (table 2).

Table 2 - Number of roundabouts in the study sample - number of lanes and type of cycle facility

	Number of lanes		
	1	2	TOTAL
1 - Mixed traffic	8	1	9
2 - Cycle lanes	38	2	40
3 - Separate cycle paths	35	3	38
4 - Grade-separated	2	1	3
TOTAL	83	7	90

Table 3 - Intersection design before roundabout construction

Traffic signals	21
No traffic signals	69
Total	90

Of the 90 roundabouts, 21 were replacing traffic signals (table 3). The other roundabouts were built on other types of intersections (intersections with stop signs, give way-signs or general priority to the right).

For the purpose of this study only roundabouts that were constructed between the year 1994 and 2000 were taken into account. Crash data were available from 1991 until the end of 2001. Consequently a time period of crash data of at least 3 years before and 1 year after the construction of each roundabout was available for the analysis. For each roundabout the full set of available crash data in the period 1991-2001 was included in the analysis. Table 4 shows the distribution of the construction years for the roundabouts in the sample.

Table 4 - Construction year according to design type

CONSTRUCTION YEAR	MIXED TRAFFIC	CYCLE LANES	SEPARATE CYCLE PATHS	GRADE-SEPARATED	TOTAL
1994	3	10	4		17
1995	2	11	8		21
1996	1	8	6	1	16
1997		2	5	1	8
1998	1	4	2		7
1999	1	3	8	1	13
2000	1	2	5		8
TOTAL	9	40	38	3	90

Exact location data for each roundabout were available so that crash data could be matched with the roundabout data. 40 roundabouts from the sample are located inside built-up areas (areas inside built-up area boundary signs, in general with a speed limit of 50km/h), 50 outside built-up areas (in general with speed limits of 90 or 70 km/h).

Extra information was collected according to the type of cycle facilities. For roundabouts with cycle lanes this extra information applied to:

- The presence of a line marking between carriageway and cycle lane;
- The presence of one or another physical barrier (e.g. a kerbstone, small concrete elements, verdure) or an elevation between carriageway and cycle lane.

When the distance between the cycle lane and the carriageway mounted to more than 1 meter, the roundabout was classified as one with separate cycle paths. Details about the roundabouts with cycle lanes in the sample are given in table 5.

Table 5 - Details - Roundabouts with cycle lanes

	Physical barrier	No barrier	TOTAL
Marking	15	22	37
No marking	1	2	3
Total	16	24	40

Table 6 - Details - Roundabouts with separate cycle paths

	Inside built-up area	Outside built-up area	Total
Priority to bicyclists	5	13	18
No priority to bicyclists	3	17	20
Total	8	30	38

A subdivision in the group of roundabouts with separate cycle paths was made according to when they were constructed with or without priority for bicyclists crossing the exit and entry lanes (see table 6).

Furthermore the colour of the cycle facility (when present) was collected (table 7). In Flanders it is common to colour cycle facilities red, although it is not compulsory. Other colours do not occur. In the case of the cycle lanes, all but one are coloured. In the group of the separate cycle paths there are some more instances of uncoloured pavements, but they remain a small minority.

Table 7 - Number of roundabouts with coloured cycle facilities according to design type

	Coloured	Not coloured
1 - Mixed traffic	not applicable	
2 - Cycle lanes	39	1
3 - Separate cycle paths	32	6
4 - Grade-separated	2	1
TOTAL	73	8

The comparison group consisted of 649 crashes with bicyclists at 172 intersection locations and is identical to the comparison group in the previous study. The total number of crashes included in the treatment group (= roundabout locations) was 411, of which 314 with only slight injuries, 90 with at least one serious injury and 7 with a fatal injury (see table 8).

Table 8 - Number of considered crashes (period 1991-2001)

Nature of the severest injury in the crash	Treatment group	Comparison group
Slight	314	486
Serious	90	142
Fatal	7	21
TOTAL	411	649

Table 9 shows the number of crashes for the treatment group (both before and after conversion into a roundabout), split up by the design type of the cycle facilities at the roundabout and by the severest injury caused by the crash.

Table 9 Number of crashes at the roundabout locations - before and after conversion

	Crashes with slight injuries	Crashes with serious injuries	Fatalities	Total
1 - Mixed traffic	31	9	0	40
2 - Cycle lanes	160	35	3	198
3 - Separate cycle paths	121	41	4	166
4 - Grade-separated	2	5	0	7
TOTAL	314	90	7	411

4. METHODOLOGY

The adopted study design was that of an Empirical Bayes before-and-after study with injury crashes with bicyclists as a measurement variable. The use of comparison groups enabled to control for general trends in traffic safety and possible regression-to-the-mean effects. No correction for specific developments in traffic volume was possible. In the first stage, the effectiveness for each roundabout location was calculated separately. Consequently the results were combined in a meta-analysis. A description of the adopted methodology can be found in Daniels et al. (2008) and is therefore not repeated.

The before-and-after design allowed to determine effectiveness-indices for each roundabout in the sample. The effectiveness is expressed as an odds-ratio of the evolution in the treatment group after conversion into a roundabout compared to the evolution in the comparison group in the same time period. An effectiveness-index above 1 respectively below 1 indicates an increase, respectively a decrease in the number of crashes compared to the average evolution on similar locations where no roundabout was constructed, while an index of 1 equals the zero-hypothesis of no effect.

Since additional data about geometric features of the roundabout were available some regression models could be fitted in order to explain the variance of the estimated values of the effectiveness-indices according to differences in the the number of lanes, pavement colour, location inside/outside built-up area etc.

5. RESULTS

Tables 10 and 11 show the results of the analyses for all injury crashes and severe injury crashes respectively. The best estimate for the overall effect on injury crashes involving bicyclists on or nearby the roundabout is an increase of 27% ($p = 0.05$). The best estimate for the effect on crashes involving fatal and serious injuries (table 11) is an increase of 42-44% ($p = 0.05$-0.06), depending on the applied dispersion-value k. None of the partial results for any of the subgroups in table 11 is significant at the 5% level. However, all the results for the separate subgroups show an increase in the number of fatal and serious crashes, except in one scenario for roundabouts with grade-separated cycle facilities (showing a status quo).

Overall, the number of injury crashes at roundabouts with cycle lanes turns out to increase significantly (+93%, 95% CI [38 to 169%]. However, for the other 3 design types (mixed traffic, separate cycle paths, grade-separated cycle paths) the best estimate is a decrease of 17% in the number of crashes, although not significant (Eff. index 0.83 with 95% CI [0.59-1.16]) (result of a separate meta-analysis on the values for those categories, not reflected in the table). Some separate analyses were made for the results within subgroup of the cycle lanes as well as within the subgroup of the cycle paths, reflecting the possible influencing effects of some particular design variables such as the type of distinction between roadway and the cycle facility (in case of cycle lanes) and the applicable priority rule (in case of cycle paths). Also these results are provided in tables 10 and 11. For reasons of clarity the presented results in table 11 for these subgroups are only those for the dispersion parameter k = value k for all injury crashes.

TABLE 10 Results – all injury crashes.

	Nr. of locations	Effectiveness- index [C.I.] (p-value)
MIXED TRAFFIC	9	0.91 [0.45-1.84] (0.79)
CYCLE LANES		
Line + barrier	15	2.06 [1.23-3.44] (0.01)
Line + no barrier	22	1.85 [1.16-2.94] (0.01)
No line + barrier	1	2.63 [0.47-14.89] (0.27)
No line + no barrier	2	0.90 [0.10-8.15] (0.93)
All cycle lanes	40	1.93 [1.38-2.69] (<0.01)
SEPARATE CYCLE PATHS		
Priority to bicyclists	18	0.79 [0.45-1.41] (0.41)
No priority to bicyclists	20	0.86 [0.50-1.48] (0.59)
All separate cycle paths	38	0.83 [0.56-1.23] (0.35)
GRADE-SEPARATED	3	0.56 [0.11-2.82] (0.48)
ALL ROUNDABOUTS	90	1.27 [1.00-1.61] (0.05)

TABLE 11 Results – crashes with fatal and serious injuries.

	Nr. of locations	Effectiveness- index [C.I.] (p-value)
MIXED TRAFFIC	9	1.77 [0.55-5.66] (0.34) ° 1.79 [0.56-5.74] (0.33) °° 1.89 [0.59-6.10] (0.28) °°°
CYCLE LANES		
Line + barrier	15	1.58 [0.67-3.71] (0.30) °°
Line + no barrier	22	1.13 [0.53-2.39] (0.75) °°
No line + barrier	1	3.18 [0.10-100.66] (0.51)°°
No line + no barrier	2	2.13 [0.19-24.09] (0.54) °°
All cycle lanes	40	1.37 [0.79-2.37] (0.26) ° 1.37 [0.79-2.35] (0.26) °° 1.34 [0.78-2.31] (0.29) °°°
SEPARATE CYCLE PATHS		
Priority to bicyclists	18	1.14 [0.50-2.59] (0.76) °°
No priority to bicyclists	20	1.74 [0.79-3.86] (0.17) °°
All separate cycle paths	38	1.43 [0.81-2.52] (0.22) ° 1.42 [0.80-2.51] (0.23) °° 1.46 [0.83-2.56] (0.19) °°°
GRADE SEPARATED	3	1.84 [0.26-12.76] (0.54) ° 1.31 [0.23-7.54] (0.76) °° 1.00 [0.18-5.49] (>0.99) °°°
ALL ROUNDABOUTS	90	1.44 [1.00-2.09] (0.05) ° 1.42 [0.99-2.05] (0.06) °° 1.42 [0.99-2.03] (0.06) °°°

° use of fixed dispersion parameter $k = 10^{-10}$
°° use of dispersion parameter k = value k for all injury crashes
°°° use of fixed dispersion parameter $k=10^{10}$

Subsequently a meta-regression procedure was applied. Maximum likelihood linear regression models (SAS-procedure GENMOD) were fitted in order to estimate the relationship between the estimated value for the effectiveness per location and some known characteristics of the roundabout locations. The available independent variables are listed in table 12.

Table 12 - Independent variables

Abbreviation	Description
INSIDE	0 = outside built-up area; 1= inside built-up area
MIXED	0 = no mixed traffic; 1= mixed traffic
CYCLLANE	0 = no cycle lane; 1 = cycle lane
CYCLPATH	0 = no separate cycle path; 1 = separate cycle path
GRADESEP	0= no grade-separation; 1 = grade-separation
SIGNALS	0 = no traffic signals; 1 = traffic signals before roundabout construction
RED	0 = not coloured, 1 = red-coloured cycle facilities (not applicable when MIXED = 1)
TWOLANES	0 = 1 lane; 1 = 2 lanes on the roundabout
LINE	0 = no marking or not applicable; 1 = marking between roadway and cycle lanes
BARR	0 = no physical element or not applicable; 1 = physical element between roundabout and cycle lanes
PRIOR	0 = no priority for bicyclists; 1= priority when crossing exit or entry lanes

All variables were dummies and could take the value 0 or 1. The estimated effectiveness per location (EFF) was used as the dependent variable in the model. EFF was a continuous, non-negative variable, showing a more or less lognormal distribution. A natural log transformation was done and the value LN(EFF) was further used for the analysis.

The functional form of the fitted model can be described as

$$LN(EFF) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon$$

where $x_1, \ldots, x_n$ denote the independent variables (all dummies) and $\beta_0, \ldots, \beta_n$ were the estimation parameters.

The generalized linear modelling procedure was applied starting from an initial set of variables including: INSIDE, MIXED, CYCLLANE, CYCLPATH, GRADESEP, SIGNALS and TWOLANES. Possible second-order effects were checked by including a number of interaction terms in the models. The interaction terms were each time calculated as the product of the values of two dummy variables, resulting in a value one in case both dummy variables had the value one, and a value zero in the other cases. Included interaction terms were cross variables for the different cycle facility types (MIXED, CYCLLANE, CYCLPATH and GRADESEP) on the one hand and the variables INSIDE, SIGNALS and TWOLANES on the other hand (thus MIXED*INSIDE, CYCLLANE*INSIDE etc.). Furthermore interaction terms were used to include some variables that are only applicable to one particular category of roundabouts: CYCLPATH*PRIOR (in case of cycle paths), CYCLLANE*BARR and CYCLLANE*LINE (both in case of cycle lanes). In a first step a model was fitted with all those variables, resulting in a deviance-value of 56.63 and two significant variables: TWOLANES (+) and TWOLANES*MIXED (-). Subsequently the correlation matrix was inspected and in case of variables with a high correlation ($\rho>0.6$), the variable with the smallest contribution to the model fit was eliminated unless both variables had a substantial individual contribution to the model fit. Furthermore non-significant variables ($p>0.1$) were gradually eliminated. Table 13 shows the model results.

Table 13 Regression results of LN(EFF) for all roundabouts (N=90), all crashes with bicyclists

Parameter	Estimate	Standard Error	Chi-Square	Pr > ChiSq
Intercept	-0.51	0.14	13.24	<0.01
CYCLLANE	1.05	0.19	31.54	<0.01
SIGNALS	0.61	0.22	7.64	0.01

Deviance = 67.86 DF = 87

The main effects for CYCLLANE and SIGNALS are positive and significant. The sign of the revealed effect is positive , meaning that roundabouts with cycle lanes, compared with the other designs, have had a worse performance regarding crashes with bicyclists. Furthermore the model shows that signal-controlled intersections that were converted into roundabouts have had a worse evolution than non-signal controlled intersections (parameter estimate 0.61, significance level 0.01) .

Some alternative models were fitted with less strict assumptions on including non-significant variables. If variables were only eliminated in case of p-values above 0.2 also the variables TWOLANES (parameter estimate + 0.89) and INSIDE (+0.31) showed a positive influence on the EFF-values (table 14). However, the value for TWOLANES was in this model only significant when the interaction effect of mixed traffic and a two-lane roundabout was also included. Note that the sample contained only one roundabout in this last case (see table 2). There was also a tendency for roundabouts inside built-up area to perform weaker than roundabouts outside urban area (parameter estimate 0.31, significance 0.11). However, since these results are less significant and in the case of the twolane-roundabouts not consistent throughout the sample, they should be treated as only indicative.

Table 14 Regression results of LN(EFF) for all roundabouts (N=90), all crashes with bicyclists

Parameter	Estimate	Standard Error	Chi-Square	Pr > ChiSq
Intercept	-0.60	0.15	16.02	<.01
CYCLLANE	0.95	0.19	25.02	<.01
SIGNALS	0.42	0.23	3.34	0.07
TWOLANES	0.89	0.39	5.21	0.02
TWOLANES*MIXED	-1.75	0.95	3.37	0.07
INSIDE	0.31	0.19	2.54	0.11

Deviance = 62.93 , DF = 84

After fitting the models for all injury crashes the same procedure was followed for the effectiveness-indices of the sub-sample of crashes with fatally or seriously injured. The chosen variables and procedures were identical to the before-mentioned. The dependent variables were the effectiveness estimates from the scenario where k = value k for all injury crashes. This resulted in a model containing two variables (CYCLPATH and the interaction term CYCLPATH*PRIOR) and showing a much weaker fit than the model for all accidents (table 15). Although not significant, the interaction term CYCLPATH*PRIOR (cycle paths with priority to bicyclists) seems to moderate the unfavourable result of roundabouts with a cycle path.

Table 15 Regression results of LN(EFF) for all roundabouts (N=90), KSI crashes with bicyclists

Parameter	Estimate	Standard Error	Chi-Square	Pr > ChiSq
Intercept	0.17	0.18	0.92	0.34
CYCLPATH	0.72	0.34	4.43	0.04
CYCLPATH*PRIOR	-0.69	0.42	2.68	0.10

Deviance = 150.32 DF = 87

6. DISCUSSION

In the previous before-and-after study the effects of roundabouts on crashes involving bicyclists were estimated (Daniels et al., 2008). The extra information about the cycle facilities on roundabouts in the present study enabled to relate the results of the previous study to different designs of cycle facilities. In our data, a clear difference in the performance level is visible for roundabouts with cycle lanes compared to other types when all injury crashes with bicyclists are considered. The presence of cycle lanes correlates with a higher value of the effectiveness-index which indicates an increase in the number of bicycle crashes. This effect was suggested earlier, e.g. by Brilon (1997). However, in their cross-sectional study, Hels & Orozova-Bekkevold (2007) found no significant effect of the presence of a cycle facility on the number of bicyclist crashes.

Although a clear statistical relationship was found, the present results should be interpreted carefully. Confounding factors might exist where was not controlled for. Moreover the specific effect for cycle lanes was not found for the subgroup of the severest crashes. Contrarily, in that group mainly the roundabouts with cycle paths seem to have generated even worse result than the other types. Nevertheless we see two main reasons to be less confident in the result for the crashes with killed and seriously injured: first there is the very low fit of the model for the severe crashes, suggesting that much of the variance is purely random and/or could be explained by other, unknown, variables. A second reason is related to the reliability of the underlying data, i.e. the estimated values for the effectiveness-indices. The results for the individual locations for the crashes with killed or seriously injured have systematically low significance values (see table 11) and moreover they are affected by the applied overdispersion parameter (see for example the influence of the applied overdispersion parameter on the estimates for the group of the grade-separated roundabouts). This forces us to rely substantially more on the results of the model for all the injury crashes, meaning that mainly roundabouts with cycle lanes perform worse. For the two remaining types of cycle facilities (mixed traffic and grade-separated), the models didn't reveal a distinct effect, which might be due to the scarcity of the data (9 and 3 observations respectively).

van Minnen and Braimaster (1994) investigated the give-way behaviour of motorists and bicyclists at roundabouts with separate cycle paths. Both the designs with and without priority to bicyclists were

included. The observations revealed that in a considerable number of cases the formal rules were not obeyed, both by motorists and bicyclists. van Minnen (1995) found in a cross-sectional study a difference between the performance of roundabouts with separate cycle paths with priority to bicyclists and separate cycle path-roundabouts without priority to bicyclists. When priority is given to bicyclists the number of serious injury crashes seems to be higher than if not (Dijkstra, 2005). However, our model for the most serious crashes produces deviating results since the sign of the interaction variable CYCLPATH*PRIOR is negative, meaning that within the group of the cycle path roundabouts priority for bicyclists moderates the unfavourable effect. Nevertheless, this last effect is not significant and it suffers from the above-mentioned uncertainties.
A Dutch before and after-study found no major differences in the evolution of crashes with bicyclists between three different roundabout design types (mixed traffic, cycle lanes, separate cycle paths) (Schoon and van Minnen, 1993). Regarding the numbers of victims however, it was concluded that at roundabouts with a considerable traffic volume, a separate cycle path design was safer than both other types. Therefore the authors recommended the use of separate cycle path designs. In a Swedish study it was concluded that the bicyclist crash rate at roundabouts with cycle crossings (i.e. roundabouts with a cycle path design) was lower compared to roundabouts with bicyclists riding on the carriageway (Brüde and Larsson, 2000).

Two roundabouts in the sample are in the case of a 'suggestion lane'. They are considered to be a part of the group with the cycle lanes. A sensitivity analysis on the results was performed by recalculating meta-analyses and assigning those two roundabouts to the group of mixed traffic. However, no important differences were found.

Earlier findings (Brüde and Larsson, 2000) suggested a weaker result for two-lane roundabouts compared to single-lanes. Our study reveals a similar tendency, but the results must be qualified as only indicative since they are insufficiently significant.

Roundabouts replacing signal-controlled intersections score weaker than roundabouts that replaced other types of intersections. A meta-analysis by Elvik (2003) revealed that the general favourable effect of roundabouts - although for all road users, not only for bicyclists - was greater on intersections previously controlled by yield signs than on signal-controlled intersections. In the present case, the same order of effect sizes seems to exist: also for crashes with bicyclists roundabouts replacing traffic signals perform worse compared to roundabouts on other types of intersections.

Some other variables and interaction terms were not significant in any of the models. Worth mentioning among these are the colour of the cycle facility (possibly relevant in the case of cycle lanes, cycle paths and to a lesser extent at grade-separated roundabouts) and the interaction terms CYCLLANE*BARR and CYCLLANE*LINE that are describing the nature of the separation between roadway and cycle lane within the group of the cycle lane roundabouts. However, also here the scarcity of the data might decrease the power of the study to find out some differences in safety performance. Generally little is known concerning the effects of line markings and physical elements between roadway and cycle lane. Schoon and van Minnen (1993) found a slightly lower number of crashes at cycle lane-roundabouts with small humps between the roadway and the cycle lane.

A limitation of this study is the absence of information about other, not included, variables that could be relevant. Possible relevant variables are vehicle speeds, radius of the central island, road width on the roundabout and on the entry/exiting lanes, entry/exit radius and traffic volume. Some of these variables might even correlate with variables in our models and therefore provide alternative explanations for the stated effects. For example, speeds on two-lane roundabouts might be higher and could therefore provide an alternative explanation for the effect of the TWOLANE-variable in our model. Probably the most important missing variable is the traffic volume, both for bicyclists and motorised vehicles. However, if the assumption can be held that both the traffic volume and the share of the different modes were not differently affected throughout the whole sample of locations by constructing a roundabout, this factor should not be highly influential. Furthermore a correlation may be present between the cycle facility type and the volume of bicyclists. It is likely that on locations with higher bicycle traffic, those designs are more frequently applied that, according to the guidelines (e.g. CROW, 2007 or MVG, 2006) are considered to be the safest and the most comfortable for bicyclists, i.e. the cycle paths and the grade-separated roundabouts. However, in practice it appears that lack of available space or budgetary constrictions often put a limit on the possibility to construct more space-consuming cycle facilities, particularly on locations inside built-up area, where more cyclists are present. This last argument may also provide an explanation for the tendency of a worse effect on locations inside built-up area (variable INSIDE) that is found in the present study.

The effects of some other variables have been investigated in different studies. Hels and Orozova-Bekkevold (2007) found a significant positive relationship between the drive curve as a proxy for potential vehicle speeds and the number of bicyclist crashes. A similar effect was reported by Layfield and Maycock (1986). Brüde and Larsson (2000) found a central island radius for single-lane roundabouts of more than 10 meter most beneficial for reducing bicycle crashes.

After regarding some effects of roundabouts on bicyclist safety and considering some influential variables, one might question what causes the weaker score of roundabouts for bicyclists. A dominant type of crashes with bicyclists at roundabouts is the one with a circulating bicyclist that collides with an exiting or entering motor vehicle (CETUR, 1992; Layfield and Maycock, 1986). Hels & Orozova-Bekkevold (2007) found that a large part of the crashes were vehicle-failed-to-give-way crashes. They suggest a possible major role of what has been called 'looked-but-failed-to see' crashes. Other concepts might be helpful to explain some parts of the effects, such as the 'law of rare events' (Elvik, 2006), stating that relatively rare events (like motorists – bicyclists encounters at roundabouts can considered to be) are more likely to increase crash rates. Further research in this area is recommended as a better knowledge of causal mechanisms is likely to facilitate adequate countermeasures.

7. SUMMARY

The main conclusions of this study can be summarized in four points:

1. The data for the study sample suggest that the construction of a roundabout generally increases the number of severe injury crashes with bicyclists, regardless of the design type of cycle facilities. The data reveal some tendency for roundabouts with separate cycle paths to perform even worse, but this effect is insure.

2. Regarding the effects on all injury crashes, roundabouts with cycle lanes perform obviously worse compared to the three other design types (mixed traffic, separate cycle paths and grade-separated cycle paths).

3. Roundabouts that are replacing signal-controlled intersections have had a worse evolution compared with roundabouts on other types of intersections.

4. Further research, preferably based on larger samples and applied in different settings, such as in other countries and under other traffic conditions is needed in order to assess the validity of the results in general. Further research is also needed in order to reveal possible causal mechanisms for crashes with bicyclists at roundabouts.

8. IMPACT ON INDUSTRY

No decisive answer can be given about which recommendations should be given to road authorities, based on the present knowledge of safety effects of roundabouts. The value of roundabouts as an effective measure to reduce injury crashes for the full range of road users has been well established (De Brabander et al., 2005; Elvik, 2003; Persaud et al., 2001). However, the contrast with the effects on the subgroup of crashes with bicyclists is remarkable and may cause a dilemma in policy making. Based on the results of the present study, it would not be recommendable to construct a roundabout anyway when safety for bicyclists is a major concern. However, based on the results for all injury crashes, a clear distinction should be made between roundabouts with cycle lanes and other types of cycle facilities.

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