Roundabouts and safety for bicyclists: empirical results and influence of different cycle facility designs

Peer-reviewed author version

DANIELS, Stijn; BRIJS, Tom; NUYTS, Erik & WETS, Geert (2008) Roundabouts and safety for bicyclists: empirical results and influence of different cycle facility designs.
In: 2008 TRB National Roundabout Conference..

Handle: http://hdl.handle.net/1942/9560

Roundabouts and safety for bicyclists: empirical results and influence of different cycle facility designs

TRB National Roundabout Conference
Kansas City, Missouri, USA – May 18-21 2008

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@uhasselt.be; tom.brijs@uhasselt.be; geert.wets@uhasselt.be
[2] Provincial College Limburg
Universitaire Campus Building E, 3590 Diepenbeek, Belgium
tel +32 11 24 92 13 e-mail erik.nuyts@phlimburg.be

ABSTRACT

Roundabouts in general have a favourable effect on traffic safety, at least for crashes causing injuries. Especially the number of severe crashes (fatalities and crashes involving serious injuries) appears to decrease after converting intersections into roundabouts.

Less is known about the safety effects of roundabouts for particular types of road users, such as bicyclists. A before-and-after study with the use of a comparison group on a sample of 90 roundabouts in Flanders-Belgium was conducted in order to assess the effects on crashes with bicyclists. This study revealed a significant increase in the number of severe injury crashes with bicyclists after the construction of a roundabout. Roundabouts with cycle lanes perform worse, regarding injury crashes with bicyclists, compared to three other design types (mixed traffic, separate cycle paths and grade-separated cycle paths). Roundabouts that are replacing signal-controlled intersections seem to have had a worse evolution compared to roundabouts on other types of intersections.

1. INTRODUCTION

Roundabouts in general have a favourable effect on traffic safety, at least for crashes causing injuries. During the last decades several studies were carried out into the effects of roundabouts on traffic safety. A meta-analysis on 28 studies in 8 different countries revealed a best estimate of a reduction of injury crashes of 30-50% (Elvik, 2003). Other studies, not included in the former one, delivered similar results (e.g. Persaud et al., 2001; De Brabander et al., 2005). All those studies reported a considerably stronger decrease in the number of severest crashes (fatalities and crashes involving serious injuries) compared to the decrease of the total number of injury crashes. The effects on property-damage only crashes are however highly uncertain (Elvik, 2003).

Less is known about the safety effects of roundabouts for particular types of road users, such as bicyclists (Daniels and Wets, 2005). Roundabouts seem to induce a higher number of bicyclist-involved crashes than might be expected from the presence of bicycles in overall traffic. In Great-Britain the involvement of bicyclists in crashes on roundabouts was found to be 10 to 15 times higher than the involvement of car occupants, taking into account the exposure rates (Brown, 1995). In Flanders-Belgium bicyclists appear to be involved in almost one third of reported injury crashes at roundabouts. Own analysis of the available crash data records reveals a number of 1118 crashes with bicyclists on a total of 3558 reported injury crashes at roundabouts during the period 1991-2001. In general, only 14.6% of all trips (5.7% of distances) are made by bicycle (Zwerts and Nuyts, 2004). The apparent overrepresentation of bicyclists in crashes at roundabouts was the main cause to conduct an evaluation study on the effects of roundabouts, more specifically on crashes involving bicyclists.

2. TYPES OF CYCLE FACILITIES

Throughout different countries different designs have been developed for cycle facilities at roundabouts. Although huge differences between design practices in different countries continue to exist, some basic design types of cycle facilities at roundabouts can be distinguished. They are ordered into four categories:

1. Mixed traffic;
2. Cycle lanes;
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 since no specific facilities for bicyclists are provided. In some countries it is common to apply the mixed traffic solution, even when bicycle 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).

Figure 1 – Roundabout with mixed traffic

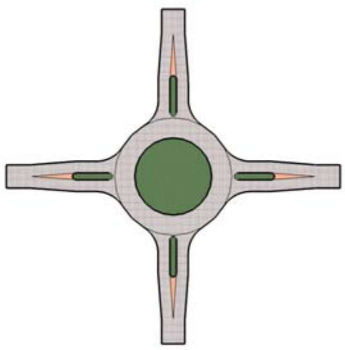


Figure 2 – Roundabout with cycle lanes

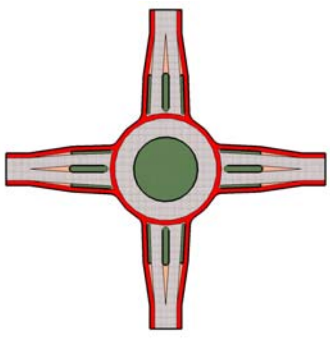


Figure 3a – Roundabout with separate cycle paths – priority to bicyclists

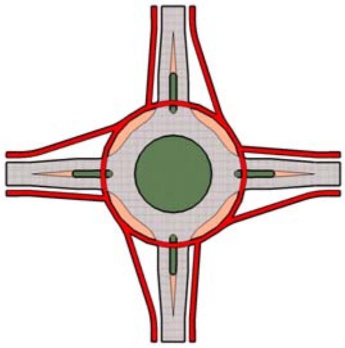


Figure 3b – Roundabout with separate cycle paths – no priority to bicyclists

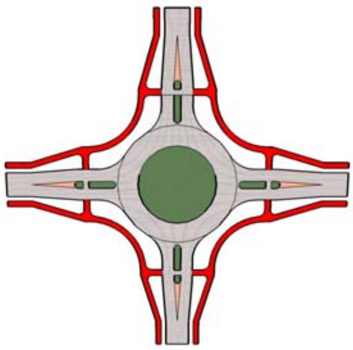
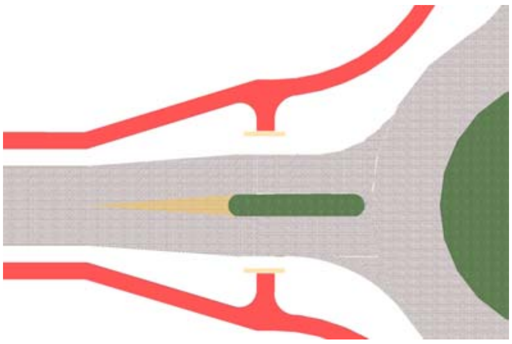


Figure 4 - - Roundabout with grade-separated cycle paths



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 outside 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 with 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.

Picture 1 – Roundabout 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) alongside roads. Since the distance between the separate cycle path and the roadway at roundabouts may mount to some meters (e. g. the Dutch design guidelines recommend 5 meters) (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. At some roundabouts, 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).

Picture 2 – Roundabout with separate cycle paths

3. DATA COLLECTION

A sample of 90 roundabouts in the Flanders region of Belgium was studied. The roundabout data were obtained from the Roads and Traffic Agency (part of the Ministry of Mobility and Public Works). The sample was selected according to the following successive selection criteria applied on the initial dataset:

- Roundabouts constructed between 1994 and 2000.
- 3 or 4 roundabouts selected randomly in each of the 28 administrative road districts in the Flanders region.

All the investigated roundabouts are located on regional roads (so-called numbered roads) owned by either the Roads and Traffic Agency or the provinces. This type of roads is characterized by significant traffic, where other, smaller and less busy roads are usually owned by municipalities. The Annual Average Daily Traffic on the type of roads in question is 11 611 vehicles per day (AWV, 2004). No information was available about the AADT on the selected roundabouts. The investigated sample can be considered as representative for roundabouts on regional roads in Flanders.

Both single-lane as well as double-lane roundabouts occur in the sample, although the former type is far more common (83 of the 90 roundabouts).

Information was collected about the type of cycle facility that is present at the roundabouts (table 1). According to the type of the cycle facilities, each roundabout was assigned to one of the four above-mentioned categories.

Table 1 - Number of roundabouts in the study sample - location and type of cycle facility

	Inside built-up area	Outside built-up area	TOTAL
1 - Mixed traffic	8	1	9
2 - Cycle lanes	24	16	40
3 - Separate cycle paths	8	30	38
4 - Grade-separated	0	3	3
TOTAL	40	50	90

21 of the 90 roundabouts were replacing traffic signals. 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 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.

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 area (areas inside built-up area boundary signs, general speed limit of 50 km/h), 50 outside built-up areas (generally with a speed limit of 90 or 70 km/h).

Furthermore the colour of the cyclist facility (when present) was noticed. In Flanders it is common to colour cyclist facilities red, although it is not compulsory. Other colours don' t occur. In the case of the cycle lanes, all but one are coloured. In the case of the separate cycle paths there are some more instances (6) of uncoloured pavements, but they are still limited to a small minority.

Two comparison groups were composed, consisting of 76 intersections inside built-up areas and 96 intersections outside built-up area respectively serving as a comparison group for roundabouts inside and outside built-up areas. For the comparison groups, intersections on regional roads were selected in the wide environment of the roundabout locations. Preference for comparison group locations was given to intersections on the same main road as the nearby roundabout location with the same type of crossing road. The road categories were found on a street map. In order to avoid possible interaction effects of the comparison group locations with the observed roundabout locations, comparison group locations had to be at least 500 meter away from the observed roundabout locations. Apart from the confirmation they aren't roundabouts, no information is available about the type of traffic regulation on the intersections in the comparison group. On the considered types of roads either signal-controlled, or priority-ruled intersections (one direction has priority) may occur.

Detailed crash data were available from the National Statistical Institution for the period 1991-2001. This database consists of all registered traffic crashes causing injuries. Only crashes where at least one bicyclist was involved were included. Crashes were divided into 3 classes based on the severest injury that was reported: crashes involving at least one fatally injured person (killed immediately or within 30 days after the crash), crashes involving at least one seriously injured (person hospitalized for at least 24 hours) and crashes involving at least one slightly injured. No distinction was made about which road user was injured, the bicyclist or any other road user such as a car occupant, a motorcyclist, another bicyclist or whoever.

Locations of crashes on numbered roads are identified by the police by references to the nearest hectometre pole on the road. All the crashes that were exactly located on the hectometre pole of the location were included in this study. Subsequently crashes that were located on the following or the former hectometre pole were added, except when the observed crash could clearly be attributed to another intersection. This approach was chosen in order to include possible safety effects of roundabouts in the neighbourhood of the roundabout as they might occur (Hydén and Várhelyi, 2000). Consequently the results should be considered as "effects on crashes on or near to roundabouts". At least one road on each location, both for the treatment group as for the comparison group, was a numbered road.

The same selection criteria were applied for crashes on locations in the comparison group as for crashes on the roundabout locations.

The total number of crashes on the 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 2). The total number of crashes in the comparison group is 649, of which 486 with only slight injuries, 142 with serious injuries and 21 with fatal injuries.

Table 2 - Number of crashes considered (crashes with bicyclists only).

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

4. METHODOLOGY

An Empirical Bayes - before and after study was made of injury crashes with bicyclists at roundabouts.

The first stage was to calculate the effectiveness for each location in the treatment group (= each of the 90 roundabouts) separately. The effect is expressed as an odds-ratio of the evolution of the number of crashes in the treatment group after the measure has been taken compared to the evolution in the comparison group over the same time period (Eq. 1). An effectiveness-index EFF_l above 1 indicates an increase in the number of crashes compared to the average evolution on similar locations where no roundabout was constructed, while an index below 1 shows a decrease in the number of crashes.

$$EFF_l = \frac{TREAT_{l,\,after} \,/\, TREAT_{l,\,before,\,regr}}{COMP_{after} \,/\, COMP_{before}} \qquad \text{(Eq. 1)}$$

The values of $TREAT_{l,after}$, $COMP_{after}$ and $COMP_{before}$ are count values and can simply be derived from the data. The value for $TREAT_{l,after}$ is the count number of crashes that happened on the location l during the years after the year when the roundabout was constructed. The values for $COMP_{after}$ and $COMP_{before}$ are the total count numbers of crashes for all locations in the comparison group respectively after and before the year during which the roundabout has been constructed.

The use of the comparison group allowed for a correction of general trend effects that could be present in the evolution of crashes on the studied locations.

The value of $TREAT_{l,before,regr}$ reflects the estimated number of crashes on the treatment location l before construction of the roundabout, taking into account the effect of regression-to-the-mean. The regression-to-the-mean effect is likely to occur at locations where a decision has been taken to construct a roundabout as the Roads and Traffic Agency considers an increased number of crashes among others as an important criterion for constructing a roundabout at a certain location. The value is calculated as a result of the formula (Eq. 2):

$$TREAT_{l,\,before,\,regr,} = w * (\mu_{(TREAT_l\,+\,COMP)} * T) + (1-w) * (\sum_{t=1}^{T} TREAT_{l,\,t}) \qquad \text{(Eq. 2)}$$

with $$w = \frac{1}{1 + k * \mu_{(TREAT_l\,+\,COMP)} * T} \qquad \text{(Eq. 3)}$$

Equation 2 expresses the estimated number of crashes at the observed location in a time period T. Equation 2 equals the weighted sum of the number of crashes on the individual location and the average number of crashes on the locations in the comparison group.

T equals the number of years in the before period. The value k expresses the statistical overdispersion factor and reflects the amount in which the data are more dispersed than would have been the case in a perfect Poisson distribution. In some cases the overdispersion factor couldn't be derived from the data themselves. In those cases, we used three scenarios, representing the range of possible values for k. A detailed technical description of the followed procedure can be found in Daniels et al. (2008).

The value w (Eq. 3) reflects the weighting of the comparison group in the estimation of the number of crashes on the treatment location in the before-period whereas (1-w) reflects the weighting of the crash history on the location itself.

Consequently a best estimate and confidence intervals for the value of EFF_l on each roundabout location could be estimated.

After doing this, a meta-analysis was carried out in order to retrieve generalized impacts on groups of locations. A meta-analysis is a useful procedure to combine results from different studies but combining the treatment effects of a set of entities within one study is conceptually highly comparable (Hauer, 1997). In our case we used the inverse of the variance of the individual results as the weighting factor for the individual location in the meta-analysis, expressing the idea that an individual result with a smaller variance is more reliable and should therefore weigh heavier in the global estimate than a result with a larger variance (Elvik, 2001; Elvik, 2005).

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 changes in factors such as number of lanes, pavement colour, location inside/outside built-up area etc.

5. RESULTS

Tables 3 and 4 show the results of the analyses for all injury crashes and only crashes with fatally or seriously injured respectively. The best estimate for the overall effect of roundabouts on injury crashes involving bicyclists on or nearby the roundabout is an increase of 27%. The best estimate for the effect on crashes involving fatal and serious injuries is an increase of 42-44%, depending on the applied dispersion-value k.

The number of injury crashes at roundabouts with cycle lanes turns out to increase significantly (+93%, C.I. [+38%;+169%]). However, for the other 3 design types (mixed traffic, separate cycle paths, grade-separated cycle paths) the best estimate is a decrease in the number of crashes (-17%), although not significant (result of a separate meta-analysis on the values for those categories, not reflected in the table). None of the partial results for one of the subgroups in table 4 is significant at the 5% level. However, all aggregated results show an increase in the number of fatal and serious crashes, except in one scenario for roundabouts with grade-separated cycle facilities which shows a status quo.

Table 3 - Results – all injury crashes.

	Nr of locations	Effectiveness-index
Mixed traffic	9	0.91 [0.45;1.84] (ns)
Cycle lanes	40	1.93 [1.38;2.69] **
Separate cycle paths	38	0.83 [0.56;1.23] (ns)
Grade-separated	3	0.56 [0.11;2.82] (ns)
All roundabouts	90	1.27 [1.00-1.61] *

ns = not significant * = $p \leq 0.05$ ** = $p \leq 0.01$

Table 4 - Results – crashes with fatal and serious injuries.

	Nr. of locations	Effectiveness-index
Mixed traffic	9	1.77 [0.55;5.66] (ns) ° 1.79 [0.56;5.74] (ns) °° 1.89 [0.59;6.10] (ns) °°°
Cycle lanes	40	1.37 [0.79;2.37] (ns) ° 1.37 [0.79;2.35] (ns) °° 1.34 [0.78;2.31] (ns) °°°
Separate cycle paths	38	1.43 [0.81-2.52] (ns) ° 1.42 [0.80-2.51] (ns) °° 1.46 [0.83-2.56] (ns) °°°
Grade-separated	3	1.84 [0.26;12.76] (ns) ° 1.31 [0.23;7.54] (ns) °° 1.00 [0.18;5.49] (ns) °°°
All roundabouts	90	1.44 [1.00;2.09] * ° 1.42 [0.99;2.05] (ns) °° 1.42 [0.99;2.03] (ns) °°°

ns = not significant * = $p \leq 0.05$ ** = $p \leq 0.01$

° use of fixed dispersion parameter $k = 10^{-10}$

°° use of dispersion parameter k = value k for all crashes (light, serious, fatal)

°°° use of fixed dispersion parameter $k = 10^{10}$

Consequently a meta-regression procedure was applied in order to estimate the relationship between the estimated value for the effectiveness per location and some known characteristics of the roundabout locations. The logarithm of the estimated effectiveness per location (EFF) was used as the dependent variable in the model. EFF is a continuous, non-negative variable (range 0.20-8.87), showing a more or less lognormal distribution.

Stepwise linear regression models were fit starting from an initial set of dummy variables including: INSIDE (location inside (=1) or outside built-up area (=0)), MIXED (1 in case of mixed traffic; 0 if not), CYCLLANE (1 in case of cycle lanes; 0 if not), CYCLPATH (1 in case of separate cycle paths; 0 if not), GRADESEP (1 in case of grade-separated cycle paths; 0 if not), SIGNALS (1 if traffic signals in before situation; 0 if not) and TWOLANES (1 in case of two-lane roundabouts; 0 if one-lane). Variables were allowed to enter and stay in the model whenever their significance level did not exceed 0.20, but in the final model all non-significant ($p > 0.05$) variables were eliminated.

Table 5 shows the regression results. The values for CYCLLANE and SIGNALS are significant at the 1%-level. Since the sign of the revealed effect is positive, it can be concluded that the presence of a cycle lane or the presence of traffic signals in the before-situation does increase the likelihood of a deterioration after a roundabout is constructed.

Table 5 - Regression results of LN(EFF) for all roundabouts, all crashes (N=90)

Variable	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	-0.50715	0.14178	-3.58	0.0006
CYCLLANE	1.05097	0.19033	5.52	<.0001
SIGNALS	0.60782	0.22361	2.72	0.0079

$R^2 = 0.2788$ $F = 16.82$ $s = 0.78$

Consequently models were fitted separately for 2 subgroups of roundabouts: roundabouts with cycle lanes and roundabouts with separate cycle paths, using some geometrical variables that apply specifically to those subgroups.

In the resulting model for the roundabouts with separate cycle paths (N=38) the variable TWOLANES was significant (p= 0.02) and showed a positive influence on the effectiveness-index. However, the goodness of fit was low (R^2 = 0.14-0.15) for both models, which makes the results to be interpreted as only indicative.

The variable PRIOR (priority for bicyclists when crossing entry/exit lanes or not) that is relevant for the case of the cycle paths, didn't appear to be significant in the model for the sub-group of the cycle paths.

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. Unfortunately, no reliable model could be fitted on the results for all roundabouts (N=90).

6. DISCUSSION

Although the safety effects of roundabouts have been studied in a number of studies in the recent and further past, specific research about the effects for particular types of road users is less common. A comparable before- and after- design was used by Schoon and van Minnen (1993) in the Netherlands. Their study provided indications of a less favourable effect of roundabouts on injuries among bicyclists compared to other road users. In our study, the effect doesn't look favourable at all since the number of injury accidents with bicyclists appears to increase. This finding could provide an explanation for the higher-than-expected prevalence of injury crashes involving bicyclists on roundabouts as we found it in the crash data in Flanders and as it was also noticed in other countries (Brown, 1995; CETUR, 1992). However, it is recommendable to perform similar studies in other countries in order to confirm whether results are comparable.

It is interesting to compare our results with a former study (De Brabander et al., 2005) that studied the effects of roundabouts on safety among all types of crashes (thus not only crashes with bicyclists) in the same region and used a strongly comparable dataset. This study revealed an overall decrease of 34% of crashes causing injuries (95% C.I. [-43%; -28%]) and a decrease of 38% [-54%; -15%] for crashes involving fatal and serious injuries.

These contradictory results for crashes involving bicyclists and all crashes raise the question whether it is recommendable or not – at least from a safety point of view – to construct roundabouts. Although roundabouts turn out to be a safe solution in general, the results for bicyclists' safety are clearly poor.

One of the restrictions of our study is the lack of data about the evolution of traffic volume on the studied locations, particularly about the evolution of motorised traffic and bicyclist traffic. By using a large comparison group it was possible to account for both general trends in traffic volume as well as possible evolutions in modal choice. But, at a local scale level, one cannot exclude the effect of roundabouts on exposure, for motorised traffic as well as for bicyclists. It is possible that some bicyclists or car drivers will change their route choice after the construction of a roundabout, either resulting in an increased use of the roundabout or a decrease in the use, depending on personal preferences. Changes in the route choice could make the results in this study weaker or stronger. If roundabouts for instance would attract bicyclists this would create a higher exposure for bicyclists at the site, but a corresponding lower risk elsewhere, in which case we are too pessimistic in our estimates. But the results might also be stronger. If bicyclists would use roundabouts less than the previous types of intersections, our estimations are even too modest. As no data on exposure were available, we couldn't account for possible changes in the choice of route. Further research in this area is recommended.

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 reflecting an estimated increase in the number of crashes. This effect was earlier suggested (Brilon, 1997). The three other design types (mixed traffic, separate and grade-separated cycle paths) didn't show a specific influence on the data. In the case of mixed traffic and grade-separated cycle paths the scarcity of the observations might play a decisive role (9 and 3 estimates respectively). In the case of the separate cycle paths (38 estimates) this is less clear. 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 to numbers of victims however, the authors concluded that at roundabouts with a considerable traffic volume, a separate cycle path design is safer than both other types. Therefore a separate cycle path design was recommended. In a recent Danish study no significant effect was found of the presence of a cycle facility (without distinction of different types) on the number of bicyclist crashes (Hels and Orozova-Bekkevold, 2007).

Regarding the severest crashes, the ones with fatally or seriously injured, the results that are presented in this paper deviate from existing knowledge. The results show an overall significant and substantial (best estimate around 42%) increase in the number of severe bicyclist crashes . However, in contrast to the results for all injury crashes the design type doesn't seem to influence the effectiveness of the roundabout for severe crashes. Thus, regardless of the design type the roundabout seems to induce an increase in the number of severe crashes with bicyclists.

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 are the ones with a circulating cyclist 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.

7. CONCLUSIONS

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

1. The results for the study sample suggest that the construction of a roundabout generally raises the number of severe injury crashes with bicyclists, regardless of the design type of cycle facilities.

2. Regarding the effects on all injury crashes, roundabouts with cycle lanes perform 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 seem to have had a worse evolution compared with roundabouts on other types of intersections.

4. Further research is needed in order to assess the validity of the results in different settings, such as other countries and other traffic conditions (e.g. depending on the prevalence of cyclists in traffic). Further research is also needed in order to extend knowledge about contributing factors and to reveal causal mechanisms for crashes with bicyclists at roundabouts.

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 proven. 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 for the severest crashes, 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 near to the carriageway and other types of cycle facilities.

8. ACKNOWLEDGEMENTS

The roundabout data were obtained from the Flemish Ministry of Mobility and Public Works - Roads and Traffic Agency. Many field workers contributed to the data collection. Preliminary results were presented to an expert group of civil servants and discussed. The authors wish to thank them for their useful information and valuable comments.

9. REFERENCES

AWV (2004). *Verkeerstellingen 2004 in Vlaanderen met automatische telapparaten*. Ministry of the Flemish Community, Road and Traffic Administration, Brussels, Belgium.

Brilon, W. (1997). Sicherheit von Kreisverkehrplätzen. *Zeitschrift für Verkehrssicherheit, 43(1)*, 22-28.

Brown, M. (1995). *The Design of Roundabouts: State-of-the-art Review*. Transport Research Laboratory, London.

CETUR (1992). *La sécurité des carrefours giratoires: en milieu urbain ou péri-urbain*, Ministère de l'Equipement, du Logement, des Transports et de l'Espace, Centre d'Etudes des Transports Urbains, Bagneux, France.

CROW (2007). *Design manual for bicycle traffic*. Ede, The Netherlands: Dutch national information and technology platform for infrastructure, traffic, transport and public space.

Daniels, S., Wets, G. (2005). *Traffic Safety Effects of Roundabouts: a review with emphasis on Bicyclist's Safety*. Proceedings of the 18th ICTCT-workshop. Helsinki, Finland, www.ictct.org.

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.

De Brabander, B., Nuyts, E., Vereeck, L. (2005). Road safety effects of roundabouts in Flanders. *Journal of Safety Research, 36*(3), 289-296.

Elvik, R. (2001). Area-wide urban traffic calming schemes: a meta-analysis of safety effects. *Accident Analysis & Prevention, 33*, 327-336.

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. (2005). Introductory Guide to Systematic Reviews and Meta-Analysis. *Transportation Research Record: Journal of the Transportation research Board, 1908*, 230-235.

Hauer, E. (1997). *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Oxford: Pergamon Press.

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

Hydén, C., Várhelyi, A. (2000). The effects on safety, time consumption and environment of large scale use of roundabouts in a built-up area: a case study. *Accident Analysis and Prevention, 32*, 11-23.

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

MVG (2006). *Vademecum fietsvoorzieningen*. Brussel: Ministerie van de Vlaamse Gemeenschap - afdeling Verkeerskunde.

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

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

Zwerts, E., Nuyts, E. (2004). *Onderzoek verplaatsingsgedrag Vlaanderen 2000-2001*. Brussels: Ministry of the Flemish Community.