Injury accidents with bicyclists at roundabouts.

Influence of the design of cycle facilities and other location characteristics.

RA-MOW-2008-001

S. Daniels, T. Brijs, E. Nuyts, G. Wets

DIEPENBEEK, 2012.
STEUNPUNT MOBILITEIT & OPENBARE WERKEN
SPOOR VERKEERSVEILIGHEID

Documentbeschrijving

Rapportnummer:	RA-MOW-2008-001
Titel:	Injury accidents with bicyclists at roundabouts.
Ondertitel:	Influence of the design of cycle facilities and other location characteristics.
Auteur(s):	S. Daniels, T. Brijs, E. Nuyts, G. Wets
Promotor:	Prof. dr. Geert Wets
Partner:	Universiteit Hasselt
Aantal pagina's:	27

Uitgave: Steunpunt Mobiliteit & Openbare Werken – Spoor Verkeersveiligheid, 2008.

Steunpunt Mobiliteit & Openbare Werken
Spoor Verkeersveiligheid
Wetenschapspark 5
B 3590 Diepenbeek

T 011 26 91 12
F 011 26 91 99
E info@steunpuntmowverkeersveiligheid.be
I www.steunpuntmowverkeersveiligheid.be

Samenvatting

Eerder onderzoek heeft aangetoond dat de omvorming van een kruispunt tot een rotonde over het algemeen een gunstig effect heeft op het aantal verkeersongevallen met gekwetsten. Een meta-analyse van 28 studies uit 8 verschillende landen kwam uit op een beste schatting van een daling van de letselernst met 30 tot 50%. Andere studies leverden gelijkaardige effecten op. In al deze studies werd een sterkere daling gerapporteerd van de zwaarste ongevallen (ongevallen met zwaargewonden of doden) dan voor de ongevallen met lichtgewonden.

Minder is geweten over de veiligheidseffecten van rotondes voor specifieke groepen weggebruikers zoals fietsers. De ongevallencijfers tonen een groter aandeel ongevallen met fietsers op rotondes dan de aanwezigheid van fietsers in het verkeer kan doen vermoeden. In Vlaanderen zijn er fietsers betrokken in bijna één op drie van alle gerapporteerde letselongevallen op rotondes terwijl slechts 14,6% van alle verplaatsingen per fiets gebeurt, goed voor 5,7% van de totale afgelegde afstand in het verkeer. De klaarblijkelijke oververtegenwoordiging van fietsers in ongevallen op rotondes was de voornaamste aanleiding om een effectiviteitsonderzoek op te zetten over rotondes, in het bijzonder over de ongevallen met fietsers.

Er werd informatie verzameld over het type fietspad dat aanwezig is op de onderzochte rotondes. Vier types werden daarbij onderscheiden: rotondes met gemengd verkeer, aanliggende fietspaden, vrijliggende fietspaden en ongelijkgrondse kruisingen.

Het onderzoek had betrekking op 90 rotondes in Vlaanderen die werden aangelegd tussen 1994 en 2000. Het ging zowel om enkelstrooks- als tweestrooksrotondes. Niettemin zijn de grote meerderheid enkelstrooksrotondes. 21 van de 90 rotondes vervingen kruispunten met verkeerslichten. De overige rotondes werden aangelegd op andere types kruispunten zoals kruispunten met voorrang voor één rijrichting en kruispunten met algemene voorrang van rechts. Verder werd informatie verzameld over de kleur van de desgevallend aanwezige fietsvoorzieningen. In Vlaanderen is het gebruikelijk om fietsvoorzieningen rood te kleuren, alhoewel het niet verplicht is.

Twee vergelijkingsgroepen werden samengesteld, bestaande uit 76 kruispunten binnen bebouwde kom en 96 kruispunten buiten bebouwde kom, en respectievelijk gebruikt voor de rotondes binnen en buiten bebouwde kom. Gedetailleerde ongevallendata waren beschikbaar via het Nationaal Instituut voor de Statistiek (tegenwoordig: FOD Economie, Algemene Directie Statistiek) voor de periode 1991-2001. Enkel ongevallen met minstens één betrokken fietser werden in de analyses opgenomen. Daarbij werden de ongevallen ingedeeld volgens de ernst van het zwaarste letsel veroorzaakt door het ongeval: ongevallen met doden (ter plaatse of binnen de 30 dagen na het ongeval), ongevallen met zwaargewonden (ziekenhuisopname voor minstens 24u) en ongevallen met lichtgewonden.

De toegepaste methode was die van de Empirical Bayes voor- en nastudie. Het gebruik van vergelijkingsgroepen liet toe om te corrigeren voor algemene trends in het aantal ongevallen en voor mogelijke regressie-naar-het-gemiddelde effecten. Via deze methode werd een effectiviteitsindex bepaald voor elke individuele onderzochte rotonde. Omdat bijkomende informatie beschikbaar was over bepaalde geometrische kenmerken van de rotondes, konden regressiemodellen opgesteld worden die toelieten om de variantie te verklaren van de geschatte waarden voor de effectiviteitsindices in functie van factoren zoals het type fietspad, het aantal rijstroken op de rotonde, de kleur van de wegverharding en de ligging binnen of buiten bebouwde kom.

De beste schatting voor het effect van de aanleg van een rotonde op het aantal letselongevallen met fietsers op en nabij de rotonde is een stijging met 27%. Als enkel wordt gekeken naar de ongevallen met doden of zwaargewonden, is de beste schatting zelfs een stijging met 42 tot 44%.

Op rotondes met aanliggende fietspaden blijkt het aantal letselongevallen met fietsers significant te stijgen (beste schatting: +93%, betrouwbaarheidsinterval [+38%;+169%]). Voor de drie overige types fietsvoorzieningen samen (gemengd verkeer, vrijliggende fietspaden en ongelijkgrondse kruisingen) is de beste schatting echter een, weliswaar statistisch niet significante, daling van het aantal ongevallen met 17%. De geaggregeerde resultaten voor de ongevallen met doden en zwaargewonden tonen niettemin voor elk van de beschreven types fietsvoorzieningen een stijging.

Lineaire regressiemodellen werden opgesteld om het verband te zoeken tussen de veiligheidsprestatie van de individuele rotondes en bepaalde gekende kenmerken van deze rotondes. Daaruit kan besloten worden dat de aanwezigheid van een aanliggend fietspad of de aanwezigheid van verkeerslichten in de voorsituatie tot een significant zwakkere prestatie leiden.

Bij de onderzochte rotondes correleert de aanwezigheid van aanliggende fietspaden met een hogere waarde van de effectiviteits-index, hetgeen neerkomt op een geschatte toename van het aantal ongevallen. Dit effect werd reeds eerder gesuggereerd in een Duitse studie. In een voor- en nastudie in Nederland werden geen grote verschillen vastgesteld in de evolutie van het aantal ongevallen tussen de drie voornaamste types van fietsvoorzieningen (gemengd verkeer, aanliggend, vrijliggend). Met betrekking tot het aantal slachtoffers werd niettemin geconcludeerd dat, op rotondes met aanzienlijke verkeersstromen, vrijliggende fietspaden veiliger zijn dan andere types. In een recente Deense studie werd geen significant effect gevonden van de aanwezigheid van één of andere fietsvoorziening op het aantal ongevallen met fietsers.

Als echter louter naar de ongevallen met doden en zwaargewonden wordt gekeken, wijken de resultaten van het onderzoek af van de bestaande kennis. De resultaten tonen een significante en substantiële toename (beste schatting ongeveer 42%) van het aantal zware ongevallen met fietsers.

Er kunnen vier conclusies worden getrokken uit het onderzoek:

1. De resultaten voor de onderzochte rotondes suggereren dat de aanleg van een rotonde over het algemeen het aantal zware ongevallen met fietsers doet toenemen, ongeacht het aanwezige type fietsvoorzieningen.
2. Als naar alle letselongevallen wordt gekeken blijken rotondes met aanliggende fietspaden beduidend zwakker te presteren dan de overige drie types (gemengd verkeer, vrijliggende fietspaden, ongelijkgrondse kruisingen).
3. De rotondes die werden aangelegd op kruispunten waar voordien verkeerslichten stonden, lijken zwakker te presteren dan rotondes op andere types van kruispunten.
4. Verder onderzoek is nodig om de validiteit van de resultaten in verschillende omstandigheden te onderzoeken, zoals in andere landen en in andere verkeersomstandigheden, bijvoorbeeld naargelang het aandeel fietsers in het totale verkeer. Verder onderzoek is ook nodig om mogelijke oorzakelijke mechanismen voor ongevallen met fietsers op rotondes bloot te leggen.

Op basis van de actuele kennis over de verkeersveiligheidseffecten van rotondes kunnen geen sluitende aanbevelingen gegeven worden over de te hanteren aanlegpraktijken. De waarde van rotondes als een geschikt middel om de verkeersveiligheid in zijn geheel te verbeteren is in het verleden ruimschoots aangetoond. Niettemin is het contrast met het effect voor de specifieke groep van ongevallen met fietsers opmerkelijk. Dit kan leiden tot een dilemma voor het beleid. Op basis van de resultaten voor de ongevallen met doden en zwaargewonden, is het mogelijk niet raadzaam om rotondes aan te leggen op plaatsen waar de veiligheid voor fietsers een belangrijk punt van zorg is. Op basis van de resultaten voor alle letselongevallen dient echter een duidelijk onderscheid gemaakt te worden tussen rotondes met aanliggende fietspaden en de overige types fietsvoorzieningen.

Summary

Roundabouts in general have a favourable effect on traffic safety, at least for crashes causing injuries. A meta-analysis on 28 studies in 8 different countries revealed a best estimate of a reduction of injury crashes of 30-50%. Other studies delivered similar results. 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.

Less is known about the safety effects of roundabouts for particular types of road users, such as bicyclists. Roundabouts seem to induce a higher number of bicyclist-involved crashes than might be expected from the presence of bicycles in overall traffic. In Flanders-Belgium bicyclists appear to be involved in almost one third of reported injury crashes at roundabouts while generally only 14.6% of all trips (5.7% of distances) are made by bicycle. 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.

Some basic design types of cycle facilities at roundabouts can be distinguished. They are ordered into four categories: mixed traffic, cycle lanes, separate cycle paths and grade-separated cycle paths.

A sample of 90 roundabouts that were constructed between 1994 and 2000 in the Flanders region of Belgium was studied. Both single-lane as well as double-lane roundabouts occur in the sample, although single-lanes are far more common. 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). 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.

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. Detailed crash data were available from the National Statistical Institution for the period 1991-2001. 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.

The adopted methodology was that of an Empirical Bayes - before and after study. The use of comparison groups allowed to control for general trends in traffic safety and possible regression-to-the-mean effects. The before-and after design allowed to determine effectiveness-indices for each roundabout in the sample. 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.

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%.

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. However, regarding the severest accidents, the aggregated results for each of the design types show an increase in the number of fatal and serious crashes.

Linear regression models 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. It is concluded that the presence of a cycle lane or the presence of traffic signals in the before-situation do increase the likelihood of a deterioration after a roundabout is constructed.

In the study data, 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 in a German study. 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). Regarding to 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 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.

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.

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 raises in general the number of severe injury crashes with bicyclists, regardless of the design type of cycle facilities.
2. Regarding the effects on all injury accidents, 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 bicyclists in traffic). Further research is also needed in order to reveal possible 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. 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 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 and other types of cycle facilities.

Table of contents

1. INTRODUCTION

1.1 Previous research

In a previous study, the authors performed a before-and-after analysis of injury crashes with bicyclists at roundabouts (Daniels et al., 2007). 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 in the applied road design in order to conduct bicyclists through roundabouts. The main research question in this study was to investigate possible differences between designs for cycle facilities regarding safety for bicyclists.

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.

This 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.

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.

1.2 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 (CROW, 1998):

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).

Figure 1 – roundabout with mixed traffic

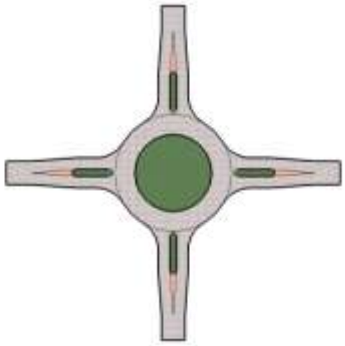


Figure 2 – Roundabout with cycle lanes

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

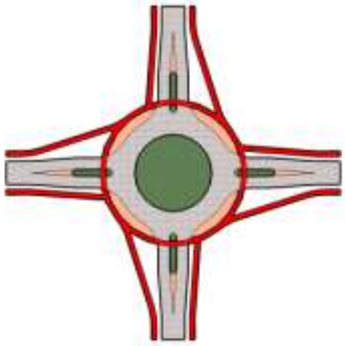


Figure 3b – Roundabout with separate cycle paths – no priority to bicyclists

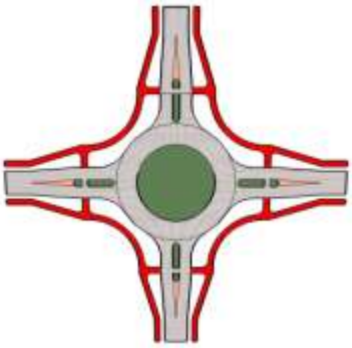
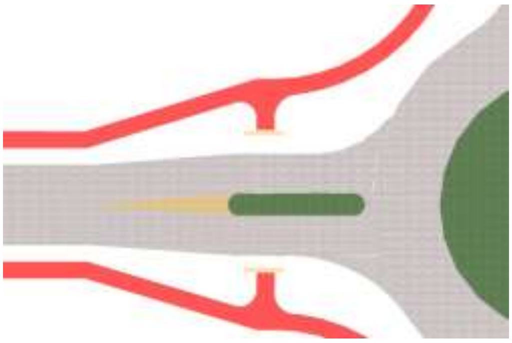


Figure 4 - - Roundabout with grade-separated cycle paths



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 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).

Picture 1 – Roundabout with cycle lanes

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

2. 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., 2007). 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 as well as 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 (Daniels et al., 2007). 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

3. 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 evolutions 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. (2007) 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 resp. 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.

4. 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).

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	21	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 accidents

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

Ordinary least squares linear regression models (SAS-procedure REGR) 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	Type of variable	N
INSIDE	0 = outside built-up area; 1= inside built-up area	Dummy	90
MIXED	0 = no mixed traffic; 1= mixed traffic	Dummy	90
CYCLLANE	0 = no cycle lane; 1 = cycle lane	Dummy	90
CYCLPATH	0 = no separate cycle path; 1 = separate cycle path	Dummy	90
GRADESEP	0= no grade-separation; 1 = grade-separation	Dummy	90
SIGNALS	0 = no traffic signals; 1 = traffic signals before roundabout construction	Dummy	90
RED	0 = not coloured, 1 = red-coloured cycle facilities (not applicable when MIXED = 1)	Dummy	81
TWOLANES	0 = 1 lane; 1 = 2 lanes on the roundabout	Dummy	90
LINE	0 = no marking; 1 = marking between roadway and cycle lanes (only in case of cycle lanes)	Dummy	40
BARR	0 = no physical element; 1 = physical element between roundabout and cycle lanes (only in case of cycle lanes)	Dummy	40
PRIOR	0 = no priority for bicyclists; 1= priority when crossing exit or entry lanes (only in case of separate cycle paths)	Dummy	38

All variables are dummies and can take the value 0 or 1. In a first step regression models were fitted for all variables except RED, LINE, BARR and PRIOR since those apply only to one or more specific categories of cycle facilities.

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. When fitting the model with EFF as a dependent variable there appeared to be a problem of heteroskedasticity in the data. Therefore a natural log transformation was done and the value LN(EFF) was further used for the analysis. After doing this the homoskedasticity assumption (checked by the White-test in SAS) and all other assumptions for a linear regression were fulfilled.

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 and $\beta_0, \ldots, \beta_n$ are the estimation parameters.

A stepwise regression procedure was applied starting from an initial set of variables including: INSIDE, MIXED, CYCLLANE, CYCLPATH, GRADESEP, SIGNALS and TWOLANES. Variables were allowed to enter in the model when their significance level did not exceed 0.2, but in the final model all non-significant ($p>0.05$) variables were eliminated.

Table 13 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

Table 13 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 is concluded that the presence of a cycle lane or the presence of traffic signals in the before-situation does increase the likelihood of deterioration after a roundabout is constructed.

Consequently models were fitted separately for two specific design types: roundabouts with cycle lanes (N=40, including variables INSIDE, SIGNALS, TWOLANES, LINE, BARR and RED) and separate cycle paths (N=38, including variables INSIDE, SIGNALS, TWOLANES, PRIOR and RED). This enabled to detect characteristics explaining the variance in the results for specific design types. The applied estimation procedure remained the same as before. In the resulting model for roundabouts with cycle lanes (N=40), the variable SIGNALS turned out to have a significant ($p = 0.03$) positive correlation (standardized estimate = 0.36) with the (log of the) effectiveness-index, meaning that roundabouts that were replacing signal-controlled intersections perform worse. 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 (standardized estimate = 0.39) 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.

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).

As before, separate analyses were consequently made for the two dominant types of cycle facilities. In the case of the cycle lanes the variable INSIDE appeared to be significant ($p < 0.01$) and positively correlated (standardized estimate = 0.53) with the (log of the) effectiveness-index. The goodness of fit of this model ($R^2 = 0.28$) was reasonable. This model was corrected for heteroskedasticity by executing an Estimated Generalised Least Squares (EGLS) parameter estimation (Verbeek, 2004). The final model for the separate cycle paths generated no significant variables.

5. DISCUSSION

In the previous before-and-after study the effects of roundabouts on crashes involving bicyclists were estimated (Daniels et al., 2007). The extra information about the cycle facilities on roundabouts in this study enabled us to relate the results of the previous study to different designs of cycle facilities. 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. 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 (Brilon, 1997). Although a clear statistical relationship was found, the 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. Future research must reveal whether the association between cycle lanes and worse results can be considered as causal or not.

The three other design types (mixed traffic, separate cycle paths, grade-separated) did not show a specific influence on the data. When they are considered as one subgroup the best estimate of the effect on all injury crashes is a decrease. Nevertheless, differences between these three types could also exist. In the case of mixed traffic and grade-separated cycle paths the scarcity of the data (9 and 3 observations respectively) is likely to limit the validity of the results. However, in the case of the separate cycle paths the number of observations (38) is considerably higher. 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).

Regarding the severest crashes, the ones with fatally or seriously injured, the presented results in this study 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 does not seem to influence the effectiveness of the roundabout for severe crashes. Thus, regardless of the design type, the conversion of an intersection into a roundabout seems to induce an increase in the number of severe crashes with bicyclists.

Two roundabouts in the sample are in the case of a 'suggestion lane'. As before-mentioned 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 cannot confirm nor deny this result. Although an effect was revealed in one subgroup (all accidents, cycle paths), the evidence is too weak to be conclusive.

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 (for all road users, not only for bicyclists) was greater on intersections previously controlled by yield signs than on signal-controlled intersections. In our case, the same order of effect sizes seems to exist: roundabouts replacing traffic signals perform worse compared to roundabouts on other types of intersections.

Other variables that were not significant in any of the models were those that are only applicable to one or more specific design types: LINE and BARR (cycle lanes), PRIOR (separate cycle paths) and RED (all except mixed traffic). They don't seem to play a distinct role. However, it must be stressed that for most of the variables also the scarcity of the data might trouble the power of the study to find out some differences in safety performance according to those criteria.

In a Dutch cross-sectional study a difference was found in the performance of roundabouts with separate cycle paths with priority to bicyclists compared with separate cycle paths without priority to bicyclists. When priority is given to bicyclists the number of serious injury crashes seems to be higher than if not (van Minnen, 1995). 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.

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 more variables that could be relevant. Possible relevant variables are vehicle speeds, radius of the central island, road width on the roundabout and the entry/exiting lanes, entry/exit radius and traffic volume. The effects of some of those 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.

6. CONCLUSIONS

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

5. The data for the study sample suggest that the construction of a roundabout raises in general the number of severe injury crashes with bicyclists, regardless of the design type of cycle facilities.
6. Regarding the effects on all injury accidents, roundabouts with cycle lanes perform worse compared to the three other design types (mixed traffic, separate cycle paths and grade-separated cycle paths).
7. Roundabouts that are replacing signal-controlled intersections seem to have had a worse evolution compared with roundabouts on other types of intersections.
8. 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 bicyclists in traffic). Further research is also needed in order to reveal possible 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 (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 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 and other types of cycle facilities.

7. ACKNOWLEDGEMENTS

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

8. REFERENCES

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

Brüde, U., Larsson, J. (2000). What roundabout design provides the highest possible safety? *Nordic Road and Transport Research*, *2/2000*, 17-21.

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

CROW (1998). *Eenheid in rotondes*. Ede, The Netherlands: Dutch national information and technology platform for infrastructure, traffic, transport and public space.

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., Nuyts, E., Wets, G. (2008). The effects of roundabouts on traffic safety for bicyclists: an observational study. *Accident Analysis & Prevention, doi:10.1016/j.aap.2007.07.016*.

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. (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*, 742-747.

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

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.

van Minnen, J. (1995). *Rotondes en voorrangsregelingen*. Leidschendam, the Netherlands: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.

van Minnen, J., Braimaister, L. (1994). *De voorrangsregeling voor fietsers op rotondes met fietspaden*. Leidschendam, the Netherlands: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.

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