

TRAFFIC SAFETY EFFECTS OF ROUNDABOUTS: A REVIEW WITH EMPHASIS ON BICYCLIST'S SAFETY

Stijn Daniels, Geert Wets

Hasselt University, Transportation Research Institute (IMOB),

Wetenschapspark 5, 3590 Diepenbeek, Belgium

tel +32-11 26 91 11

stijn.daniels@uhasselt.be; geert.wets@uhasselt.be

INTRODUCTION

Roundabouts almost exist as long as cars do. Roundabouts in their actual design originate from large traffic circles as they were built in France in the beginning of the 19th Century. In 1903 the Paris architect Eugène Hénard developed the principle of an intersection where all the road users (at that time mainly horses and coaches) had to make a circulatory movement around an obstacle in the middle.

Later on, especially in Great Britain much experience was acquired with roundabouts. (Brown, 1995; Certu, 2000; Thai & Balmeffrezol, 2000). Give-way-priority to the circulatory traffic on roundabouts was generalised in Great Britain in 1966.

Roundabouts have become common in Europe during the 80's and the 90's of the twentieth century. In the United States the use of roundabouts is rather limited (Persaud et al., 2001), although it is increasing.

The aim of this paper is to give an overview of safety effects of roundabouts. Emphasis is put on effects for bicyclists.

THEORETICAL SAFETY EFFECTS OF ROUNDABOUTS

There are different reasons why roundabouts could be safer than other types of intersections (FHWA, 2000; Elvik & Vaa, 2004). Generally they can be divided into two groups: effects on speeds and effects on conflicts between road users.

Effects on speeds:

- The speeds of the different vehicles on the roundabout are low and homogenous. This means that the relative speeds (speeds of the different road users in comparison to each other) are low. As the same goes for vulnerable road users, such as bicyclists, this is considerably different from the situation on conventional intersections where often large differences in speeds are recorded.
- Traffic entering a roundabout is forced to slow down, due to the lateral displacement it has to make. The resulting absolute speed is low and gives time to road users to overview the situation and to anticipate to potential conflicts.

Effects on conflicts:

- Roundabouts modify or eliminate potential conflict points between road users. Particularly the potentially dangerous conflicts are eliminated, like right-angle collisions or frontal collisions.
- All traffic on the roundabout is one way traffic. Road users only need to look to the traffic coming from one direction and to wait for a time gap to enter the roundabout.
- Roundabouts eliminate left-turning movements (in countries driving on the right).
- Traffic entering the roundabout has to give priority to the circulating traffic. This causes approaching traffic to be cautious when entering the roundabout.

On a roundabout, crossings of road users are eliminated as potential conflicts. The number of locations where traffic flows merge or diverge is only the half of the number of conflict points on conventional four-leg intersections. In total, the number of conflict points on a single-lane roundabout is reduced from 32 to 8 in comparison with a conventional intersection.

Besides conflicts with other road users, other types of conflicts might occur. The central island of a roundabout, for example, appears to be an obstacle that might induce a raised level of single-vehicle accidents.

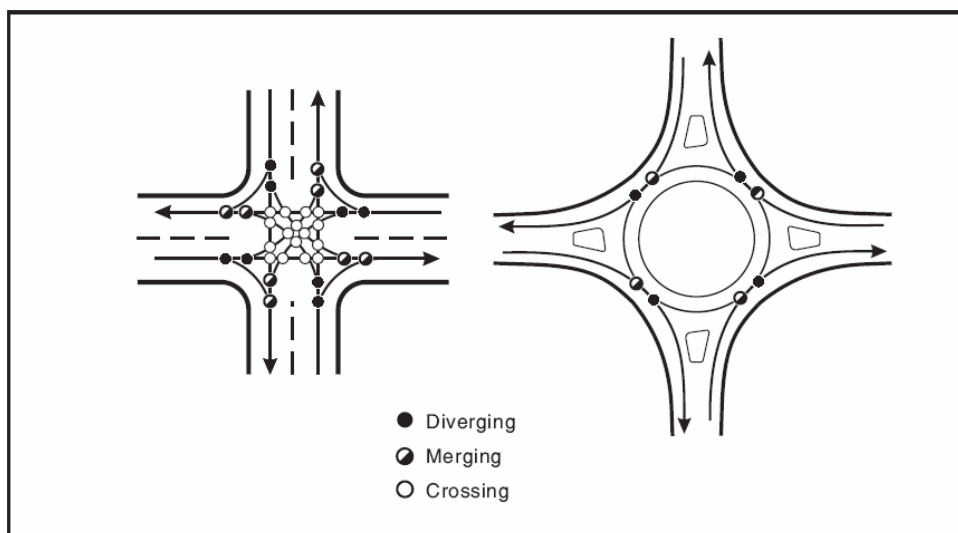


Figure 1. Vehicle conflicts on a single-lane roundabout. Source: FHWA (2000)

Safety aspects on double-lane roundabouts are somewhat different. In comparison to single-lane roundabouts they have additional conflict points due to the changing of lanes on the roundabout and to the double approaching or exit lane (however not necessarily present).

With respect to pedestrians, roundabouts reduce a certain number of potential conflicts that occur on conventional intersections:

- o Conflicts between high-speeding vehicles and pedestrians crossing the street.
- o Conflicts between right-turning vehicles and pedestrians crossing the street (on signalled as well as other intersections).
- o Conflicts between left-turning vehicles and pedestrians crossing the street (on signalled as well as other intersections).

The situation for bicyclists is somewhat different. The number of conflicts with bicyclists depends on the design of the roundabout. If there are no particular cycle facilities, bicyclists are mixed with other road users on the roundabout. Consequently they meet the same

conflict points as other (motorised) road users. Nevertheless, the number of conflicts could be higher than for other road users, due to the higher differences in speeds between bicyclists and motorised road users and also due to the poorer visibility of bicyclists in comparison with motorised vehicles. (Brown, 1995; FHWA, 2000).

CLASSIFICATION OF EFFECTS

The safety effects of roundabouts could be described schematically as a chain of events, according to figure 2. In a first step (1) an intersection can be converted into a roundabout or into another intersection type, which is not further considered here. Within the group of roundabouts a large variation of design types is possible according to some geometric features like central island radius, curvature of entry and exit lanes, number of lanes, lane width, type of cycle facilities, road markings and lighting. In a second step (2) there will be some consequences on speeds and conflicts (as mentioned above). Besides those effects there might be possible effects on traffic operation, intersection capacity, emissions, urban design etc... These latter effects are not further considered in this paper.

Changes in speeds and conflicts lead to effects on accidents (3), which is step 3. The fourth step are the consequences of the accidents, that roughly can be divided into injury and non-injury accidents (4). Finally, effects could be not equal for all road users which is expressed in step 5.

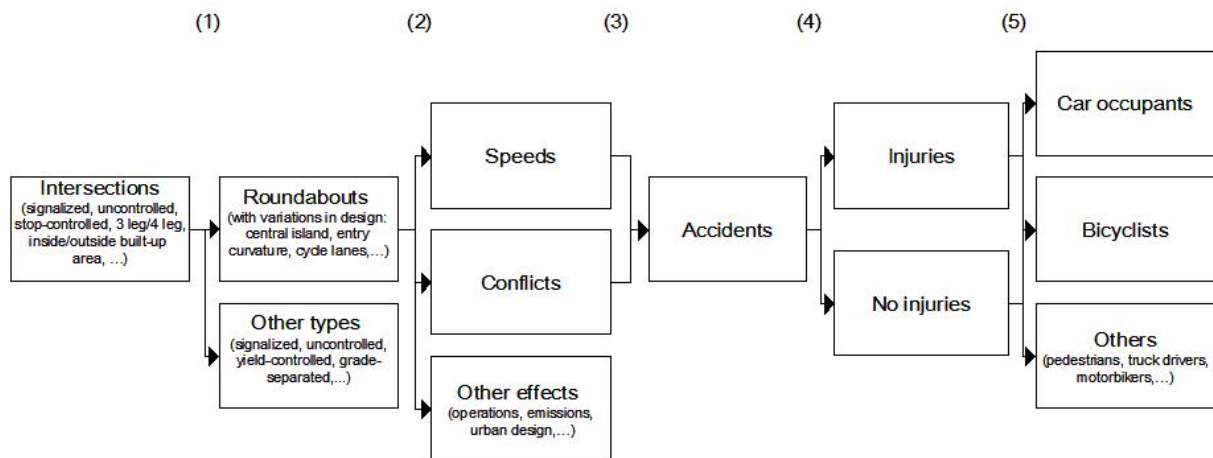


Figure 2. Roundabouts and traffic safety: chain of events.

This paper continues with research results about safety effects of roundabouts. For reasons of clarity, the description is organised according to the schema in figure 2.

RESEARCH RESULTS ON ROUNDABOUT SAFETY FOR ALL ROAD USERS

SELECTION OF STUDIES

Most common technique in road safety analysis to evaluate safety effects of a treatment is the observational before and after study. In an observational before and after study accident frequencies before and after a certain measure (e.g. change in road design) are compared to each other. However it would be wrong just to compare accident frequencies before and after the measure, since there are 3 confounding effects that should be taken into account (Hauer, 1997):

- 1) Accidents are of a stochastic nature. Even when no safety measure is taken on a particular location and the characteristics of passing traffic would remain the same, a natural fluctuation in the number of accidents will occur. This fluctuation is only based on chance. To analyse safety effects properly, one should consequently not rely only on the counted number of accidents (e.g. the number of accidents in one year). It is needed to estimate values, as well for the number of accidents that occurred before as for the number of accidents after the measure.
- 2) As traffic is not a well-controlled experimental environment, there are always some general trends that might also influence the number of accidents on the area under investigation. For example, there could be changes in traffic volume, a higher or lower level of drink driving, modifications in enforcement level, laws etc... These general trends are likely to result in a changing number of accidents on a location, even when no specific measures are taken. In order to isolate the effect of a specific measure, one should consequently distinct the effect of the measure itself from the effect of general trends.
- 3) Road authorities tend to treat locations not randomly. They use ranking systems, usually based on available accident frequencies or accident rates, to determine what locations need a particular treatment. Consequently, we shouldn't consider the locations with a specific treatment (e.g. roundabouts) as a random sample, as this sample consists of selected locations based on their accident records. As we know about the stochastic nature of accidents, one could expect that the number of accidents on that type of locations would decrease – at least partly, even if no specific measure would be taken. This effect is called 'regression to the mean'. As this effect could also occur on locations with a treatment, it is obvious that the change in the number of accidents should not be attributed fully to the treatment itself. In that case a certain part of the effect has to do with chance elements and would also have occurred if no measure would have been taken.

To avoid wrong estimations, an observational before-and-after study should take into account the above-mentioned effects. If not, the study results are less reliable. Simple before-and-after studies, which do not control for any confounding factors should never be trusted (Elvik, 2002; Hakkert & Gitelman, 2004). Where possible, only studies were included that explicitly controlled for confounding factors. Unfortunately this was not always possible.

EFFECTS OF THE ADRESSED TYPE OF INTERSECTION

Road authorities tend to convert specific types of intersections into roundabouts. A decision to build a roundabout could depend of the number of legs, the amount of traffic, the composition of the traffic (cars, trucks, bicycles,...), the location, former accidents etc.

Some studies found the reduction of the number of victims to be higher on roundabouts outside built-up area than on roundabouts within built-up area (Schoon & van Minnen, 1993; MET, 2003). The decrease in the number of injury accidents was found to be higher on

intersections that were yield-controlled before they were converted into a roundabout than on signalized intersections. (Schoon & van Minnen, 1993; Elvik, 2003). However, these effects were quoted by the authors to be uncertain. Converting intersections into roundabouts could also have more effect on accidents in four-leg intersections than in three-leg intersections, although either this effect is unsure (Elvik, 2003).

EFFECTS ON SPEEDS

The theoretically assumed effects on speeds have been proven by research. Average car speeds on roundabouts decrease significantly, in comparison with the situation before the roundabout was constructed. The speed decrease is higher when measured closer to the roundabout (Hydén & Várhelyi, 2000; van Minnen, 1994). For distances above 300 meter no speed effects couldn't be measured anymore. The speed of approaching cars is highly influenced by the lateral displacement forced by the roundabout. The lateral displacement is determined by the diameter of the central island and the angle of the approaching lane. The speed reducing effect is already large at a 2 meter deflection (Hydén & Várhelyi, 2000).

EFFECTS ON CONFLICTS

The number of traffic conflicts on roundabouts seems to increase rather than to decrease (van Minnen, 1994). Nevertheless, this author found conflicts to be less severe than before. The number of conflicts with vulnerable road users (pedestrians and bicyclists) hardly changed (van Minnen, 1994). Other research reported a status quo in the number of conflicts between cars, but recorded oppositely a decrease in the number of conflicts, both between bicyclists and cars as well as between pedestrians and cars (Hydén & Várhelyi, 2000). Regarding the theoretical reduction of conflict points (e.g. from 32 to 8 for 4-leg roundabouts) these results are somewhat surprising. At least this means that the number of conflicts is not directly proportional with the number of conflict points. As the number of conflict points would theoretically be reduced from 32 to 8, having the same number of conflicts after construction of a roundabout would consequently mean that the number of conflicts per conflict point on average multiplied by four.

According to van Minnen (1994) people comply well with priority rules on roundabouts, as long as the entering traffic volume is not too large. With higher volumes, the number of offences against priority rules increases remarkably.

EFFECTS ON INJURY ACCIDENTS

In the past decades quite some research was done about the safety effects of introducing roundabouts on intersections. Although numbers and percentages often vary strongly, there are quite some studies indicating a strong reduction of injury accidents after construction of a roundabout (Green, 1977, cited in Brown, 1995; Persaud et al, 2001; MET, 2003; Elvik, 2003; De Brabander et al, 2005). The decrease is higher for accidents with deaths and serious injuries than for accidents with only slight injuries (Green, 1977, cited in Brown, 1995; Persaud et al, 2001; MET, 2003; Elvik, 2003; De Brabander et al, 2005).

There exists a directly proportional relationship between measured speeds and the number of accidents on a roundabout. The number of injured has even a quadratic relationship with the speeds. Furthermore a positive relationship was measured between traffic volume and the number of accidents (Brüde & Larsson, 2000).

EFFECTS ON NON-INJURY ACCIDENTS

Discussion exists about the effects of roundabouts on accidents with property damage only. A properly performed before-and-after-study on 23 roundabouts in the USA (Persaud et al,

2001) found a significant reducing effect of roundabouts on all types of accidents (property damage and injury accidents). Nevertheless, other authors conclude that the average effect of roundabouts on non-injury accidents is highly uncertain (Elvik, 2003, based on a meta-analysis of 28 studies).

EFFECTS ON DIFFERENT TYPES OF ROAD USERS

Not so much has been done about the safety effects of roundabouts for different types of road users. According to Schoon & van Minnen (1993) the safety effects of roundabouts are not equally distributed over the different types of road users: safety effects for car occupants and pedestrians are much better than safety effects for bicyclists and mopeds. Nevertheless the registered effects for mopeds and bicyclists were still favourable.

Oppositely, Hydén & Várhelyi (2000) reported a large reduction in injury accident risk for bicyclists and pedestrians, based on conflict observations, whereas they found no risk reduction for car occupants.

DESIGN OF CYCLE FACILITIES ON ROUNDABOUTS

Regarding to different types of road users, roundabouts as well as other types of intersections could have different safety effects. Particularly for bicyclists it is interesting to look to some specific research results. For a good understanding we start with an overview of different possible designs of cycle facilities at roundabouts.

There are some alternatives to deal with bicyclists at roundabouts. Most basic treatment is to mix them with motorised traffic. When cycle lanes are provided, they can be constructed next to the carriageway or on a certain distance. Further in this paper, 4 situations are treated: mixed traffic, adjacent cycle lanes and separated cycle lanes with or without priority for bicyclists at crossings.

Note there exist at least two other alternatives. The first is treating the bicyclist the same way as a pedestrian, which means to let him getting off his bicycle and to cross lanes as a pedestrian. The second is a grade separated intersection where bicyclist tunnels or bridges are constructed which should exclude any conflict between bicyclists and motorised road users. These two alternatives are not further considered.

SITUATION 1: MIXED TRAFFIC

The most basic treatment is to consider the bicyclist as a vehicle and to let him ride around the roundabout the way like car drivers have to do. So car drivers and bicyclists are mixed together, what could be called a “**mixed traffic solution**” (see fig. 3)

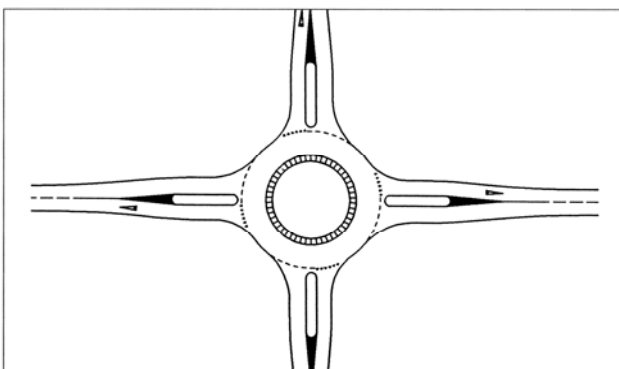


Figure 3. Roundabout with mixed traffic. Source: CROW (1998)

SITUATION 2: ADJACENT CYCLE LANES

Cycle lanes can also be marked on the roundabout, adjacent to the carriageway. When constructed in this way bicyclists and motorised vehicles have their own facilities (see fig. 4), although there is no physical barrier between motorised vehicles and bicyclists.

There is supposed to be a huge risk of conflicts between motorised vehicles turning to the right and bicyclists circulating around the roundabout. Particularly severe conflicts between trucks and bicyclists might happen because of the limited sight (blind area) of truck drivers when turning to the right while a bicyclist is driving next to them.

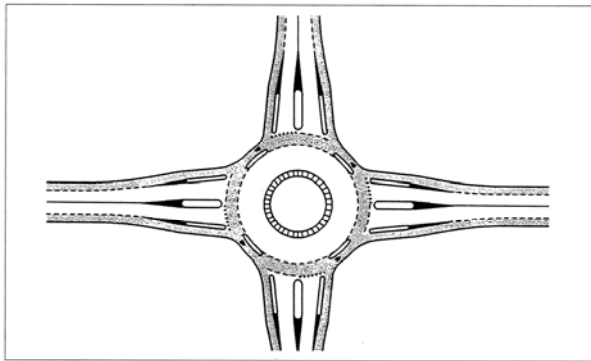


Figure 4. Roundabout with adjacent cycle lanes. Source: CROW (1998).

SITUATION 3: SEPARATED CYCLE LANES – PRIORITY FOR BICYCLISTS

A third solution is to construct a bicycle lane separated from the roundabout. In that case the bicyclist has to cross one or more lanes when circulating a roundabout. Consequently the number of conflicts between bicyclists and motorised vehicles should decrease as both bicyclists as well as motorised vehicles are better aware of the presence of each other as their driving curves are more orthogonally.

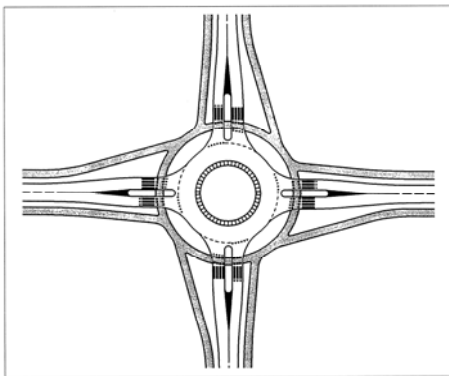


Figure 5. Roundabout with separated cycle lanes. Priority for cyclists. Source: CROW (1998).

A particular consideration has to be made about the priority rules at the roundabout. Where it is generally accepted to give traffic circulating around the roundabout priority to traffic approaching the roundabout (offside priority), it is still not clear what is the best for bicyclists.

When the roundabout is designed as either a mixed traffic roundabout or one with adjacent cycle lanes, it is quite reasonable to consider bicyclists as vehicles and to give them priority. However, when separated cycle lanes are constructed, there is room for discussion whether

cyclists should have priority or not. In situation 3 the bicyclist gets priority when crossing the approaching and exiting lanes.

SITUATION 4: SEPARATED CYCLE LANES – NO PRIORITY FOR CYCLISTS

Situation 4 is pretty similar to situation 3 as it provides for a separated cycle lane. The difference with situation 3 is made by the priority rule for bicyclists crossing the approaching and exiting lanes. In situation 4, the bicyclist has to give priority, whereas in situation 3 he got priority.

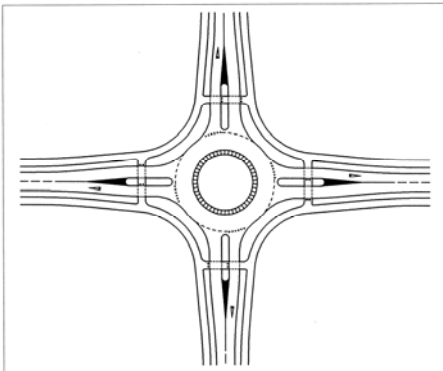


Figure 6. Roundabout with separated cycle lanes. No priority for bicyclists. Source: CROW (1998).

RESEARCH RESULTS CONCERNING BICYCLIST'S SAFETY

Similar to the results of general roundabout safety, the results for bicyclists can be classified following the schema in figure 2.

EFFECTS OF THE ADRESSED TYPE OF INTERSECTION

Roundabouts with smaller traffic volumes (less than 10.000 vehicles per day and less than 1.000 bicyclists per day) are safer for bicyclists than roundabouts with higher traffic volumes (Brüde en Larsson, 2000).

EFFECTS ON CONFLICTS

As an alternative to the observational before and after study based on reported accidents, some investigations were made using a traffic conflicts technique. A conflict observation study (Van Minnen, 1994) revealed that the number of conflicts with bicyclists and mopeds did not decrease after the construction of a roundabout. Nevertheless this study reported a shift to less serious conflicts.

In another Dutch research project, observations were made on the priority giving behaviour between motorised vehicles and bicyclists on roundabouts with separated cycle lanes (van Minnen & Braimaster, 1994). On roundabouts with priority for bicyclists (situation 3 as mentioned above) about 20% of the bicyclists, despite their priority status, appeared to stop and give priority to motorised vehicles. However, on roundabouts without priority for traffic from the cycle lane (situation 4), bicyclists received priority in 33% of the cases. This effect appeared to be much higher with approaching traffic (46% of the cases) than with exiting traffic (14% of the cases).

A higher number of car drivers gave priority to bicyclists when the cycle lane was adjacent to the roundabout than when there was a separated cycle lane (Räsänen en Summala, 2000).

Bicyclists tend to offence some traffic rules when entering or leaving roundabouts. In 2 till 13% of the observed cases within a Dutch study, bicyclists used the cycle crossing in the prohibited direction (van Minnen & Braimaster, 1994). Furthermore, more than 40% of the bicyclists gave no priority when entering the roundabout (Hydén & Várhelyi, 2000).

EFFECTS ON ACCIDENTS

Roundabouts seem to induce a higher level of bicyclist-involved accidents than could be expected regarding the presence of bicycles in total traffic. In Great-Britain bicyclist's involvement in accidents on roundabouts was found to be 10 till 15 times higher than the involvement of car occupants, taken into account the exposure rates (Maycock and Hall, 1984, cited in Brown, 1995).

Nevertheless, roundabouts appear to have made traffic situation safer, also for bicyclists. However, opposite to the major results that were noticed for traffic on roundabouts in general (see before) the results for bicyclists were at a considerably lower level. Schoon en Van Minnen (1993) studied safety records of 185 roundabouts and reported a bicyclist's traffic victims reduction of 30% compared to the period before construction of the roundabout, while overall traffic victims decreased with 95% (car occupants), motorcycles (63%), pedestrians (63%) and other road users (64%). Unfortunately the study design was that of a simple before-and-after-study.

Some efforts were made to determine whether one or another priority rule on roundabouts with separated cycle lanes was safer for bicyclists. Accident rates for bicyclists seemed to be higher (0,16 victims per million passages) on roundabouts with priority for bicyclists (situation 3) compared with roundabouts where the crossing bicyclist had to give priority (0,04 victims per million passages, situation 4) (van Minnen & Braimaster, 1994). Dijkstra (2004) compared two scenario's, differing from each other in the way crossing bicyclists got priority or not (situation 3 compared with situation 4), and concluded that a scenario with a general use of situation 3 (priority to bicyclists) would lead to a slight increase in the number of serious injuries compared to a scenario with general use of situation 4 (no priority for bicyclists).

TYPE OF CYCLE FACILITIES

Schoon en Van Minnen (1993) investigated also the number of bicycle accidents related to the type of cycle facilities on roundabouts: no particular cycle facilities, an adjacent cycle lane on the roundabout and a separated cycle lane. They concluded that differences in the accident frequency between the several types were small. However, regarding to injuries instead of accidents they concluded that separated cycle lanes (situations 3 and 4) performed better than both the mixed traffic (situation 1) and adjacent lane (situation 2) alternatives.

EFFECTS OF DESIGN ELEMENTS

Generally, smaller and one-lane-roundabouts seem to be safer for bicyclists then larger or multi-lane roundabouts (Brüde en Larsson, 1996). Since smaller roundabouts seem to be safer than large ones, the opposite is true for the dimension of the central island. Roundabouts with a central island of more than 10 meter are safer for bicyclists than roundabouts with smaller central islands (Brüde en Larsson, 2000).

CONCLUSIONS

Roundabouts have proven to contribute to traffic safety. On average, reconstruction of an intersection into a roundabout causes a considerable decrease in the number of injury accidents. The effects on accidents with deaths and serious injuries are higher than effects on accidents with slight injuries. The effects on accidents with property damage only are unsure. Further research is needed to determine more clearly differences of effects depending on the before-types of intersections or the location properties such as the road category or the location within or outside built-up area.

The safety effects of roundabouts are considered to be caused by effects on speeds and effects on conflicts. Redesigning of an intersection into a roundabout causes a significant speed reduction in the neighbourhood of the intersection. There exists a correlation between speed and lateral displacement on the roundabout. The effects on conflicts however are not clear.

There are indications that roundabouts cause an injury accident reduction also for bicyclists. However, there is a lack in the evidence. At least the observed decrease in accident numbers is smaller for bicyclists' accidents compared to accidents with other road users.

No final evidence exists about the differences in safety level between different types of cycle facilities. The available research results indicate that roundabouts with separated cycle lanes are safer than roundabouts with mixed traffic or roundabouts with adjacent cycle lanes. The rate of bicycle accidents (number of bicycle accidents per vehicle kilometre) on roundabouts with separated cycle lanes and priority for bicyclists is somewhat higher compared to separated cycle lanes with no priority for bicyclists. A larger central island appears to be safer for bicyclists.

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