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Summary

Roundabouts have been increasing in number in the Netherlands since the 1980s, and the number of roundabouts has more than doubled since 1998. The application of roundabouts in road design was particularly strong during the Sustainable Safety Start-up Programme, which started in 1997 and continued until 2002, when many intersections were reconstructed into roundabouts. In the literature, the effects of reconstructing intersections into roundabouts on the number of crashes on those locations have been documented in before and after studies and, although the reported effects vary, the overall reduction in crashes is significant. However, the question remains: did roundabouts contribute to the improvement of road safety in the Netherlands?

This study evaluates the effects on road crash casualties and takes into consideration all crashes on all known roundabouts built in the Netherlands during the period of 1999 to 2005, not just a sample. Before and after crash and roundabout information is used and specific attention is paid to fatalities and (police reported) serious road injuries. A cross-section comparison of road junctions and roundabouts is also made.

The locations of roundabouts are stored in a database of the road network in the Netherlands which is updated yearly. Linking construction year of individual roundabouts and before and after traffic casualties at these locations is achieved through the use of a Geographic Information System (GIS). Crashes in the before period were selected based on their geographical location, within a certain distance from the roundabout. Several checks and improvements of the data have been undertaken to achieve the best possible quality of the data used for the analysis. In some cases, the location of the original intersection (if existent at all) need not be within that area. This causes the number of casualties in the period before the construction of roundabouts to be somewhat underestimated and therefore results will be biased towards unfavourable effects for roundabouts.

Study findings are consistent with other studies. However, the data set and method applied result in statistically significant effects for aggregated fatal casualties not previously obtained in the literature, even though the method is biased towards the opposite. Fatality data aggregation from a large data set allows the application of conventional before and after tests to fatal casualties which are rare and random occurrences, particularly when small samples of intersections are selected. The effect on the number of hospitalized casualties and all casualties is also examined and the applicability and opportunities of this method to other studies is discussed. As far as interpretation of the results for casualties is concerned, care has to be taken, as underreporting of casualties, especially for non-motorized vehicle crashes, is a serious problem.

Although a before and after approach was taken, the values determined are general in nature due to the aggregation method, and aggregation of all 2,009 roundabouts implemented between 1999 and 2005. The results are not to be used as predictive values, but are rather intended as average

summary values. In other words, the aggregate road safety consequences of the reconstruction of all intersections in the Netherlands that were converted into roundabouts have been evaluated. This was done instead of making a new estimate of the general effectiveness of the reconstruction of an intersection into a roundabout. It seems that roundabouts built from 1999 to 2005 have been effective for road safety in the Netherlands, resulting in a reduction of about 76% in fatal casualties and about 46% in (police reported) killed or seriously injured casualties. If these results hold, about 12 lives were saved and 102 killed or hospitalized casualties were prevented in 2006.

Contents

1. Roundabouts in the Netherlands

Since the 1980's, roundabouts have been increasing in number in the Netherlands and since 1998 their number has more than doubled. The application of roundabouts in road design was particularly strong during the Sustainable Safety Start-up programme, beginning in 1997 and extending until 2002, when many intersections were reconstructed into roundabouts. The effects of these reconstructions on the number of crashes at such locations have been documented in the literature in before and after studies and, although the reported effect varies, overall the reduction in crashes is significant.

This study reviews the overall effects on road casualties of roundabouts built in the Netherlands during the period of 1999 to 2005, for which before and after crash and roundabout location information is available. Since all roundabouts constructed during this period are included in the analysis, rather than a (limited) sample, possible selection bias due to sample selection is removed. It is, however, considered likely that the actual decision to reconstruct intersections was not random.

The locations of roundabouts are maintained in a database of the road network in the Netherlands, and is updated yearly. Through the use of a Geographic Information System (GIS) the linking of construction year of individual roundabouts and before and after traffic casualties at these locations is possible for the entire network. Crashes in the before period were selected based on their geographical location, within a certain area around the roundabout. Several checks and controls of the roundabout location and date of construction were undertaken to improve the quality of the data used for the analysis. In some cases, the location of the original intersection (if existent at all) need not be within that area. Because of this, the number of casualties in the before period of roundabouts will be somewhat underestimated and results will therefore be biased towards unfavourable effects for roundabouts.

Number of roundabouts	1998	1999	2000	2001	2002	2003	2004	2005
Mini roundabout	1,348	1,681	1,796	1,992	2,401	2,677	2,824	2,917
Roundabout	129	155	198	363	525	532	527	526
Total	1,477	1,836	1,994	2,355	2,926	3,209	3,351	3,443

Table 1.1. *Number of roundabouts in the Netherlands during study period (source: NWB).*

The number of roundabouts in the road network during the study period is presented in *Table 1.1.* From the start, it is important to note that the present study considers all locations coded as roundabouts in the Dutch national roads GIS-database (NWB) and although these are all likely to be "modern" roundabouts rather than the older traffic circles, this difference was not confirmed or evaluated. NWB distinguishes mini roundabouts and defines them as single lane roundabouts less that 35 m in diameter. However, this definition is not applied consistently.

The present report aggregates fatality data to allow the application of conventional before and after tests to fatal casualties which are rare and random occurrences. Findings are consistent with other studies. However, the method applied results in statistically significant reductions for aggregated fatal casualties, even though the method is biased towards the opposite. The effect on the number of hospitalized casualties and all casualties was also examined. For this purpose we used the police registered data on hospitalized casualties. This data is known to be subject to underreporting. For crashes in which at least one motorized vehicle was involved, the underreporting is known to have increased from 27% in 1993 to 41% in 2008. For crashes in which no motor vehicle was involved, only a few percent of the casualties is registered: this was 8.5% in 1993 and decreased to 4.5% in 2008 (Reurings & Bos, 2009). Thus, police reported casualties are to a large extent casualties in crashes with motorized vehicles. Non-motorized vehicle crash casualties amount to half the total number of seriously injured inpatients. This is shown by the hospital registration of serious road injuries. This registration contains no information of the location of the crash (Reurings, 2010). Therefore, these crashes are not taken into account in this report.

All modes of transport were aggregated and therefore the analysis represents the overall social impact. Closer examination of effects on individual transport modes is possible, but has not been carried out in the present research.

Although a before and after approach was taken, the resulting values are general in nature due to the aggregation methodology. The results are not to be used as predictive values, but should rather be considered as average, summarized values of the longer term roundabout construction programme; the more important question is whether the programme worked, rather than to which extent (also considering the bias). The main safety indicators used are the number of seriously injured, i.e. fatalities and inpatients.

The Dutch literature and a selection of recent roundabout before and after studies with robust methodologies are reviewed in *Chapter 2*. This will provide an informative view of general agreements and variability among results. Although the majority of research has focused on the effect of specific factors such as traffic control or traffic volumes with various changes reported, the focus in the literature review is on the overall effect most comparable with the results of this study.

Chapter 3 presents a cross section study of roundabouts and conventional intersections, focusing on the share of serious injuries as an indicator of safety performance. *Chapter 4* covers the before and after analysis of roundabouts constructed during the period considered in this study; discussion of the data collection and verification method and aggregation method are an important part of *Chapter 4*. Finally, *Chapter 5* discusses and relates the results of *Chapters 3* and *4* and concludes the report.

2. Literature review

Effects of roundabouts have been well documented in international literature and include reduced traffic delay, reduced emissions, a reduction of (some types of) crashes and a reduction of crash severity (SWOV, 2010). Traffic volumes after construction generally rise, contrary to popular belief of traffic avoiding roundabouts (Persaud et al., 2000). A summary of Dutch roundabout studies focused on road safety, methodologies and study findings is listed in *Table 2.1*, with a particular focus on overall effects. Variation of effect among different types of roundabouts, urban or rural, various 'before' traffic controls and operating speeds, as well as lane configuration and diameter are evident. These differences are too specific to be appropriate for summarizing the overall effect of the application of all roundabouts in the Netherlands

Cross-sectional studies compare crash or casualty rates on various facilities and compare and contrast the differences in level of safety extended to road users. In the Netherlands, the use of cross-sectional studies has primarily been used to compare the effectiveness of various priority or bicycle facility schemes (Van Minnen, 1995; Van Minnen, 1998). These studies have used small samples of roundabouts (compared to this study). Cross-sectional studies are well suited to comparing characteristics of similar facilities, but reveal little about the effect of specific changes to the traffic network.

In the Netherlands, studies of before and after situations have reported various reductions in crashes or severities as presented in *Table 2.1*. These findings are similarly variable in the international literature and this variability is largely attributable to the choice of controlling features and the safety indicator, generally the number of crashes or the number of injury casualties. Facilities for vulnerable road users are increasingly present in the literature, and cyclists in particular have been identified as having an increased risk of serious injury at roundabouts (Daniels et al., 2008). It is unclear if their surprising result is due to the specific conditions in Belgium. Their result may indicate that overall reduction in casualties at roundabouts may be at the expense of compromising the safety of vulnerable road users.

One of the main criticisms of before and after studies is that naïve comparisons of the number of crashes with and without the treatment may include changes in safety due to other factors. The main factor discussed in the literature is the regression to the mean phenomenon (e.g. Persaud & Lyon, 2007). If a roundabout is selected to be built due to a higher than average crash rate, then it is natural that a lower rate would follow to achieve a return to the mean value even if the roundabout had not been built; if a roundabout is introduced at the same time this natural reduction may also be attributed to the treatment. Furthermore, the construction of a roundabout may result in changes to traffic patterns and volumes, for instance resulting in 'crash migration' (diverted traffic may cause crashes elsewhere, at another location) which will be reflected in the crashes accordingly. Similarly, background changes in the safety setting such as enforcement level, vehicle safety, and advertising campaigns may also result in fewer crashes at the location even if the roundabout had not been built.

Author	Year	Country	Study type	Findings
Dijkstra	2004	NL	Before-after	Priority cyclist: 11% reduction serious road injuries Without priority cyclist: 87% reduction serious road injuries
Van der Dussen	2002	NL	Before-after	Non casualty: 20% reduction Casualty: 70% reduction
Grontmij	2002	NL	Meta analysis	All crashes: 53-60% reduction All casualties: 26-90% reduction
Van Minnen	1990	NL	Before-after	Urban: 86% reduction casualties, 54% reduction crashes Rural: 90% reduction casualties, 60% reduction crashes
Van Minnen	1995	NL	Cross section	Cyclist accommodation
Van Minnen	1998	NL	Cross section	Best practice for right of way rules
Schoon & Van Minnen	1993	NL	Before-after with comparison	Urban: 69% reduction of casualties Rural: 86% reduction of casualties Reduction by user type: Occupant 95% Scooter 63% Cyclist 30% Pedestrian 89% Total casualties 70% All crashes: 50% reduction
Weijmans et al.	2002	NL	Evaluation of experimental roundabouts (before-after)	Priority intersection to roundabout 80% reduction of casualties Signalized to roundabout 60% reduction of casualties
Persaud et al.	2000	US	Before-after with regression to mean	Urban signalized to roundabout 32% reduction crashes 68% reduction casualties Stop control to roundabout reductions Urban: 61% crashes, 77% casualties 1 lane 61%, more lanes 15% Rural: 58% crashes, 82% casualties Urban and rural un-signalized to roundabout 39% reduction crashes 76% reduction injury 89% reduction serious injury and fatal (non-significant)
De Brabander et al.	2005	BE	Before-after with regression to mean	All locations to roundabout (specific results also by speed limits): 34% reduction in crashes 30% reduction in light injury crashes 38% reduction serious injury crashes
De Brabander & Vereeck	2007	BE	Before-after with regression to mean	All locations to roundabout (also speed &VRU's): 39% reduction in injury crashes 38% reduction in light injury crashes 17% reduction serious injury crashes
Daniels et al.	2008	BE	Before-after with regression to mean	27% increase cyclist injuries 41-46% increase serious injury or fatal casualties for cyclists Larger increases in urban areas than rural areas

Table 2.1. *Roundabout literature of effects of roundabouts, primarily Dutch.*

Robust, statistically based, before and after studies, such as Persaud & Lyon (2000), De Brabander et al. (2005), De Brabander & Vereeck (2007), and Daniels et al. (2008) have determined specific crash reductions based on factors such as the number of legs, traffic volumes, speed limits, urban or rural land use, road users, and the previous traffic control scheme. However, these studies, which control for regression to mean and background effects, require large amounts of data in terms of traffic volumes, safety performance functions, and comparison locations with similar data requirements. The data requirements generally limit the size of the sample and, as a consequence of the small number of fatalities observed at these locations, the reductions reported are limited to overall injury severity; no reported significant findings were found in the literature specifically for fatalities. These studies are, therefore, best suited to prediction of the effect of specific changes, rather than overall effects nationally or on fatalities specifically.

3. Cross section study of severity distribution

To investigate the overall effect of roundabouts on casualties in the Netherlands from a cross-sectional study approach all intersections are taken as a comparison group for roundabouts. However, it is difficult to make strong comparisons between the two groups. This has several reasons.

1. Although the number of roundabouts in the Netherlands is relatively well-known, the number of conventional intersections and those which are potential roundabout locations are unknown. To be able to comment on the average effect of roundabouts, the share of different crash severities in each of the groups is examined to see if the distribution of severities in the two groups is different.

2. The traffic volumes related to both conventional intersections as well as to roundabouts are unknown. This limits the possibilities for analysis. Traffic exposure data in the Netherlands is mainly based on national mobility surveys, rather than on counts on specific road segments or intersections. Therefore, indicators like crashes per million entering vehicles by intersection type are unavailable. Although these figures are not available, some observations can still be made on the basis of the available data, namely, the number of casualties at conventional intersections and roundabouts, and the relative share of the various crash severities.

Although the number of roundabouts is known, the effect on safety is unclear because it is unclear what share of the conventional intersections they replace. The literature review indicates that the number of crashes decreases after the construction of a roundabout. However, without a known number of conventional intersections the change in the number of crashes of a given severity cannot be confirmed. Another approach that can be taken is to compare the share of serious casualties at roundabouts to the share at conventional intersections. Knowing the number of casualties on roundabouts, an estimate can be made of the number of serious casualties that would have occurred if the roundabouts had been conventional intersections.

The Dutch National Roads Database (NWB) indicates that the number of roundabouts in the Netherlands has nearly doubled during the period 1999 - 2005 (*Figure 3.1*). During the same period the number of fatalities at roundabouts has also nearly doubled. If only the number of casualties is examined, it could appear that conventional intersections are becoming safer, and that roundabouts are becoming less safe. However, the increase in casualties at roundabouts can, for the most part, be attributed to the large increase in the number of roundabouts.

The safety performance in terms of casualty rates of roundabouts compared to that of comparable intersections is unknown. This is due to lack of knowledge about the number of locations that may be converted into roundabouts. While the literature indicates reduced crash and casualty rates among relatively small samples, rate comparisons are not possible with the available data in the Netherlands.

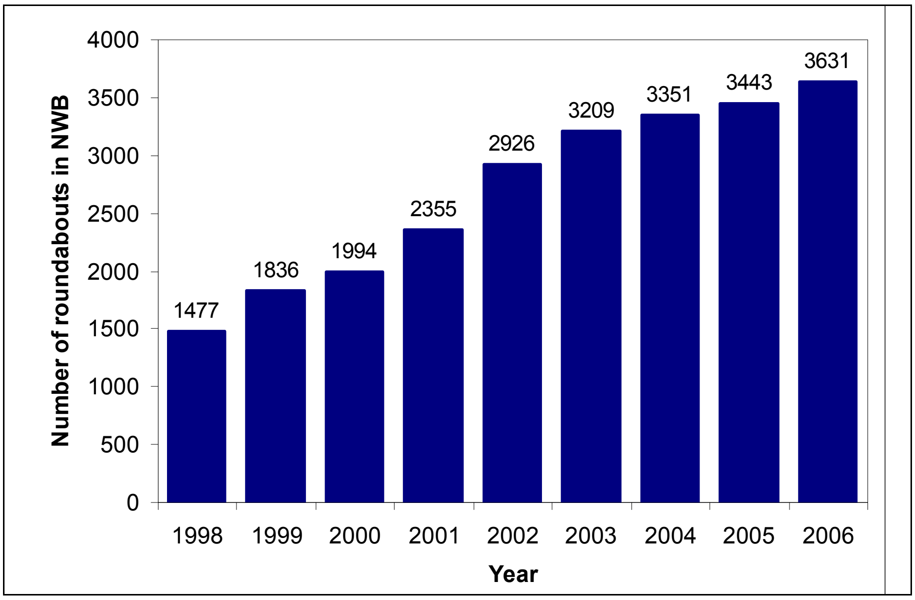

Figure 3.1. *Number of roundabouts in the Netherlands 1998 to 2006. Source: NWB.*

The number of fatalities at conventional intersections in the Netherlands consistently decreased during the study period (*Figure 3.2*) but the number of fatalities at roundabouts increased, possibly due to the increasing number of roundabouts. Similar trends are evident in hospitalized casualties and slightly injured casualties, presented in *Figure 3.3* and *Figure 3.4* respectively, albeit with smaller variations due to the larger numbers of these casualty types.

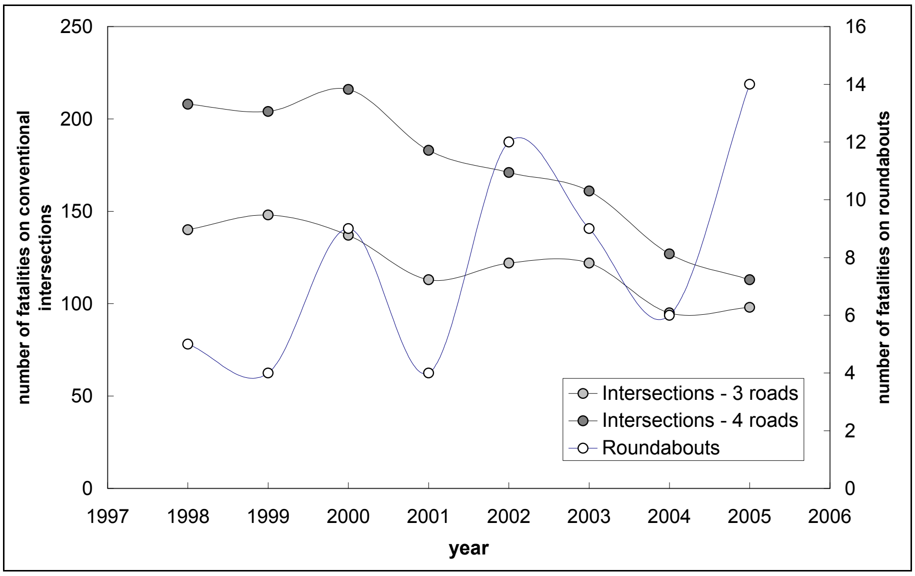

Figure 3.2. *Fatalities at conventional intersections and roundabouts in the period 1998-2005.*

The development of the number of casualties at roundabouts in the Netherlands relatively closely matches the increasing trend in the number of roundabouts: roughly doubling between 1998 and 2005. The decline in all types of casualties at intersections reflects the general declining trend in casualties in the Netherlands, but the decrease in serious casualties at intersections (*Figures 3.2* and *3.3*) is declining at a slower rate. This indicates that even though casualties at intersections are decreasing, the largest reductions are to be found in the slightly injured casualties (*Figure 3.4*), rather than a more desirable decrease in serious injuries. This can be attributed to a decreasing reporting rate of minor injury crashes.

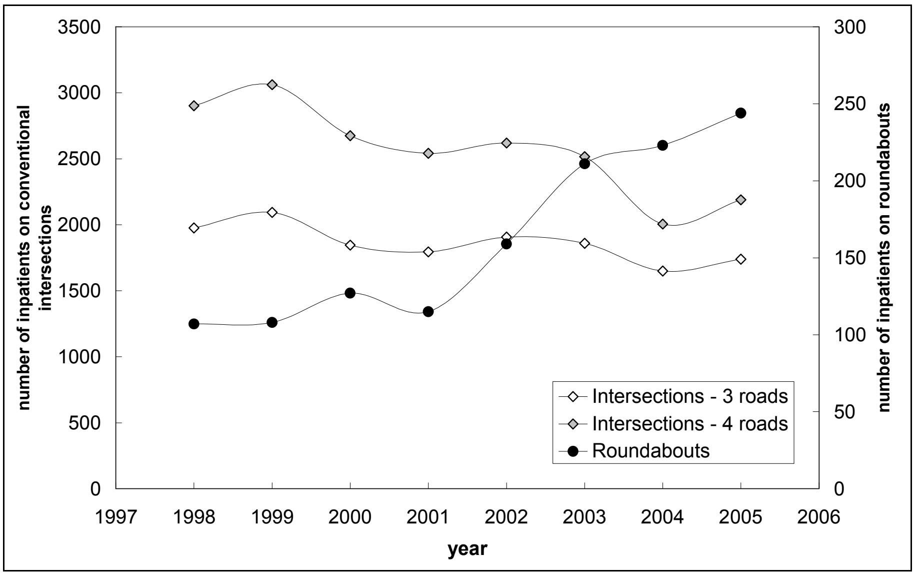

Figure 3.3. *Serious road injuries at conventional intersections and roundabouts 1998-2005.*

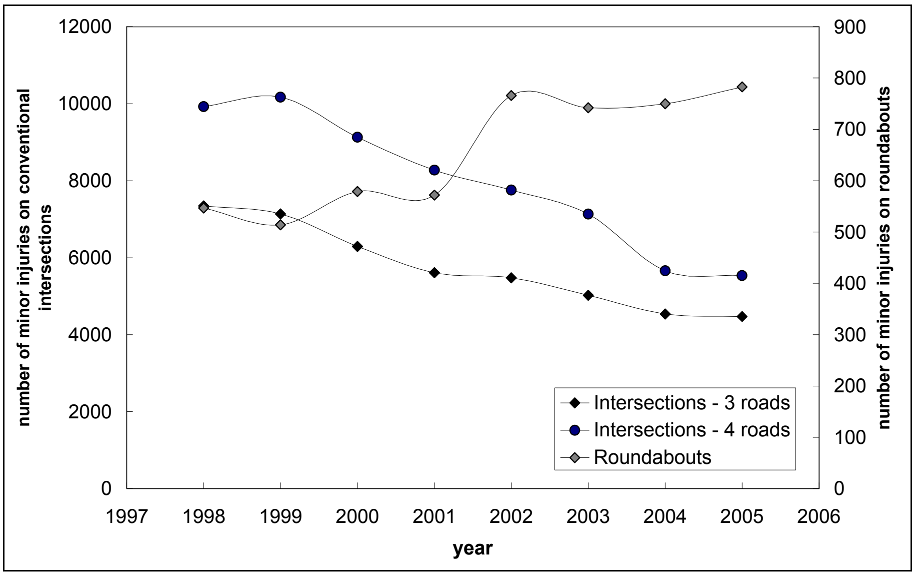

Figure 3.4. *Slightly injured casualties at conventional intersections and roundabouts 1998-2005.*

Developments in the shares of the different modes of transport at roundabouts and conventional intersections revealed that, consistent with recent literature (Daniels et al., 2008), the share of cyclist and moped injuries has been increasing at roundabouts. In 2005, 50% of serious road injuries at roundabouts were cyclists as opposed to 35% and 30% for 3 arm and 4 arm intersections respectively (AVV-BRON). Furthermore, between 2002 and 2005 the share of cyclist serious road injuries at roundabouts increased, but remained stable at conventional intersections. The share of pedestrian casualties at all intersection types is consistently around 5%. The number of fatalities among vulnerable road users at roundabouts is unclear due to the low number of casualties. Despite overall improvement in road safety, the evaluation of cyclist involvement and facilities is, therefore, an important topic for the safety advancement of roundabouts. The shift towards increased cyclist involvement in crashes results in higher casualty severity and is likely to reduce the overall effect of roundabouts. This topic warrants further research.

The proportion of fatalities as a percentage of all casualties at three- and four-arm conventional intersections and roundabouts is an intrinsic indicator that the overall share of fatalities is lower at roundabouts than at conventional intersections (*Figure 3.5)*. Similarly, *Figure 3.6* illustrates the similarities in the numbers of serious road injuries at the conventional intersections and the smaller share of serious road injuries at roundabouts.

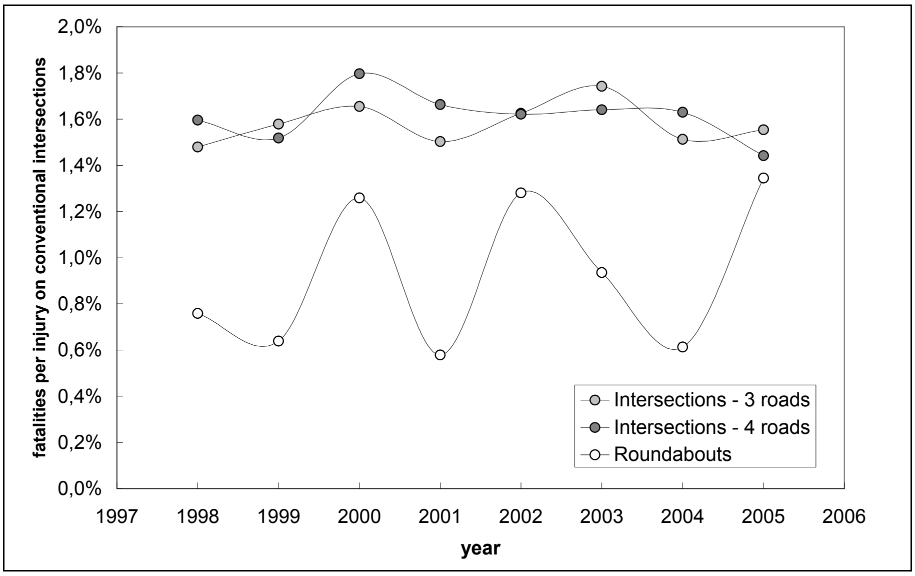

Figure 3.5. *Fatalities as percentage of all casualties for conventional intersections and roundabouts.*

The average share of fatalities among all casualties between 1998 and 2005 is 0.9%, while the shares among conventional 3 and 4 arm intersections, with averages of 1.6% and 1.75% respectively, are nearly twice as high. In *Figure 3.5* it is remarkable that the variations in the shares of fatalities at intersections are much smaller than those at roundabouts; this is due to the variability of the small number of fatalities at roundabouts. It is also interesting to see the similarity of the fatality shares at 3 and 4 arm intersections. The share of fatalities at all junction types appears to be relatively stable.

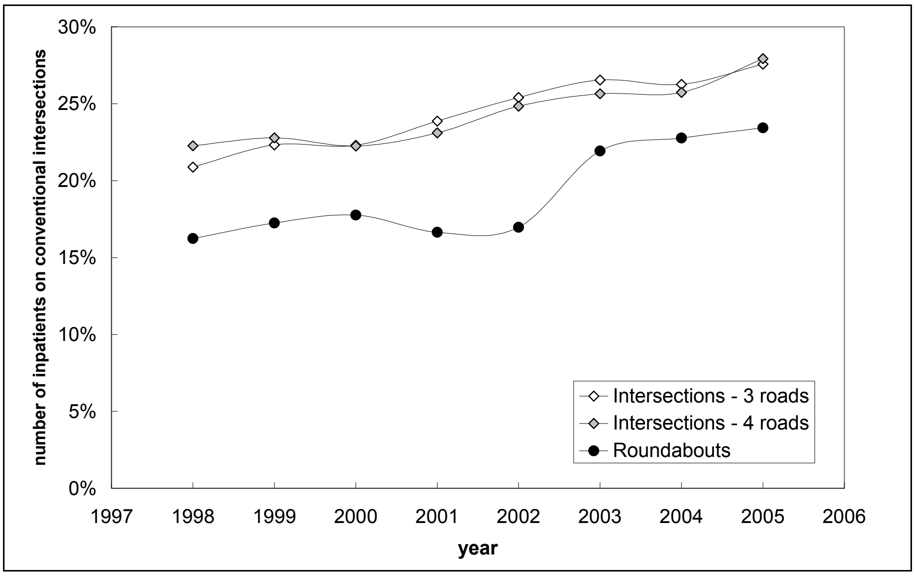

Figure 3.6. *Serious road injuries as a percentage of all casualties for conventional intersections and roundabouts.*

The average share of serious road injuries at all junctions has been increasing during the period 1998-2005. The share of serious road injuries at roundabouts, an average of 19.6%, is smaller than that at conventional intersections, 23.3% for both 3 and 4 arm intersections; once more the shares at 3 and 4 arm intersections are remarkably similar. The increasing trends in *Figure 3.6* are due to relative decreases in minor injuries in all cases apparent in *Figure 3.4* as compared to *Figures 3.2* and *3.3*, possibly as a result of changes in crash registration rates for the slighter casualties.

4. Roundabout before and after study

The effect of transforming intersections into roundabouts on the number of serious crashes and casualties, those with fatalities and serious road injuries, has been evaluated for the periods before and after the construction of roundabouts. Although roundabouts have been studied extensively in before and after studies, the findings regarding the impact on serious crashes and casualties are generally limited. This is due to the small numbers of casualties as a result of the rare and random nature of serious crashes. In this study, large scale data aggregation has been carried out to obtain fatal crash and fatality counts potentially sufficient for statistically significant analysis. Data for this purpose has been obtained from the Dutch national roads database (Nationale Wegen Bestand, NWB), and the Dutch database of registered crashes (Bestand geRegistreerde Ongevallen Nederland, BRON) which have been spatially related in ArcGIS 9 published by ESRI.

It is important to note in advance that the aggregation of several years of data, while resulting in sufficient numbers to allow statistical analyses of serious casualties, draws on casualties from so many locations that the results of this study should be seen as average summary values of all roundabouts. Furthermore, the sample obtained for fatalities and fatal crashes appears to be just sufficient for statistical analysis, and disaggregation by road type, road user, or roundabout type may not be feasible. Although the numbers of serious crashes and serious road injuries are sufficient to allow these types of disaggregation, the average situation is presented to complement the analysis of fatalities. The analysis of the effect of specific changes on all types of crashes is best accomplished with more detailed studies such as Dijkstra (2004), Persaud et al. (2000), De Brabander et al. (2005), De Brabander et al. (2007), and Daniels et al. (2008). Future studies of this type will continue to be important in revealing specific effects such as cyclist and pedestrian facilities and other roundabout issues which may emerge and which may not be evident at the national level.

Another issue which needs to be mentioned is the degree to which crashes are registered. If a change in reporting practice were to occur, a drop in registered crashes would be possible and could erroneously be attributed to the roundabout rather than to a policy change in the registration process. To avoid this potential pitfall a comparison group can be used, which would also be subject to the same change. Changes beyond those exhibited in the control group are then attributable to the measures rather than to a background effect.

Other intersections which were converted to roundabouts at a later phase within the study period were selected as a comparison group. These intersections are the least biased group since they were also appropriate for conversion into a roundabout. Furthermore, they capture the background effects of the road safety situation changes in the Netherlands, due to such factors as enforcement, policy change, environmental conditions, vehicle improvements, and so on.

The methodology used for statistical analysis of the independence of the before and after periods is required, since crash data from the same year may have occurred in a before period or in an after period, depending on when the roundabout at each of the different locations was built. The method that was developed appears to reveal significant effects on serious crashes and casualties; in previous studies, fatality numbers were too low to obtain statistically significant effects with conventional tests, if such effects existed at all.

Common variables used in before and after studies which are difficult to control in this study are:
- traffic volumes;
- previous traffic control;
- number of lanes or roundabout type;
- traffic mix;
- speed limits.

These limitations are partially due to the absence of such data in the GIS, but primarily to the large number of roundabouts, as a result of the aim to evaluate the overall effect of roundabouts on casualties rather than the effect in specific cases. Since the overall effect of the program is of interest, lower levels of stratification are considered acceptable.

4.1. Data collection and quality controls

Data collection for this study was carried out within ArcGIS 9, and data was extracted from the NWB (road inventory) and BRON (crashes and casualties) databases which were previously spatially coded within the GIS.

Roundabouts in the NWB have been catalogued since 1998, prior to which they were treated as road segments. Until 2005, the roundabout information was updated every year to provide an annual summary of all roundabouts at the end of the year, in the form of polygon-shaped roundabout entities. The definition of roundabouts in the NWB is quite broad and includes some intersections which are round in layout but with insufficient diameter to operate as a roundabout. Similarly, some roundabouts in the NWB are very large traffic circles, most of which were constructed before the study period and likely not to be included. Although both extremes are possible, no distinction was made and all entities coded as roundabouts built during the study period were considered.

Some uncertainty exists as to the quality of the data in terms of when the roundabouts were actually built and operational, as opposed to when they were entered into the NWB; a time lag is suspected. Another difficulty is that the date of construction of the roundabouts is not included as an attribute of the roundabout polygons. In order to obtain the construction date all polygons from all years, a total of 20,591 polygons, were sorted to determine the unique roundabout identification numbers and assign the earliest occurrence as the construction year. During this process it became clear that some roundabouts in previous years had been assigned a different roundabout ID; these cases, 70 in total, were inspected visually and the earliest construction date was assigned to the most recent roundabout ID. In several cases it was clear that the quality of the survey or drafting of the road network was at fault, and that once the geometry was corrected a new

ID was assigned even though the junction represented the same location. In total 3,451 unique roundabouts were found, with the distribution by year shown in *Table 4.1*.

Year	1998	1999	2000	2001	2002	2003	2004	2005	Total
Number of new Roundabouts NWB	1,442	338	160	363	587	307	150	104	3,451
Number of new Roundabouts BRON with crashes	925	289	142	315	526	235	91	68	2,591

Table 4.1*. New unique roundabouts in NWB by construction year and total with matching BRON crash data.*

The 1998 value in *Table 4.1* includes all roundabouts in the Netherlands up to 1998; the other years represent newly constructed roundabouts according to the NWB. Roundabouts which were removed prior to 2005, 82 roundabouts in total, were visually inspected and not included in the analysis sample.

Once all of the unique roundabouts with earliest NWB construction dates had been obtained, all crashes within 40 metres of the roundabout polygons, to include approach and departure crash casualties, were obtained from the BRON crash and casualty data. This resulted in a total of 114,135 crashes in the 1994 to 2006 crash data years, of all severities including property damage only. Previous spatial linking of crashes to roundabouts has been undertaken in the Netherlands, but only for crashes after the construction of the roundabout; the crash history at these locations prior to roundabout construction is also needed to comment on the safety effect of the roundabouts. As crashes that occurred within 40 metres of later reconstructed roundabout polygons were selected, some bias may be introduced. For example, the intersection replaced by the roundabout may not have been (entirely) located within 40 metres of the polygons belonging to the roundabout it replaced. This can be caused by the new roundabout being built close to the location of the intersection it replaces to allow traffic to continue during the reconstruction period or, possibly, because corrections were made to the digital map, where entire sections can be virtually relocated. The roundabout may not replace an intersection at all, for instance because it is in a newly constructed part of the road network. An intersection may also have been reconstructed when an additional arm is added to an intersection, which is likely to render the before and after periods difficult to compare. It is not known to what extent these issues affect the current analysis, but is assumed it will have a negative effect on the counts in the before period.

Each crash record contains a road situation code. This code indicates whether the crash was coded as an 'intersection crash' or a 'roundabout crash, which makes it possible to verify the NWB construction date'. In the case of a crash being coded as a roundabout crash prior to the NWB record of a roundabout existence it is probable that there was a time lag between the roundabout being built and it being registered in the NWB. It is unlikely that a crash at a conventional intersection would be coded as a roundabout crash and it is, therefore, reasonable to assume that if the crash record indicates that it is a roundabout, it actually is. All crashes, including property damage only, were used to verify the construction date in this manner and in the analysis period a total of 40 roundabouts were found with roundabout crash records which pre-dated the NWB construction date. Only three of these roundabouts had earlier dates that were still within the construction period being considered, 1999 to 2005, the other 37 were removed from the analysis sample as they were not constructed within the study period. The number of lagging entries in the NWB was anticipated to be larger and the small number of locations for which a correction was required attests to the quality of the NWB.

There was a relatively large number of locations for which no crashes were recorded in the 1994 to 2006 period, a selection of these locations (40 in total) was visually inspected in the GIS and in Google Earth. They were primarily located in residential areas or at locations where traffic volumes are anticipated to be very low.

The fact that there are 478 locations, which amounts to 22% of the roundabouts constructed in this period, without any crashes in the before or after period suggests that roundabouts are also constructed as a design or policy choice, rather than only as a reaction to high crash rates. The latter is likely to result in a selection effect bias. It should however be noted that the proportion of roundabouts without crashes at all increases in the latter years of the study, from about 10% in the earlier phase to about 30% near the end. This phenomenon could be caused by limited availability of existing locations with non-zero crash counts, but somewhat more likely is due to the Sustainable Safety Start-up Programme, ending in 2002, in which many *existing* locations were reconstructed into roundabouts.

The phenomenon of many locations for which no crashes are recorded suggests that there will be many locations with a few crashes. The fact that the number of roundabouts having 'roundabout crashes' predating the date the roundabout was officially introduced in the database is small, therefore does not mean that the other roundabouts' official introduction dates are mostly correct. In fact, as crashes are apparently rare, roundabouts may have been constructed (much) earlier than the date they were introduced in the database or when the first "roundabout crash" occurred. Therefore the possibility of an extended transition period should be considered.

A total of 2,009 roundabouts were built between 1999 and 2005. These roundabouts are the sample for the study, and indeed represent the largest available sample of roundabouts built in this period for which recent crash data exists. The annual distribution of the construction year of the sample is presented in *Table 4.1*. Underreporting in the Netherlands has been studied (SWOV, 2007) and fatalities are the casualty severity least affected by this phenomenon, in 2005 92% of fatalities were reported, followed by serious road injuries at 53%. Although the registration rates for slightly injured casualties and property damage only are uncertain, the registration rate for property damage is estimated at approximately 20%.

4.2. Before and after tests and results

4.2.1. *Introduction*

All crash records were compiled by year of occurrence and casualty severity and assigned to individual roundabouts by construction year. Summary tables of these totals are presented in *Appendix A* for reference. There a brief discussion is given based on graphical information. In *Appendix B* a before/after comparison is made for locations that in a certain year have been reconstructed into roundabouts, for locations that in that particular year have not yet been reconstructed into roundabouts and for locations that have recently been reconstructed into roundabouts. Both the number of fatal crashes and the number of crashes with serious road injuries (short for crashes resulting in serious road injuries) have been compared. The results of this analysis are promising, pointing towards a positive effect of roundabouts. However, due to statistical dependencies between the comparisons, it is difficult to determine the statistical significance of the effectiveness, and therefore it is impossible to reliably quantify the effect.

In order to determine the statistical significance of the effectiveness and to quantify the effect of reconstructing intersections into roundabouts, a generalized linear model has been built. This model compares the development of the number of crashes and casualties, only fatalities or with serious road injuries in the construction years to the developments in other construction years.

In addition, the effect is also quantified by comparing the development of the number of both fatalities and killed or seriously injured (KSI), at intersections that were not reconstructed into roundabouts and were in operation throughout the entire period. Please note the discussion about the quality of the data and the design above.

4.2.2. *Results*

4.2.2.1. Generalized linear model

Using the generalized linear model, a reduction in the number of fatalities is found at the magnitude of 71% (95% confidence interval: between 40% and 86%reduction). Effectively, this means a reduction on the considered roundabouts of about 9 fatal crashes in 2006 and 8 in 2007.

With respect to the KSI *(killed or seriously injured (inpatient))*, this results in a 37% reduction in the number of KSI (95% confidence interval: between 21% and 49% reduction). Effectively, this means a reduction on the considered roundabouts of about 66 KSI in 2006 and 62 KSI in 2007. *Table 4.2* and *Table 4.3* summarize the results.

Type	**Relative Effect**	lower 95%	upper 95%
Fatal crashes	**71%**	40%	86%
Fatalities	**76%**	49%	89%
KSI crashes	**37%**	21%	49%
KSI	**46%**	32%	57%

Table 4.2*. Estimated effect of the conversion of intersections into roundabouts on crashes and casualties (fatal or KS I (killed or seriously injured (inpatient))).*

Type	Reduction in 2006	Reduction in 2007
Fatal crashes	9	8
Fatalities	12	11
KSI crashes	66	62
KSI	102	97

Table 4.3*. Estimated effect of the conversion of intersections into roundabouts on casualties and crashes (fatal or KSI (killed or seriously injured (inpatient))) in terms of casualty and crash counts.*

4.2.2.2. Comparison with the development of the number of casualties on intersections

A second approach compares the development of the number of casualties at locations that have been converted into roundabouts during the study to the development of the number of casualties at intersections. The results are quite similar to the results derived from the generalized linear model.

Casualties	Year of reconstruction								
	1999	2000	2001	2002	2003	2004	2005	Sum	Weighted mean
N locations	338	160	363	587	307	150	104	2,009	
ratio =after/before	0.09	0.87	0.37	0.18	0.30	0.00	4.49		0.48
Reduction in fatalities	-5.34	-0.05	-2.00	-4.63	-2.50	-1.40	0.78	-15.13	
ratio = after/before	0.44	0.47	0.63	0.48	0.48	0.65	0.42		0.51
Change in KSI	-27.68	-8.93	-16.45	-41.96	-18.49	-4.88	-6.88	-125.25	

Table 4.4*. Overview of the parameters N (the number of roundabouts reconstructed in year y), the rates of reduction and the yearly reduction (in 2006) due to these reconstructions, for the number of fatalities and the number of KSI (killed or seriously injured (inpatient)).*

5. Discussion

The present analysis uses crash data linked to GIS-registered location data. The properties of these location data are analyzed by comparing GIS-data in consecutive years and junctions can be identified to be either a roundabout or an intersection. In this way, locations can be found where an intersection is converted into a roundabout, together with the approximate year of reconstruction. Crashes in the before period (when the junction was an intersection) were selected based on their geographical location, within a distance of 40m from of the current roundabout polygons.

Two main problems arose from this approach:

1. In some cases, the location of the original intersection (if existent at all) need not be within the chosen area. In those cases where elements of the original intersection were further than 40m away from the polygons of the current roundabout, not all or none of the crashes were attributed to the before period of that roundabout. Because of this, the number of casualties and crashes in the before period of roundabouts will be somewhat underestimated and results of the study will therefore be biased towards unfavourable effects for roundabouts.
2. The date a roundabout first appears in the database of the road network in the Netherlands need not be the actual date the intersection was reconstructed into a roundabout. In addition, the location may have been closed for traffic during the period in which it was reconstructed into a roundabout. Some effort has been made to correct for this effect, for instance by looking for crashes coded by the police as occurring on a roundabout, while the crash date predated the official reconstruction date.

In addition, many roundabouts were constructed during the Sustainable Safety Start-up Programme. As a consequence, intersections with more crashes may have been reconstructed earlier than intersections with fewer crashes. The latter were not necessarily safer intersections. If this is true, which must be seriously considered, the results of this study should not uncritically be used to estimate the general effect of converting intersections into roundabouts. The study is then better regarded as a study into the effect of the reconstruction of the intersections that have actually been converted into a roundabout in the Netherlands, rather than a study into the effect of the reconstruction of intersections into roundabouts in general. It should however be noted that a substantial proportion of new roundabouts did not have any crash at all, neither before being 'reconstructed' nor after being reconstructed. It is unlikely that these locations were selected due to a high crash count. Whether this means that a location's crash history did not always play a role in the decision to reconstruct it into a roundabout remains to be determined. It is quite possible that in fact two populations of locations were investigated: one of locations which did not have a crash history at all because those locations were completely new, and the other of existing locations, which may have had a high crash rate. This remains unclear until substantial effort is put into recovering the past history of each specific location. Based on a pilot study it appears that it is possible to determine whether a roundabout is in fact new or whether it replaces an intersection. In fact, some further detail can be recovered from older network data which may help judge whether before and after situations are sufficiently comparable, but the balance between effort and reward needs to be looked into first.

The results of the study into the effectiveness of roundabouts in terms of a relative reduction in crash or casualty occurrence do not reveal strong evidence of a diminishing effectiveness when later reconstruction years are considered. This result could be considered in contradiction with the possibility that intersections with more crashes tend to be selected for reconstruction first (and included in the earlier reconstruction years). Intersections with fewer crashes would then tend to be included in the later reconstruction years. Although formally not directly related, it is possible that locations with more crashes or casualties may have been more dangerous and could therefore potentially reveal larger reductions, either because measures could be more effective, or by chance. However, while the more dangerous intersections may gain more from a reconstruction in terms of the absolute number of casualties of crashes, it remains to be seen if this translates into a different relative gain.

The two problems listed above also interfere with the present analysis. The fact that this study includes roundabouts that could not have had any crashes at all in the before period not only biases the results, but may also obscure any difference in effectiveness, because locations could be included where no effect could be achieved at all, at a scale that is different per reconstruction year. The second aspect is the misspecification of the reconstruction year. As correction is more likely for locations that have more crashes, locations with fewer crashes are more likely to end up not being corrected and thus will be assigned to a later reconstruction year.

With respect to the crash data used in this study, some caution must be taken when interpreting the results for serious road injuries and non-fatal crashes resulting in serious road injuries. Recent research (Reurings & Bos, 2009) revealed that more than 90% of seriously injured casualties in crashes without motor vehicles are not registered by the police. Injured casualties in crashes involving motor vehicles are far more often registered by the police. Despite the fact that almost half the number of crashes are non-motorized bicycle crashes, our results are dominated by data on crashes with motorized vehicles.

6. Conclusions

The present study is intended to evaluate the overall effect of the conversion of intersections into roundabouts on the number of crashes and casualties in the Netherlands. Since the 1980s the number of roundabouts in the Netherlands has increased substantially. The increase was particularly strong during the Sustainable Safety Start-up Programme, which started in 1997 and continued until the year 2002. In that period many intersections were reconstructed into roundabouts and many new roundabouts were built. According to the Dutch National Roads Database (NWB), the number of roundabouts increased from 1,442 in 1998 to 3,451 in 2005.

In this study, the effectiveness of improving road safety by reconstructing intersections into roundabouts is determined by comparing the development of the annual crash or casualty occurrence on newly constructed roundabouts to appropriately chosen control samples. The first approach that was taken compares the development of the aggregate annual crash or casualty counts of reconstructed locations in a particular year to the development of the aggregate annual crash or casualty counts of locations reconstructed in other years. The alternative approach that was used compares the development of the aggregate annual crash or casualty counts of all locations reconstructed into roundabouts to the development of the aggregate annual crash or casualty counts of all intersections not reconstructed into roundabouts within the study period. The latter approach has primarily been used as a comparison with the first approach. Both approaches yield similar results.

Acknowledging the reservations in the discussion, study findings appear to be consistent with results in literature. The data set and methods applied result in statistically significant results for aggregated fatal casualties and crashes not previously obtained in literature, even though the method is biased towards the opposite. The only other study which estimated a fatality reduction was Persaud et al. (2000), an estimate of 89% reduction; although the authors cautioned that this was not a statistically defendable value.

The effect for fatal crashes is estimated to be a 71% reduction in the number of fatalities (95% confidence interval: between 40% and 86% reduction). Effectively, this means a reduction on the considered roundabouts of about 12 fatalities in 2006 and 11 in 2007.

In summary, the results for crashes and casualties are presented in *Table 6.1.*

The reconstruction of roundabouts may be subject to diminishing returns as the general road safety situation improves. This justifies further monitoring of roundabout performance in the future, but currently the safety benefits of roundabouts are significant. As some studies report potential adverse effects of roundabouts for vulnerable road users, one focus of future roundabout research should be at the accommodation of vulnerable road users.

	Relative effect	lower 95%	upper 95%	Effect 2006	Effect 2007
Fatalities	76%	49%	89%	12	11
KSI casualties	46%	32%	57%	102	97
Fatal crashes	71%	40%	86%	9	8
KSI crashes	37%	21%	49%	66	62

Table 6.1*. Summary of effects of the 2009 intersections reconstructed into roundabouts taken from Tables B.7 to B.10.*

The present study estimated the aggregated effect on road safety of about 2000 intersections that were reconstructed into roundabouts in the period 1999 - 2005. There are approximately 1500 more roundabouts in the Netherlands. In the years 2003 - 2008, annually about 9 people were killed in road crashes on roundabouts in the Netherlands. On the roundabouts considered in this study, the number of fatalities was 2 in 2003, 5 in 2004, 6 in 2005 and 4 in 2006 (no later data was used in this study). This means that although older roundabouts (before 1999) are fewer in number than those built later, the older roundabouts on average counted somewhat more fatalities in road crashes. Assuming the relative effect of saving about 76% on the number of fatalities found in this study is representative for the older roundabouts, this would tentatively mean that approximately 27 fatalities are prevented annually (a little more than twice the 12 fatalities prevented mentioned in *Table 6.1*) due to the use of roundabouts instead of intersections in the Netherlands.

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Appendix A Crashes and casualties by roundabout construction year

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-5	1994	1,003	9	78	10	92	85	99	286
-4	1995	1,000	7	46	7	57	92	135	291
-3	1996	939	9	49	12	61	89	132	294
-2	1997	890	7	44	8	51	60	133	252
-1	1998	806	3	28	3	30	55	73	161
0	1999	895	2	24	2	30	57	83	172
1	2000	779	3	19	3	21	36	62	122
2	2001	668	0	23	0	23	28	56	107
3	2002	640	0	22	0	23	34	50	107
4	2003	617	0	26	0	28	21	63	111
5	2004	503	1	24	1	27	35	47	110
6	2005	472	0	18	0	18	28	39	85
7	2006	514	0	25	0	25	31	42	98
Roundabouts: 338									

Table A.1. *Before and after data for roundabouts constructed in 1999.*

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-6	1994	323	1	24	1	33	23	42	99
-5	1995	348	0	21	0	22	31	36	89
-4	1996	322	3	20	4	23	30	34	91
-3	1997	314	0	16	0	19	21	26	66
-2	1998	311	1	17	1	21	26	27	75
-1	1999	240	1	7	1	7	21	14	43
0	2000	262	1	8	1	8	12	34	55
1	2001	199	0	5	0	5	7	19	31
2	2002	220	1	2	1	2	19	16	38
3	2003	192	0	8	0	8	8	17	34
4	2004	238	0	14	0	15	26	16	57
5	2005	241	1	11	1	11	21	9	42
6	2006	195	0	8	0	8	9	19	36
Roundabouts: 160									

Table A.2. *Before and after data for roundabouts constructed in 2000.*

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-7	1994	1,127	4	64	4	81	99	123	307
-6	1995	1,220	5	66	5	76	100	131	312
-5	1996	1,103	4	62	4	73	72	135	284
-4	1997	1,075	6	53	7	66	83	97	253
-3	1998	1,027	4	38	4	44	68	113	229
-2	1999	937	2	33	2	45	62	84	193
-1	2000	786	0	23	0	30	42	68	140
0	2001	860	0	28	0	34	52	101	187
1	2002	720	2	20	2	22	28	88	140
2	2003	743	0	30	0	30	27	70	129
3	2004	505	1	22	1	22	34	49	106
4	2005	466	1	29	1	33	24	44	102
5	2006	595	2	33	2	37	40	48	127
Roundabouts: 363									

Table A.3. *Before and after data for roundabouts constructed in 2001.*

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-8	1994	1,799	6	122	6	134	166	187	493
-7	1995	1,752	14	104	15	116	156	220	507
-6	1996	1,613	11	95	11	115	140	164	430
-5	1997	1,625	9	100	9	110	141	210	470
-4	1998	1,535	4	89	5	117	145	154	421
-3	1999	1,343	9	74	10	88	85	148	331
-2	2000	1,141	5	48	7	56	84	119	266
-1	2001	911	0	31	0	32	51	102	185
0	2002	1,009	3	41	3	45	61	116	225
1	2003	915	1	47	1	50	37	109	201
2	2004	650	1	32	1	35	51	54	141
3	2005	619	2	34	2	35	49	74	160
4	2006	698	0	37	0	39	56	66	161
Roundabouts: 587									

Table A.4. *Before and after data for roundabouts constructed in 2002.*

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-9	1994	707	5	38	6	42	64	83	195
-8	1995	631	5	37	5	48	50	64	167
-7	1996	647	1	42	1	50	55	77	183
-6	1997	653	7	34	9	45	56	74	184
-5	1998	674	5	36	5	47	56	61	169
-4	1999	648	1	30	1	33	60	78	172
-3	2000	580	3	34	4	36	39	50	129
-2	2001	497	5	26	5	31	39	52	127
-1	2002	321	0	18	0	23	26	43	92
0	2003	411	1	17	1	19	17	35	70
1	2004	299	1	11	1	11	23	21	56
2	2005	288	1	17	1	17	19	23	60
3	2006	314	1	18	1	20	19	24	64
Roundabouts: 307									

Table A.5*. Before and after data for roundabouts constructed in 2003.*

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-10	1994	234	2	13	2	13	18	23	56
-9	1995	223	2	8	2	10	18	24	54
-8	1996	243	0	18	0	19	15	36	70
-7	1997	224	2	14	2	17	13	17	49
-6	1998	270	2	15	2	19	20	25	66
-5	1999	266	2	15	2	16	13	29	60
-4	2000	234	0	10	0	11	18	32	61
-3	2001	199	1	13	1	15	20	17	53
-2	2002	149	4	10	4	11	9	13	37
-1	2003	125	0	7	0	7	6	13	26
0	2004	129	1	6	1	6	2	9	18
1	2005	117	0	10	0	11	6	7	24
2	2006	95	0	6	0	7	3	10	20
Roundabouts: 150									

Table A.6*. Before and after data for roundabouts constructed in 2004.*

Datum year	Calendar year	# Crashes	# Fatal Crashes	# Inpatient Crashes	# Fatalities	# Inpatients	# First aid injuries	# Light Injuries	# All casualties
-11	1994	165	3	9	3	9	10	15	37
-10	1995	169	3	6	4	8	15	15	42
-9	1996	151	2	12	2	15	5	21	43
-8	1997	166	1	5	1	6	10	16	33
-7	1998	195	0	10	0	16	12	15	43
-6	1999	179	0	8	0	11	18	25	54
-5	2000	162	0	11	0	11	12	11	34
-4	2001	156	0	11	0	11	17	22	50
-3	2002	142	1	19	1	26	22	17	66
-2	2003	129	0	13	0	17	6	17	40
-1	2004	103	0	4	0	4	7	3	14
0	2005	91	1	8	1	9	8	11	29
1	2006	110	1	3	1	4	6	11	22
Roundabouts: 104									

Table A.7. *Before and after data for roundabouts constructed in 2005*

Appendix B Before and after tests and results

Introduction

All crash records were compiled by year of occurrence and casualty severity and assigned to individual roundabout locations by construction year. Summary tables of these totals are presented in *Appendix A* for reference.

When compiled by construction year, roundabouts which were built earlier appear to have relatively large casualty counts in the before period, as shown in *Figure A.1*. Roundabouts built in 2000, 2004 and 2005, however, appear to have somewhat lower counts in the before and after periods. This result even holds for the average number of KSI per location, although weakly for the number of killed casualties and the number of fatal crashes, as a further analysis below reveals. This may indicate that the high frequency crash locations have mostly been converted to roundabouts and that the effect of roundabouts at the remaining locations may be (much) smaller. This is an area that requires further research, particularly in the light of recent literature (De Brabander et al., 2005) which suggests a shift of casualty burden to cyclists and vulnerable road users. If there is no overall reduction in casualties but an increase in vulnerable road user involvement, then other intersection measures may be more appropriate. The trends do not reveal a general increase in the number of casualties just before intersections are converted into roundabouts. This means that based on the casualty counts, there is no reason to suspect that its recent crash history has affected the probability of an intersection being converted into a roundabout.

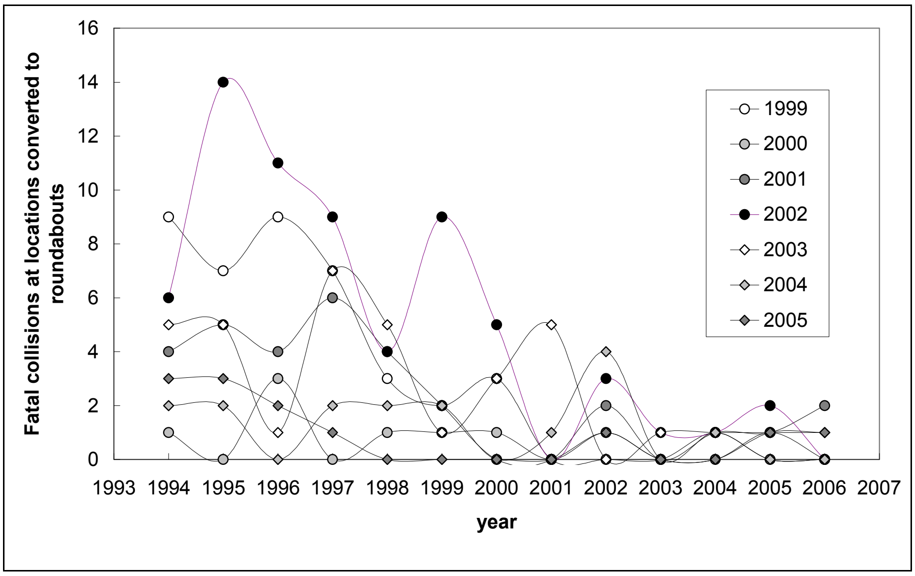

Figure B.1. *Compiled fatal crash histories by construction year.*

Simple before/after comparison

As a first test to see whether there was a crash reduction, a 2 x 2 table is created for each construction year *y*. Each table consists of a column containing the number of crashes at the intersections in year *y*-1 and the number of crashes at the intersections (at that time roundabouts) in year *y*+1 after the year of reconstruction. This means that the number of crashes in the construction year itself, is omitted. This is because it is suspected that the actual reconstruction may have affected the crash figures, for instance because the location may have been closed for traffic. The second column contains similar data for the same crash years from intersections converted into roundabouts in construction year y+2.

		Year of reconstruction				
		y -2	*y* -1	*y*	*y*+1	*y*+2
Crash year	*y* -2	recon.				
	y -1		recon.	**A1**		**B1**
	y			recon.		
	y +1			**A2**	recon.	**B2**
	y+2					recon.

Resulting in a table

	Experimental (*y*)	Control (*y*+2)
Before (y-1)	A1	B1
After (*y*+1)	A2	B2

The use of locations converted to roundabouts one year later is likely to reduce the difference concerning the policy of choosing intersections to be reconstructed between the comparison locations and experimental locations.

For each 2 x 2 table it can be determined whether the number of crashes at roundabout locations decreased more compared to the control group, the number of crashes at roundabout locations increased compared to the control group, or there was no difference (a tie). If the installation of roundabouts has no effect on safety, one would expect the number of crashes on roundabouts to decrease compared to the control group as often as the number of crashes on roundabouts to increase compared to the control group.

In this manner ten comparisons can be made: five tables based on fatal crash counts, and five tables based on serious injury crash counts (thus not including fatalities). All ten comparisons turned out favorable for the reconstruction of intersections into roundabouts. The statistical significance of this result is difficult to determine, however, as some cells are shared among tables and the tests, therefore, are not independent of each other.

A further comparison can be made with locations that had just been converted into roundabouts:

		Year of reconstruction				
		y -2	*y* -1	*y*	*y*+1	*y*+2
Crash year	*y* -2	recon.				
	y -1	**C1**	recon.	**A1**		B1
	y			recon.		
	y +1	**C2**		**A2**	recon.	B2
	y+2					recon.

Resulting in a table

	experimental (*y*)	Control (*y*-2)
Before (*y*-1)	A1	C1
After (*y*+1)	A2	C2

Of these ten comparisons seven favor the construction of roundabouts, while one (for fatal crashes) is a tie and two (one for fatal crashes, one for serious injury crashes, not for the same construction year) would favor the intersection.

More formal comparison based on generalized linear models

Introduction

Although these results look promising, they do not constitute a reliable statistical test for the significance of the effectiveness of roundabouts. However, the results show that, if there is an effect at all, it is not just for special cases.

As the results so far are quite promising, a further effort to investigate the significance of a *single* effect (one single value for all) of the reconstruction of intersections into roundabouts is undertaken based on this data matrix: the annual number of crashes or casualties on locations that have been converted into roundabouts within the study period. As in the previous approach, the reconstructed locations are used as a control group for other locations. In the first step, an effect is estimated assuming the relative effect is the same for all locations. At a later stage, it is attempted to determine whether the effect of reconstructing of intersections into roundabouts may be different for different reconstruction years.

Finally, the effect is also assessed by comparing the development of the number of casualties at (locations that have been converted into) roundabouts to the development of the number of casualties at intersections that existed during the entire period, but were not converted into roundabouts. This is done for both fatalities and for KSI.

Specification

The first attempt was made by building a generalized linear model for the annual number (counts) of:

1. fatal crashes;
2. fatalities (killed casualties);
3. crashes involving either fatalities or serious road injuries, or both;
4. fatalities or serious road injuries (KSI).

These counts are recorded per crash year (1994 - 2006), and are accumulated over all roundabouts of a certain reconstruction year (that is, the year of introduction of a roundabout into the database, 1999 - 2005).

For each analysis involving one of the four above counts, the counts are denoted by y_{jk}, where *j=1994,…, 2006* denotes the year, and *k=1999,…, 2005* denotes the reconstruction year of the roundabout. In addition, the number of locations (n_k) per reconstruction year *k* was recorded.

It is assumed that the counts per crash year and per reconstruction year are linearly dependent on the number of locations reconstructed in that year. As indicated above, the possibility should be considered that in general locations with higher safety reduction potential were converted into roundabouts first, and locations with less potential were generally converted at a later date. This possibility is likely to be identified by the number of casualties or crashes per location recorded before the beginning of the study. Therefore, it is assumed that the reconstruction year of a roundabout has an effect on its average count. This is implemented by allowing each reconstruction year to have its own average count per location. This figure may differ between reconstruction years, and it is anticipated that later reconstruction years have a lower average count per location than earlier reconstruction years. However, the average count is not assumed to be different between locations within one reconstruction year. Note that at a later stage, it is determined whether the effect of reconstructing intersections into roundabouts differs between reconstruction years.

Finally, it is assumed that the counts develop log-linearly over time[1]. This resulted in the basic model:

$$E(y_{jk}) = n_k \times effect(year_j) \times effect(buildyear_k)$$

Due to the nature of the procedure used to establish the date of construction, some roundabouts may actually have been constructed (long) before the registered reconstruction year. When no crashes are registered identifiable as having occurred at a roundabout in the period between actual reconstruction and postponed registration of the roundabout at that location, this error remains unobserved. Assuming it is indeed true that the reconstruction of intersections into roundabouts does have a positive effect on road safety on those locations, which is to be determined, this would

[1] A categorical effect for calendar year has also been considered, but has not been fully explored.

result in counts tending to drop *before* the formal reconstruction date of the location. Moreover, due to the period needed for reconstruction, counts may start dropping even before the actual date the newly constructed roundabout was opened to traffic.

The current analysis accounts for this effect by separately analyzing the four types of count data both *including* certain observations and (separately) *excluding* certain observations.

In order to determine an effect of the reconstruction of intersections into roundabouts on the number of casualties, the basic model is extended with a dummy effect:

$$\mathrm{int}\,ervention_{jk} = \begin{cases} 1 & j \le k \\ \exp(\alpha) & j > k \end{cases}$$

to be included in the model:

$$E(y_{jk}) = n_k \times effect(year_j) \times effect(buildyear_k) \times \mathrm{int}\,ervention_{jk\ jk}$$

Estimation details

An overdispersed Poisson model was fitted to the counts (in parallel, negative binomial models were developed, but are not reported here). Results are satisfactory. Three software packages (SAS, R and Mathematica) were used to overcome complications in the actual estimation procedures. Only very limited overdispersion is found (about 1.1) for the fatal crash model. The reconstruction year effect was *not* statistically significant. In the subsequent analysis, this variable however was retained for the time being (for instance to allow it to interact with the roundabout effect).

Effect	Model	Exclude reconstruction years	Estimate of α	95% Lower Confidence Limit	95% Upper Confidence Limit	Chi-Square	Pr > ChiSq
isRoundabout	Base model	reconstruction year, year before	-1.2321	-1.9794	-0.5043	11.12	0.0009

Table B.1. *Likelihood ratio test for the effect of roundabouts "estimate" on the number of fatalities.*

In the subsequent analysis, both the year the roundabout was introduced in the database and the preceding year were excluded from analysis (but were included later to assess the sensitivity of the results for this choice).

The sensitivity of the analysis to assumptions and data availability was tested by fitting the same model

1. without discarding the year of transition and the preceding year; in addition discarding the year before the preceding year; and in addition even discarding the year before that year (the official reconstruction year, and three years before that point.

Effect	Sub-model	Exclude reconstruction years	Estimate of α	95% Lower Confidence Limit	95% Upper Confidence Limit	Chi-Square	Pr > ChiSq
isRoundabout	Drop reconstruction years	None	-0.5769	-1.2633	0.0801	2.95	0.0858
isRoundabout	Drop reconstruction years	Only reconstruction year	-0.6792	-1.4280	0.0453	3.37	0.0663
isRoundabout	Drop reconstruction years	reconstruction year, two years before	-1.0613	-1.9119	-0.2223	6.16	0.0131

Table B.2. *Sensitivity of the effect of roundabouts "estimate" to the choice whether or not to include the data for the reconstruction year, and one or two of the preceding year(s).*

It is clear that the choice as to which years to include in the analysis is of some importance. Though not always significant at the 5% level, the significance of the effect is still substantial (all are significant at the 5% level considering fatalities instead of fatal crashes). Unless the assumptions with respect to the actual reconstruction period of the roundabouts turn out to be very wrong, it is decided that the choice to exclude the year before the official reconstruction year is probably correct. Furthermore it is interesting to note that the results deleting *two* years previous to the reconstruction are similar to the results deleting *one* year previous to the reconstruction. The inclusion or exclusion of the number of crashes in the year immediately preceding the reconstruction (possibly biased, and subject to regression to the mean) for selection effects) apparently did not have a major impact on the estimate. Note that the first model, without excluding any year, could have been specified including the reconstruction year in the after period. Currently it is included in the before period: the after period starts the year *after* the introduction into the database. In the current model this assumption had no discernable effect.

2. Discarding initial years: 1994; 1994 and 1995; up to discarding 1994 through 1998.

Effect	Last year to exclude	Estimate of α	95% Lower Confidence Limit	95% Upper Confidence Limit	Chi-Square	Pr > ChiSq
isRoundabout	1994	-1.0628	-1.9060	-0.2358	6.36	0.0117
isRoundabout	1995	-1.2575	-2.2312	-0.3032	6.69	0.0097
isRoundabout	1996	-0.9720	-2.0985	0.1358	2.95	0.0856
isRoundabout	1997	-1.1914	-2.6086	0.1931	2.84	0.0919
isRoundabout	1998	-1.2316	-2.8967	0.3740	2.25	0.1334

Table B.3. *Sensitivity of the effect of roundabouts "estimate" to the choice whether or not to include initial years of the data.*

Obviously, the more data is removed from the analysis, the more the power of the analysis is diminished. This is reflected by the decreasing significance of the effect descending the table (when more years are removed from the analysis). Interestingly, the estimate is not strongly affected by this procedure.

3. discarding 2006 and 2005 as well as 2006.

Effect	First year to exclude	Estimate of α	95% Lower Confidence Limit	95% Upper Confidence Limit	Chi-Square	Pr > ChiSq
isRoundabout	2005	-1.3748	-2.2193	-0.5933	12.35	0.0004
isRoundabout	2006	-1.2714	-2.0283	-0.5445	11.97	0.0005

Table B.4. *Sensitivity of the effect of roundabouts "estimate" to the choice whether or not to include final years of the data.*

This analysis, together with the previous one, suggests that the results are not very sensitive to the actual choice of years considered. Although one can never be certain, it appears that adding an additional year is not likely to change the statistical inference.

4. discarding each observation year in turn, one at a time.

Effect	Calendar year excluded	Estimate of α	95% Lower Confidence Limit	95% Upper Confidence Limit	Chi-Square	Pr > ChiSq
isRoundabout	1994	-1.0628	-1.9060	-0.2358	6.36	0.0117
isRoundabout	1995	-1.3706	-2.1526	-0.6110	12.69	0.0004
isRoundabout	1996	-1.1139	-1.8723	-0.3736	8.75	0.0031
isRoundabout	1997	-1.1822	-1.9742	-0.4058	8.94	0.0028
isRoundabout	1998	-1.2874	-2.0595	-0.5308	11.18	0.0008
isRoundabout	1999	-1.3038	-2.0761	-0.5447	11.38	0.0007
isRoundabout	2000	-1.5358	-2.3549	-0.7360	14.29	0.0002
isRoundabout	2001	-1.0593	-1.8353	-0.2979	7.46	0.0063
isRoundabout	2002	-1.1328	-1.9036	-0.3839	8.87	0.0029
isRoundabout	2003	-1.1229	-1.8773	-0.3894	9.09	0.0026
isRoundabout	2004	-1.2431	-2.0599	-0.4605	9.85	0.0017
isRoundabout	2005	-1.3075	-2.1154	-0.5372	11.30	0.0008
isRoundabout	2006	-1.2714	-2.0283	-0.5445	11.97	0.0005

Table B.5. *Sensitivity of the effect of roundabouts "estimate" to the choice whether or not to exclude a specific calendar year of the data.*

This analysis reveals that it is not likely that the results of a certain calendar year determined the significance of the effect of the construction of roundabouts. Note that excluding the year 2000 yields the largest point estimate for the effect of the construction of roundabouts.

5. discarding each reconstruction year in turn, one at a time.

Effect	Reconstruction year excluded	Estimate of α	95% Lower Confidence Limit	95% Upper Confidence Limit	Chi-Square	Pr > ChiSq
isRoundabout	1999	-0.9748	-1.7669	-0.2026	6.14	0.0132
isRoundabout	2000	-1.2759	-2.0328	-0.5416	11.75	0.0006
isRoundabout	2001	-1.3882	-2.2711	-0.5442	10.57	0.0011
isRoundabout	2002	-1.1753	-2.0465	-0.3271	7.42	0.0065
isRoundabout	2003	-1.1941	-2.0535	-0.3577	7.88	0.0050
isRoundabout	2004	-1.0522	-1.8202	-0.2998	7.55	0.0060
isRoundabout	2005	-1.5041	-2.2640	-0.7643	16.12	<.0001

Table B.6. *Sensitivity of the effect of roundabouts "estimate" to the choice whether or not to exclude a specific reconstruction year of the data.*

This analysis reveals that it is not likely that the results of a certain reconstruction year determined the significance of the effect of the roundabouts. If the locations that were reconstructed into roundabouts early in the analysis period had a larger drop in casualties or crashes compared to locations converted later, this table would reveal smaller effects at the top of this table, and gradually larger effects at the bottom. This can only be observed in part, as excluding reconstruction year 1999 results in a smaller effect for roundabouts (-0.9748) compared to -1.2321 while excluding reconstruction year 2005 results in a *larger* effect for roundabouts (-1.5041). These results are not very convincing as an indication of the presence of a selection effect: initial locations have more potential to improve than later locations.

The effect of the reconstruction year is not significant in both the model for fatalities and the model for fatal crashes. It is, however, significant in the models for killed and seriously injured (fatalities plus serious road injuries) casualties and crashes. The effects for the reconstruction years 1999, 2001 and 2002 are largest, while the effects of *2000*, 2004 and 2005 are lowest. The year 2003 is in the middle. This means that the roundabout locations for the reconstruction years 1999, 2001 and 2002 had a relatively large number of casualties or crashes per location, while the locations of 2000, 2004 and 2005 had a relatively low number of casualties or crashes per location while 2003 is in the middle. The position of the locations reconstructed in the year 2000 deserves some attention. A further analysis is performed allowing for a separate effect of the reconstruction into roundabouts for each reconstruction year.

The sensitivity of this analysis to assumptions and data availability was tested by performing the same sensitivity analysis as was used for a single effect, as described above. Only in a few cases, the negative binomial model converged properly. Except for one case, none of the interactions were significant, indicating that one single effect for the reconstruction of intersections into roundabouts might be sufficient; the data used in this study does not reveal statistical evidence that there is a difference. If the calendar year 2000 is *excluded* from the analysis, the interaction effect is only just significant in a Poisson regression model (4% for fatalities, 2% for fatal crashes). It should be noted that in both cases, one test was significant out of 31 tests. Inspecting both models it can be seen that the effects of the reconstruction year 2004 in particular are odd. However, the significance of the interaction is not caused by the odd solution for the specific effect for 2004, as can be concluded from a further analysis which in addition excludes the data for reconstruction year 2004. It is not yet fully understood what causes the significance of the interaction to be so sensitive to the presence of the calendar year 2000 data. As both after period years of the reconstruction year 2000 locations had no fatal crashes or fatalities, the size of the estimated effect is very large, only limited by the precision of the estimation procedure due to the log-linear nature of the model (which may partly explain a few of the estimation problems this project had to cope with). No other after period has zero casualties or crashes. Not considering locations from reconstruction year 2004 results in not considering the reconstruction year which shows the largest relative decrease after being transformed into a roundabout, which may bias results.

The analysis above reveals that the significance of the effect is not very sensitive to the choice of years considered in the analysis. However, the results may be sensitive to the choice of which period around the reconstruction of the roundabouts to exclude. It is therefore probably a good idea to improve on the determination of this period in a future study into the effects of roundabouts in the Netherlands. Furthermore, a future study should again consider the possibility of an interaction between reconstruction year and effect, or, when possible, between implementation type and effect.

A similar analysis has been performed for the killed or seriously injured. However, the likelihood ratio tests for the reconstruction year failed in the sensitivity analysis for excluding years 1999, 2000 and 2003, as well as the sensitivity analysis excluding reconstruction year 2000. The analysis itself is satisfactory. No time is available to solve this issue.

Results

The effect α is estimated using the overdispersed Poisson model at -1.23 (95% confidence interval: (-1.98, -0.50)), which means 100*(1-Exp(α)) = 71% reduction in the number of fatalities (95% confidence interval: between 40% and 86% reduction). Effectively, this means a reduction on the considered roundabouts of about 9 fatal crashes in 2006 and 8 in 2007. Application of a negative binomial model yielded very similar results, in particular for the fatal crashes, and fatalities. For the killed and seriously injured, result based on negative binomial distribution assumptions indicate slightly higher effect sizes for transforming intersections into roundabouts, but the difference is not very "significant".

In this case α is estimated at -0.46 (95% confidence interval: (-0.68, -0.28)) and the p-value of the likelihood ratio test is below 0.0001. which means 100*(1-Exp(α)) = 37% reduction in the number of killed or seriously injured (95% confidence interval: between 21% and 49%reduction). Effectively, this means a reduction on the considered roundabouts of about 66 killed or seriously injured in 2006 and 62 killed or seriously injured in 2007.

Type	Distribution	Estimate of α	Lower 95%	Upper 95%	**Relative Effect**	Lower 95%	Upper 95%
Fatalities	Neg. bin	-1.27	-1.95	-0.58	**72%**	44%	86%
Fatalities	Poisson	-1.23	-1.98	-0.50	**71%**	40%	86%
KSI	Neg. bin	-0.54	-0.79	-0.32	**42%**	27%	54%
KSI	Poisson	-0.46	-0.68	-0.24	**37%**	21%	49%

Table B.7*. Estimated effect of the transformation of intersections into roundabouts on crashes (fatal or killed or seriously injured (inpatient)) for both Poisson and negative binomial assumptions.*

Type	Distribution	Estimate of α	Lower 95%	Upper 95%	**Relative Effect**	Lower 95%	Upper 95%
Fatalities	Neg. bin	-1.43	-2.14	-0.72	**76%**	51%	88%
Fatalities	Poisson	-1.42	-2.20	-0.67	**76%**	49%	89%
KSI	Neg. bin	-0.73	-0.98	-0.50	**52%**	39%	62%
KSI	Poisson	-0.61	-0.85	-0.38	**46%**	32%	57%

Table B.8*. Estimated effect of the transformation of intersections into roundabouts on casualties (fatal or killed or seriously injured (inpatient)) for both Poisson and negative binomial assumptions.*

Type	Distribution	2006 (without)	2006 (with)	Effect 2006	2007 (without)	2007 (with)	Effect 2007
Fatalities	Neg. bin	13.04	3.67	9	12.03	3.39	9
Fatalities	Poisson	12.61	3.68	9	11.60	3.38	8
KSI	Neg. bin	199.00	115.98	83	190.43	110.99	79
KSI	Poisson	178.95	112.98	66	169.25	106.86	62

Table B.9*. Estimated effect in terms of crash counts of the transformation of intersections into roundabouts on crashes (fatal or killed or seriously injured (inpatient)) for both Poisson and negative binomial assumptions.*

Type	Distribution	2006 (without)	2006 (with)	Effect 2006	2007 (without)	2007 (with)	Effect 2007
Fatalities	Neg. bin	15.59	3.71	12	14.51	3.46	11
Fatalities	Poisson	15.40	3.71	12	14.31	3.45	11
KSI	Neg. bin	258.68	124.97	134	250.08	120.81	129
KSI	Poisson	222.17	120.46	102	211.22	114.52	97

Table B.10*. Estimated effect in terms of casualty counts of the transformation of intersections into roundabouts on casualties (fatal or killed or seriously injured (inpatient)) for both Poisson and negative binomial assumptions.*

Due to time constraints no further model variants have as yet been considered.

Appendix C Comparing with the development of the number of casualties on intersections

In a second approach the development of the number of casualties at locations that were converted into roundabouts during the study is compared to the development of the number of casualties at intersections.

To that end a reference group was taken consisting of intersections from the "NWB" which were not reconstructed into roundabouts and which existed for the whole period. These numbers are further referred to as $F_{I,\ ref}(t)$, the reference number of fatalities on intersections in year *t*. *Figure C.1* shows the development of the number of fatalities at these intersections.

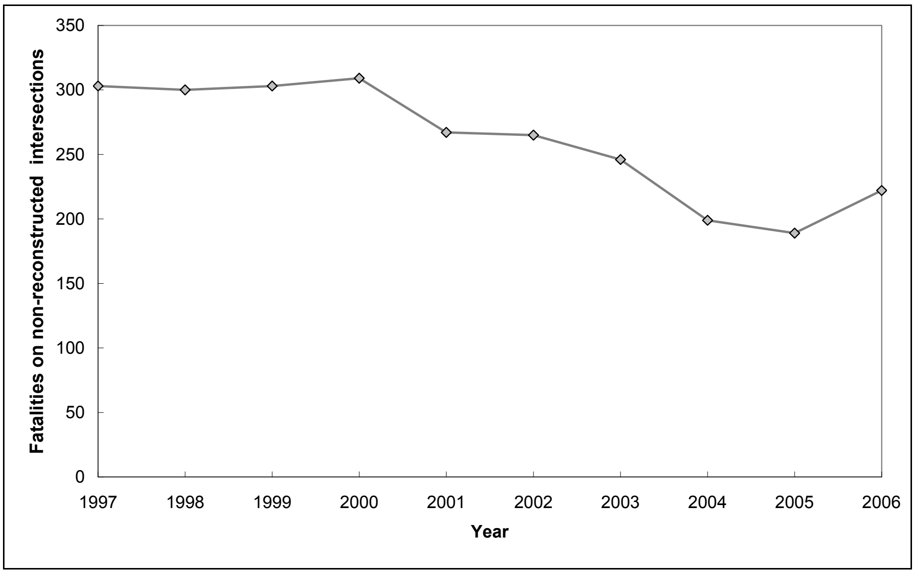

Figure C.1. *The reference number of fatalities $F_{I,\ ref}(t)$, the number of fatalities at intersections that were not reconstructed into roundabouts.*

We then scale the time series of the number of fatalities on this reference set of intersections, to the number of fatalities at intersections that were reconstructed. These numbers are referred to as $F_{R,\ y,\ before}(t)$ and $F_{R,\ y,\ after}(t)$, for the number of fatalities at intersections reconstructed into roundabouts in a specific year '*y*', where '*before*' refers to before reconstruction and '*after*' refers to after reconstruction, and '*R*' refers to roundabouts. This procedure was used for sets of intersections reconstructed in the same year '*y*'. For each set we calculated a scaling factor $\alpha_{y,\ before}$ and a scaling factor $\alpha_{y,\ after}$, such that $\alpha_{y,\ before}$ x $F_{I,\ ref}\ (t)$ optimally predicts $F_{R,\ y,\ before}(t)$ using maximum likelihood.

To reduce the consequences of the potential early decrease in the number of crashes, we use the years until *t*=*y-2* only, the last year before reconstruction, and the reconstruction year are not used in the calculation. Other periods have been considered, but results are not reported here.

The same procedure is applied to $\alpha_{y, after}$.

Thus, for each reconstruction year y, the optimal scaling factor of the development number of fatalities at intersections before reconstruction is matched with the complementary scaling factor for after reconstruction. The ratio between those scaling factors, $\alpha_{y, after}/\alpha_{y,before}$ is calculated. This ratio indicates the relative reduction in the number of fatalities at intersections, after reconstruction into roundabouts.

As an example, *Figure C.2* shows how the reference number of fatalities at intersections is scaled so as to fit the number of fatalities on intersections, reconstructed into roundabouts in 1999, both before and after the reconstruction year 1999. The resulting values of the α's is:

$\alpha_{1999, before} = 0{,}0264$; $\alpha_{1999, after} = 0{,}0024$;

and the ratio $\alpha_{1999, after}/\alpha_{1999, before} = 0{,}09$; This ratio indicates the remaining fraction of fatalities, after reconstruction of an intersection. This ratio corresponds to a reduction factor that is equal to 1 minus this ratio.
The reduction also corresponds to an annual number of fatalities saved. This number is calculated by subtracting the values for $\alpha_{y, before}\, F_{I, ref}(t)$ and $\alpha_{y, after}\, F_{I, ref}(t)$.

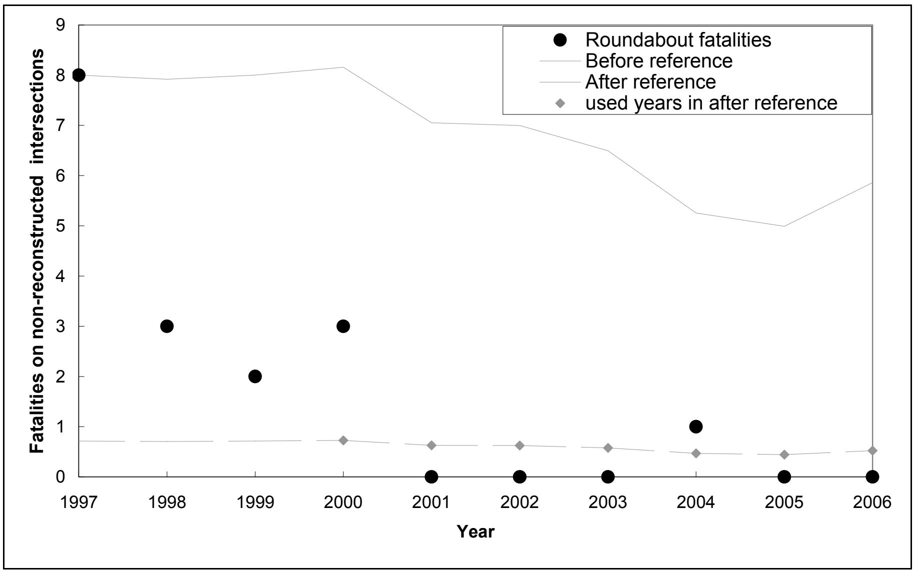

Figure C.2. *The number of fatalities at intersections that were reconstructed into roundabouts in 1999. The reference number of fatalities at intersections that were not reconstructed, is scaled to these numbers in the before period (until 1997) and in the after period (from 2000 onward).*

The resulting values for $\alpha_{1999, before}$, $\alpha_{1999, after}$, their ratio, and the contribution to the decrease in the annual number of fatalities in the Netherlands is given in *Table C.1*. The net ratio 0,48 is calculated as the mean ratio, weighted with the number of roundabouts reconstructed in each year. It corresponds to a reduction factor of 0,52.

Fatalities	Year of reconstruction								
	1999	2000	2001	2002	2003	2004	2005	Sum	Weighted mean
N	338	160	363	587	307	150	104	2,009	
Scaling factor before	0.0264	0.0017	0.0143	0.0255	0.0162	0.0063	0.0010		
Scaling factor after	0.0024	0.0014	0.0054	0.0047	0.0049	0.0000	0.0045		
Ratio = after/before	0.09	0.87	0.37	0.18	0.30	0.00	4.49		0.48
Reduction fatalities	-5.34	-0.05	-2.00	-4.63	-2.50	-1.40	0.78	-15.13	

Table C.1*. Overview of the parameters N (the number of roundabouts reconstructed in year y), $\alpha_{y, before}$, $\alpha_{y, after}$, the reduction factor ($\alpha_{y, after}/\alpha_{y, before}$), and the annual reduction (in 2006) due to these reconstructions, for the number of fatalities.*

Thus, based on this model, the net number of lives saved in 2006 as a result of the reconstruction of 2009 intersections into roundabouts between 1999 and 2005 is 15.

The same procedure was applied to the number of Killed or Seriously Injured (KSI), hospitalized casualties. There, the number of seriously injured on the set of non-reconstructed intersections, $KSI_{I, ref}(t)$, was used as a reference. These numbers are shown in *Figure C.3*.

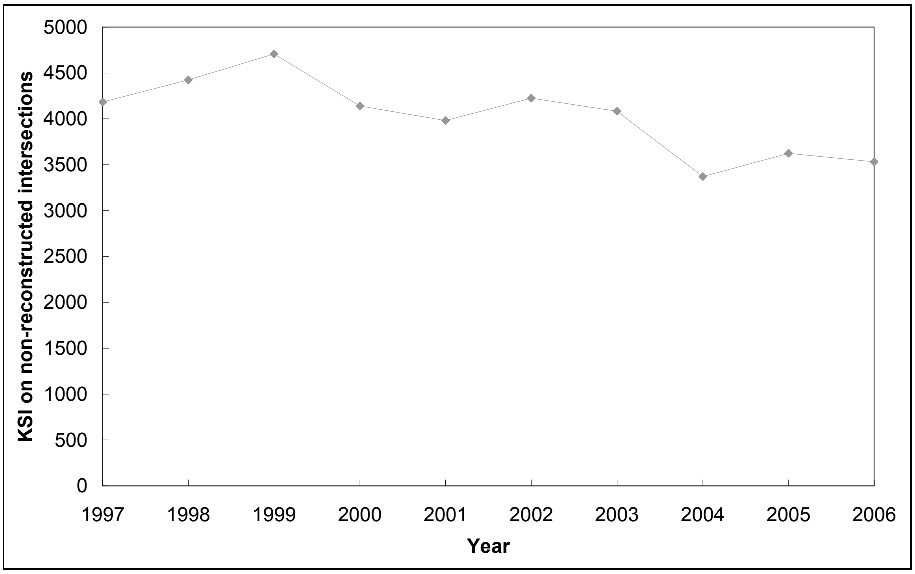

Figure C.3*. The reference number of KSI $K_{I, ref}(t)$, the number of fatalities on intersections that were not reconstructed into roundabouts.*

In a way exactly similar to the analysis of the reduction of the number of fatalities, we calculated the reduction in the number of KSI. *Table C.2* gives the result. It shows that the reconstructed roundabouts reduce the number of KSI by roughly a factor 0.51, resulting in a net 125 KSI saved in 2006.

KSI	Year of reconstruction								
	1999	2000	2001	2002	2003	2004	2005	Sum	Weighted mean
N	338	160	363	587	307	150	104	2,009	
Scaling factor before	0.0141	0.0048	0.0126	0.0230	0.0101	0.0039	0.0034		
Scaling factor after	0.0063	0.0022	0.0080	0.0112	0.0048	0.0025	0.0014		
Ratio = after/before	0.44	0.47	0.63	0.48	0.48	0.65	0.42		0.51
Reduction killed or seriously injured	-27.68	-8.93	-16.45	-41.96	-18.49	-4.88	-6.88	-125.25	

Table C.2. *Overview of the parameters N (the number of roundabouts reconstructed in year y), $\alpha_{y, before}$, $\alpha_{y, after}$, the reduction factor ($\alpha_{y, after}/\alpha_{y, before}$), and the yearly reduction (in 2006) due to these reconstructions, for the number of KSI.*