

What roundabout design provides the highest possible safety?

In Sweden, as in several other countries, the number of roundabouts is on the increase. According to a study recently carried out by the VTI, roundabouts with a maximum permissible speed of 50 km/h are typically safer for motorists than grade-separated intersections. Single-lane roundabouts can be just as safe for cyclists as other types of intersection, and for pedestrians they are perhaps safer than any other type.

At the beginning of the 1980s, there were only about 150 roundabouts in Sweden. Now, there are almost 1000, and within the next 10-year period the number may rise to at least 1500.

It has been known for some time that a roundabout is a very safe type of intersection, eliminating most serious injuries involving motor vehicle occupants. As far as the safety of vulnerable road users, i.e. cyclists and pedestrians, is concerned, earlier results were not as unambiguous and positive. There were worries, especially in regard to cyclists, that safety may even deteriorate as a result of introducing roundabouts. There were also different views on detail design and whether cyclists should be allowed to mix with motorists on the carriageway or segregated on separate cycle paths with special cycle crossings adjacent to the pedestrian crossings near the roundabouts.

In an endeavour to improve the state of knowledge in this field, VTI was commissioned by the Swedish Road Administration to study accident and injury risks at roundabouts with different layouts in different traffic environments.

Three different studies

According to a preliminary survey, there were about 700 roundabouts in Sweden in autumn 1997. All but 50 of these were surveyed in the field to classify them with respect to geometric design, speed level, etc.

Additional data on the number of accidents and the number of injured over the period 1994–1997, as well as the number of vehicles, cyclists and pedestrians passing through the roundabouts, were later collected for some of the roundabouts surveyed. Three studies were subsequently performed; speed analysis in 536 roundabouts, analysis of safety of cyclists and pedestrians in 72 roundabouts and analysis of motorist safety in 182 roundabouts.

In conjunction with the survey, one run was made to measure the speed towards, through and out of each roundabout. The run was performed slightly more aggressively than would be the case with a normal motorist. The objective was to obtain indirect measures of the factors (layout, regulation, etc) affecting safety at roundabouts.

Separate relationships for speed when entering, circulating in and exiting the roundabout were estimated using multiple non-linear regression analysis:

$$\text{Speed} = a \times b^{x_1} \times c^{x_2} \times d^{x_3} \times e^{x_4} \times \dots$$

where x_1, x_2, x_3, x_4 etc are dummies (0/1 variables) indicating different properties. The regression coefficients $b, c, d, e \dots$ show the estimated effects for each property.

The results obtained indicate the following:

- Speed is higher at a speed limit of 70 km/h than at 50 km/h, and higher when the general speed limit is higher than the local limit.
- Speed is on average higher if the roundabout has multiple lanes.
- Speed is *lower* if the radius of the central island is 10-20 m than if it is smaller or larger.
- Provision of additional trafficable area around the central island has no effect on speed.
- Flaring the approach to the left reduces speed into and through the roundabout.

The results appear in all respects to be very reasonable, and have also been found to be in very good agreement with the relationships obtained in the accident and injury analyses described below.

More accidents to cyclists if there is more than one lane

The pedestrian and cyclist (PC) analysis comprises 72 roundabouts, most of those which in the preliminary survey were judged to have at least 100 cyclists per day. At these 72 roundabouts, there were a total of 67 police reported accidents involving cyclists, 58 of which resulted in injury.





Single-lane roundabout with centre island radius 10-20 m reduces speed

ries, during the period 1994–1997. There were no fatalities in the accidents, but 10 persons had serious injuries and 48 slight injuries.

At 52 of the roundabouts, there were no accidents involving cyclists. Eight roundabouts account for 48 accidents to cyclists, with 9 serious and 32 slight injuries. Four of the roundabouts with the most accidents have two lanes, and at three roundabouts cyclists use the road without separate bicycle crossings.

Statistical processing entailed simple tabulations, correlation and regression analyses, etc. The factor which was initially found to have the greatest effect on the number of accidents involving cyclists, apart from the number of motor vehicles and cyclists, was the number of lanes. From then on, the accident material was therefore

treated separately for two-lane and single-lane roundabouts.

The observed numbers of accidents and injured are compared to predicted values according to previous VTI studies of “conventional” intersections, including those controlled by signals.

As can be seen in *Table 1*, at the two-lane roundabouts the total observed numbers of accidents and injuries are more than twice those predicted. For the single-lane roundabouts, on the other hand, there is very good agreement between the observed numbers of accidents and injuries and the predicted numbers.

The above prediction models for the number of bicycle (and pedestrian) accidents contain only the number of entering

motor vehicles and the number of crossing cyclists (and pedestrians) as explanatory variables. According to previous studies (of “conventional” or signal controlled intersections), these factors were found to explain almost the entire variation in the number of accidents, apart from the purely random variation.

According to the prediction models, for example, an intersection with 10,000 motor vehicles and 1000 crossing cyclists per day is expected to have approximately 0.2 bicycle accident annually, or in other words one bicycle accident every 5 years. For an intersection with an equal number of motor vehicles and 1000 pedestrians, the number of accidents involving pedestrians is expected to be half the above number.

No. of lanes	No. of roundabouts	Veh. per day, average	Cycles per day, average	No of accident years	Observed number of					Predicted number of				
					Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries	Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries
1 lane	58	11066	1075	163	28	24	0	5	19	35,7	30,2	0,1	9,6	19,5
≥ 2 lanes	14	23375	1397	53	39	34	0	5	29	19	16	0,3	5	9,9

* At least one leg with a PC crossing has two lanes

Table 1. Bicycle accidents at single-lane and two-lane* roundabouts.



It may be noted that no bicycle accidents have occurred at roundabouts which have the lowest number of both motor vehicles (< 10,000 per day) and cyclists (< 1000 per day). See *Table 2*.

Flow class	Veh. per day, average	Cycles per day, average	No. of roundabouts	No. of accident years	Observed No. of accidents	Pred. No. of accidents
Lower flows	6463	476	20	50	0	4.9
Larger flows	13488	1390	38	113	28	30.7

Table 2. Bicycle accidents at single-lane roundabouts with different flows.

Fewer bicycle accidents if radius of central island > 10 m and if there are special bicycle crossings

Regression analyses concerning single-lane roundabouts indicate that a central island radius (including any additional trafficable area around the central island) >10 m is most beneficial for reducing the number of bicycle accidents. This is also shown by *Table 3*. In addition, roundabouts with

Radius of central island	Veh. per day, average	Cycles per day, average	No. of roundabouts	No. of accident years	Observed No. of accidents	Pred. No. of accidents
< 10 m	9464	1050	30	87	19	18.4
> 10 m	12782	1101	28	76	9	17.2

Table 3 Bicycle accidents at single-lane roundabouts of different radii.

a central island radius greater than 10 m have both a lower number of bicycle accidents per year and a lower bicycle accident rate (number of bicycle accidents per million crossing cyclists).

The regression analysis indicates that for cyclists it is safer to bypass a roundabout on a bicycle crossing than to travel on the carriageway. Nine of the 58 single-lane roundabouts can be characterised as “cyclists mainly on the carriageway”. These nine roundabouts account for 15 of the total 28 accidents (see *Table 4*). These raw numbers also indicate that cyclists face a greater risk when travelling through a roundabout on the carriageway.

Overall, at single-lane roundabouts there were 18 accidents involving cyclists on the carriageway and 10 accidents with cyclists on a bicycle crossing. At the same time, the total number of cyclists bypassing the roundabouts on a bicycle crossing

is about 1.7 times the number travelling through them on the carriageway. If we construct the risk index as “No. of accidents per the sum of the products no. of motor vehicles x no. of cyclists”, the risk

is about 2.5 times greater for cyclists on the carriageway than for cyclists on a bicycle crossing.

Location of bicycle crossings?

An issue that is often discussed is what distance is desirable between the bicycle crossing and the roundabout itself. The study provides no answer to this. According to earlier VTI studies concerning “con-

ventional” or signal controlled crossings, however, there are indications that a distance of approximately 2-5 m might be the best. The entering motorist would then as a first stage be able to pay attention to cyclists on the crossing, and in the second stage he would have space beyond the bicycle crossing to give way to vehicles on the roundabout. However, this should be investigated further.

Cyclists travelling on	Veh. per day, average	Cyclists per day, average	No. of roundabouts	No. of accident years	Observed No. of accidents	Pred. No. of accidents
Bicycle crossing	10478	1011	49	134	13	26.9
Carriageway	14268	1422	9	29	15	8.6

Table 4. Bicycle accidents at single-lane roundabouts with cyclists on bicycle crossings and on the carriageway.

Safe for pedestrians, particularly at single-lane roundabouts

Table 5 (see page 20) sets out the observed and predicted numbers of accidents and injuries involving pedestrians. Overall, during the investigation period there were 15 pedestrian accidents with one killed, 2 seriously injured and 10 slightly injured. Twelve of the accidents occurred at the two-lane roundabouts and only 3 on single-lane roundabouts.

For the two-lane roundabouts, there is almost perfect agreement between the observed and predicted values. For the single-lane roundabouts, however, the observed values are substantially (3-4 times) lower than those predicted.

The results suggest that roundabouts pose no problems for pedestrians compared to “conventional” or signal controlled intersections. The results also clearly show that for pedestrians single-lane roundabouts are much safer than two-lane roundabouts.

Accidents involving motor vehicles

During the period 1994–1997 (a total of 563 accident years) the 182 roundabouts studied had a total of 456 police reported accidents involving motor vehicles only, of which 88 (19%) resulted in injuries. There were no fatalities in these accidents, but 17 persons (15%) sustained serious injuries and 93 (85%) slight injuries.

The material is dominated by roundabouts in the half-central or outer areas of towns. They typically have four legs and a posted speed limit of 50 km/h, but there are also about twenty roundabouts in the countryside where the speed limit on some approaches is 70 km/h. Half the roundabouts have more than 10,000 entering motor vehicles per day. The largest number is 44,500. More than 10 roundabouts have more than 25,000 entering motor vehicles per day.



Traffic volume and speed have the greatest influence on accidents

The factors which usually have the greatest influence on the numbers of accidents and injured, given a certain type of intersection, are the volume of traffic and the speed of vehicles. When it comes to accident rate and injury rate (numbers of accidents and injured per million entering vehicles) the volume of traffic obviously has less effect since these indices are already normalised with respect to the volume of traffic.

The regression equations drawn up for accident rate and injury rate use the factors

No. of lanes	No. of roundabouts	Veh. per day, ave.	Pedestrians per day, ave.	No. of accident years	Observed number of					Predicted number of				
					Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries	Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries
1 lane	58	11066	486	163	3	2	0	0	2	11,2	9,3	0	2,3	5,7
≥ 2 lanes	14	23375	1338	53	12	10	1	2	8	10,4	8,9	0,1	2,8	6

* At least one leg with a PC crossing has two lanes

Table 5. Pedestrian accidents at single-lane and two-lane* roundabouts.

“total number of entering motor vehicles per day” and the speeds measured when entering, circulating and exiting the 182 roundabouts surveyed.

The results are in very good agreement with previous investigations. The number of accidents is directly proportional to speed, while the number of injured has an even greater and more quadratic relationship with speed. The accident and injury rates exhibit a slight positive relationship with total traffic. The fact that this relationship is weak for roundabouts compared to intersections is also in good agreement with previous results.

The lower the speed limit, the lower the risk and the number of injured per accident

Table 6 further bears out the significance of speed for accident risk and the number of injured per accident at roundabouts. In the table, a breakdown has been made by the highest local speed limit on the roundabout and also the highest general speed limit within 600 m of the roundabout. It is evident from the table that the risk of injury and the number of injured are greatly influenced by both the local and the gen-

eral speed limit. It should be noted that the safe travelling speed through a roundabout may be lower than the posted speed limit. Recommended speeds are not posted in Sweden.

Radius of 10-25 m best?

The introductory simple tabulations showed that the factors most likely to influence accident rate and injury rate are speed, number of legs, number of lanes and radius. Here, the term “radius” denotes the radius of the central island itself, including any additional trafficable area

greater than about 25 m, are the most dangerous, but the pattern is fragmented. The reason seems to be that the larger the radius, the more often there is a speed limit of 70 km/h and two lanes. It is likely that there is an optimum situation with the lowest accident and injury risks for radii somewhere between 10 and 25 m. A shorter radius than 10 m often gives a “straight” driving path for straight through traffic with potentially high travel speeds. A very long radius also gives a straighter path than a moderate radius.

around this. The results indicate that the accident and injury rates are higher if the speed limit is 70 km/h, if there are four legs, if there are two lanes and if the radius is very large.

Analyses at greater depth in which several factors were considered at the same time have shown that it is primarily the factor 50 or 70 km/h that explains the differences in risk, and possibly also the factors 3 or 4 legs and the number of lanes. As regards the radius, there appear to be indications that the very largest radii,

New prediction model

Several approaches were tested in constructing new prediction models or standard values for accident rate, number of injured per accident and injury rate. The model finally chosen for the accident rate is as follows:

$$\text{Predicted accident rate} = 0.1353 \times 0.86^{3leg} \times 1.88^{speed70} \times 1.20^{2lanes}$$

where the dummy variables *3leg*, *speed70* and *2lanes* are equal to 1 if there are three legs (0 if there are four), if the maximum

Speed limit, local	Speed limit, general	No. of roundabouts	Accident rate*	No. of injured per accident	Injury rate**
50	50	81	0.15	0.12	0.018
50	70	49	0.17	0.23	0.039
50	90	20	0.18	0.43	0.078
70	70	14	0.17	0.28	0.047
70	90	16	0.27	0.38	0.103
70	110	2	0.46	0.35	0.162
Totals		182	0.17	0.24	0.041

* Number of accidents per million entering vehicles
 ** Number of injured per million entering vehicles

Table 6. Accident rate, number of injured per accident and injury rate for different speeds.



local speed limit is 70 km/h (0 if 50 km/h) and if there are two lanes on the roundabout (0 if there is one). According to estimated regression coefficients, the accident rate is reduced by about 14% if there are three legs, increased by about 88% if the maximum local speed limit is 70 km/h, and increased by about 20% if there are two lanes on the roundabout. The speed factor is the only significant variable. The coefficient of determination with respect to the number of accidents is below 55%.

Alternatively, the following model, which is somewhat more complicated for practical purposes but has a somewhat better coefficient of determination, might be used:

$$\text{Alt. predicted accident rate} = 0.1130 \times 0.92^{3\text{legs}} \times 1.84^{\text{speed}70} \times 1.40^{\text{loclow}} \times 1.17^{2\text{lanes}}$$

The dummy variable *loclow* is equal to 1 if the maximum general speed limit within 600 m of the roundabout is higher than the local maximum speed limit. According to this prediction model, the accident rate increases by about 40% if the general speed limit is higher than the local limit.

Designing a prediction model for injury rate is much more difficult. The number of injured is only a quarter of the number of accidents, and also has a larger random spread in relative terms. In view of this, it

was decided to build a prediction model for injury rate in a slightly different way. The observed injury rates were quite simply fitted to a function of the predicted accident rate. The level was fitted to the function with a multiplicative factor and the dispersion with an exponential factor. The following results were obtained:

$$\text{Predicted injury rate} = 0.8178 \times (\text{Predicted accident rate})^{1.6871}$$

$$\text{Alt. Predicted injury rate} = 0.7215 \times (\text{Alt. Predicted accident rate})^{1.6119}$$

The coefficients of determination for the number of injured are just below, and just above, 40%.

The predicted number of injured per accident is obtained by simply dividing the predicted injury rate by the predicted accident rate – or by first predicting the number of injured and the number of accidents, and performing the division.

Safer than a grade-separated intersection

Table 7 sets out a number of comparisons between the expected numbers of accidents and injured in one year at roundabouts and at grade-separated intersections.

A comparison is first made for an intersection with four legs in a “town outer area”, with 10,000 motor vehicles entering

per day, of which 30% is secondary road traffic. The general speed limit is assumed to be 70 km/h. The roundabout is assumed to have one lane. The roundabout is further assumed to have a local speed limit of 50 km/h, while the grade-separated intersection maintains a limit of 70 km/h.

In the second case, the comparison is made for an intersection in the countryside, with 5000 motor vehicles entering per day, of which 20% is secondary traffic. The general speed limit is assumed to be 90 km/h. The roundabout is assumed to have one lane and to have a speed limit of either 50 or 70 km/h. The grade-separated intersection is assumed to have a speed limit of either 70 or 90 km/h.

As seen in the above comparisons, from the traffic safety standpoint a roundabout is even somewhat better than a grade-separated intersection, at least if it is assumed that a speed higher than 50 km/h is not permitted locally on the roundabout.

For an average roundabout, with 10,000 motor vehicles entering per day and 30% secondary road traffic, it may be expected that there will be one police reported accident every 2 years, one injured person every 10 years and one seriously injured person every 50 years – and practically never any fatalities.

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Photographs: Cover illustrations for the two VTI Bulletins

Type of intersection	General speed limit	Local speed limit	Motor vehicles entering per day	Percentage of secondary road traffic	Pred. no. of accidents	Pred. no. of injured	Pred. no. of seriously injured or killed***
Roundabout*	70	50	10 000	0.30	0.49	0.10	0.015
Roundabout**	70	50	10 000	0.30	0.58	0.13	0.020
Grade sep.	70	70	10 000	0.30	0.51	0.16	0.032
Roundabout*	90	50	5 000	0.20	0.25	0.05	0.008
Roundabout*	90	70	5 000	0.20	0.46	0.15	0.022
Roundabout**	90	50	5 000	0.20	0.29	0.07	0.010
Roundabout**	90	70	5 000	0.20	0.53	0.18	0.027
Grade sep.	90	70	5 000	0.20	0.23	0.08	0.016
Grade sep.	90	90	5 000	0.20	0.26	0.10	0.020

* Single-lane roundabout
 ** Single-lane roundabout (alternative prediction model)
 *** For roundabouts, the percentage of seriously injured or killed is assumed to be 15%

Table 7. Comparison between expected numbers of accidents and injured in one year at a roundabout and at a grade-separated intersection.