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Signal Control of Roundabouts

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Abstract

During the last decade many traffic signal controlled intersections have been replaced by roundabouts. There has been a trend towards the establishment of roundabouts where pedestrians and cyclists need to be considered specifically, sometimes by including one or more signal controlled crosswalks. Knowledge on adequate design, control and effects of different solutions, particularly with accessibility and traffic safety in mind, has been limited in Sweden. This lack of knowledge was the basis for a project in 2007 financed by the Swedish National Road Administration and which was divided into two parts.
In the first part an inventory of available knowledge on signal controlled roundabouts both in Sweden and abroad was carried out.
The following alternative forms of signal control were determined for the projects aspects:
A1: Signal controlled crosswalks at the approach and in the direct vicinity of the gyratory (off signal).
A2: Signal control of crosswalks at the approach up- and downstream.
B1: Complete signal control of an approach. The crosswalks on both directions are passed in a single step.
B2: Complete signal control of an approach. The crosswalks are passed in two steps (with intermediate stops).
C: Coordinated, fully signal control of the roundabout.
In the second part of the project accessibility analysis for the different alternatives was carried out with the help of field studies and calculations using the traffic modeling tool TRANSYT for signal optimization and VISSIM for evaluation of the effects. The traffic safety aspects were analyzed with the aid of specific interviews with the regulatory organizations, accident statistics from STRADA (Swedish Traffic Accident Data Acquisition) and field studies of traffic behavior at two roundabout locations.
The project concluded following recommendations regarding accessibility and safety:
• Alternative (A1) should be avoided from both a capacity and a traffic safety aspect. Use B.
• Alternative (A2) should be placed a minimum of 22 m from the roundabout due to both capacity and a traffic safety aspects.
• Alternative (B2), which has higher capacity than (B1) can be applied if there is a need for signalized crosswalks.
• Alternative (C) can be considered due to capacity constraints at high pedestrians' flow of several approaches

Keywords: Signalized roundabout; Crosswalks; Delay; TRANSYT; VISSIM; STRADA

1. Introduction

1.1 Background

During the last decade intersections with traffic signals have been replaced with roundabouts along major roads. In urban areas there is a demand for roundabouts which have to be designed considering pedestrians, cyclists and sometimes bus priority needs. One of the solutions to this problem is to install signals at one or more crosswalks, which limits blocking of vehicle movements to red time only. Another solution is to install coordinated

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signal control in all the approaches and at the crosswalks to avoid blocking the circulating streams. There is a need to improve the knowledge concerning suitable design and control and the effects of different solutions.

The project Signal Control of Roundabouts was initiated by professor em. Karl-Lennart Bang, KTH and Ramböll and financed by Swedish Road Administration (VV), with the purpose to scan available knowledge and to carry out data collection and study road-user behaviour and traffic impacts. The project should also support the development of user manuals and recommendations in the form of "Guidelines for design and signal control of roundabouts" (VGU).

1.2 Scope and methodology

The work included the following steps:

- Inventory of available knowledge about traffic signals in roundabouts with focus on geometry, traffic flow, type of signal control, and the results of empirical impact studies.
- Determination of criteria and data-collection for evaluation of traffic signals in roundabouts with and without pedestrians.
- Selection of roundabouts for field study and data collection of traffic behaviour and impacts, which have been used as input data for simulation trials.
- Analysis and synthesis of the results compared with practical experiences and accident statistics from STRADA.
- Using TRANSYT 13 to optimise coordinated signal timing,
- Using VISSIM 5 to evaluate and compare the impacts of different types of signal controlled roundabouts including crosswalks,
- Recommendations for Road Design Manual (VGU) about application of traffic signals in roundabout, as well as the needs for further studies.

2. Inventory of international knowledge

In this study an international state-of-the-art was conducted concerning design and control of signal regulated roundabouts. This state-of-the-art shows that there are large variations between countries and how they handle signalized roundabouts. A short summary follows.

2.1. Advantages with signal control of roundabouts

There are several advantages with signal control of roundabout according to Brown (1995) and Stevens (2005). With the aid of the signals the delay can be more balanced in the roundabout and to decrease the delay in coordinated networks through balancing flows and give the possibility for bus priority. By using signals for metering, the queues can be handled and prevent that they block for example nearby intersections. In addition the guide FHWA points out that signals may be used where “disabled pedestrians and/or school children are present at high volume (Inman and Davis, 2007).

2.2. Different types of signal control

According to Natalizio (2005) and Stevens (2005) the two main signal controls of roundabouts are: *direct control* and *indirect control*. *Direct control* rules both external and internal links in a roundabout while *indirect control* rules only the inflows to the roundabout. The roundabout can either get *full* or *partial signal control* and signals can either be used permanently or during part-time.

2.3. Criterion for using signals at roundabouts

The FHWA guide points that the fully signalized roundabouts must meet geometric design criteria that are very different from recommended designs for unsignalized roundabouts (Robinson, et alder. 2000). In the Netherlands signalized roundabouts are only constructed when there is sufficient space to store vehicles in the circulatory roadway. A signalized roundabout is considered only when a signalized intersection does not provide sufficient capacity (Fortuijn and Carton, 2005).

Signals in U.K. were installed at roundabout crosswalks to improve vehicle operations, rather than to provide pedestrian access (Inman and Davis, 2007). According to Guichet (2005) the new French guidelines for urban intersections indicate that roundabouts may be signalized for pedestrian safety under the following conditions

- There is a pedestrian island that provides adequate pedestrian refuge between the two directions of vehicle travel.
- The crosswalks are at least 15 m from the circular roadway and are offset.

2.4. Number of signal lens at the crosswalks

U.K. standard is three-lens signals (i.e., red, amber, and green lenses) near to the circular roadway. While in Australia the two-lens (amber and red) signals begins with flash amber, then goes to solid amber, and then to red. When not active, the signals are unlit (off) at the roundabout entrance, this avoids the confusion drivers might experience, if they received a green signal only a few meters upstream of the yield control (Baranowski, 2004).

2.5. Distance to the circular roadway

The FHWA guide suggests that crosswalks need to be 20 to 50 m from the yield line to avoid queues of exiting vehicles backing up from the crosswalk signal into the circulatory roadway (Robinson, et al. 2000).

In U.K. the addition of signals only 7 to 10 meters upstream of the yield line. This is according to Barry Crown, previously conducted research for the Transportation Research Laboratory (TRL), as drivers are accustomed to the priority of circulating vehicles at roundabouts and they do not be confused (Inman and Davis, 2007).

In France crosswalks have been moved, in some cases, to be adjacent to the circular roadway. But the new guidelines indicate that the crosswalks are at least 15 m from the circular roadway (Guichet, 2005).

2.6. Flared entries and exits

The flared design is intended to increase roundabout vehicle capacity. Where at-grade crosswalks are included, they are to be placed away from flared entries or exits (Brown, 1995). Figure 1 illustrates the difference between the typical U.S. design and the U.K. practice.

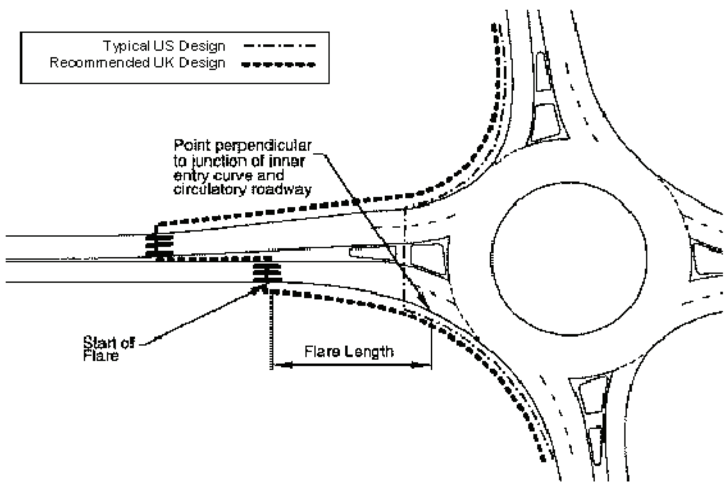

Figure 1 Explanation of flared entry and exit geometry (Brown, 1995)

2.7. Offset crosswalks

Offset of the crosswalks for the two directions of travel are recommended in U.K and France (Figure 1), but not in Australia. When signals are installed, the length of the red phase can be reduced by more than half by signaling the two halves of the crossing separately. The shortened red phases also minimize the chance of block back. To prevent pedestrians from continuing across the splitter island and into the lane that is not stopped, guardrails are installed to force pedestrians to use the offset crosswalk.

2.8. Empirical safety study

A study of 36 months of before and after safety analysis of 20 signalized roundabouts has been carried out in London. It was found that signalization of "standard" roundabouts resulted in a 28 % decrease in crashes, which was statistically reliable at the 0.01 level. The largest crash reductions were for bicycle involvement 58 % and for merge collisions 58%. The reduction in pedestrian involved crashes 23 % was not statistically reliable (TLSM, 2005).

3. The projects classification of signalized roundabouts

Signalized roundabouts were classified for the purpose of this project in three main types:

3.1. Type A: Signal control of crosswalks (Indirect Control)

One or more crosswalks on the roundabouts legs: The movements through the roundabout take place under the usual rules of "Inside priority" (giveaway). Type A is divided into two subgroups, lit and unlit signal (part-time) (see Figure 2):

- Type A1, Off signal (near to the roundabout)
If a crosswalk is located close to the roundabout the signal does not display the green to avoid confusing drivers, if they received a green signal only a few meters upstream of the yield control.

- Type A2, On signal (far from the roundabout)
If a crosswalk is located far enough from the roundabout, the signal may show green set.

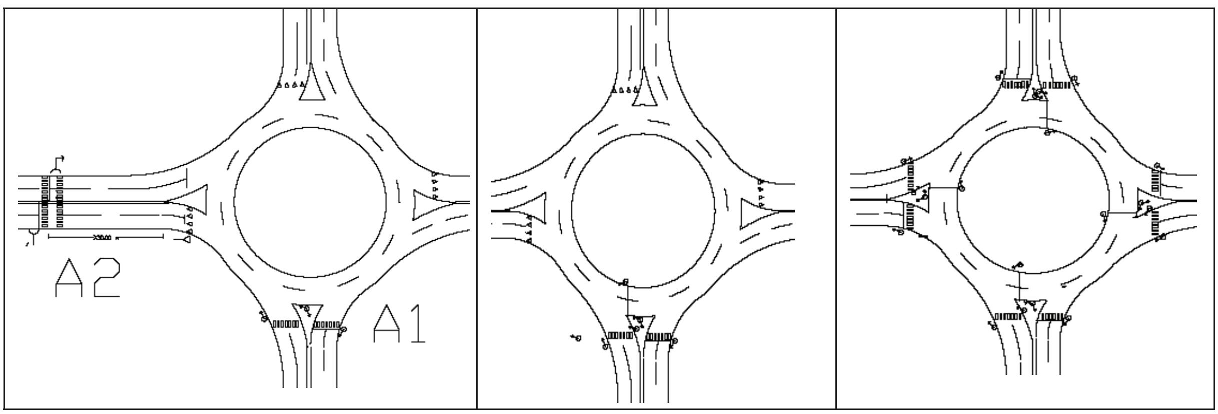

Figure 2 Signal controlled types A1, A2, B (in the middle) and C (to the right)

3.2. Type B: Complete signal control of one or two legs (Direct Control)

One or two legs of the roundabout are fully signalized with the stop line in circulation, while the conflict between the circulating traffic and the second legs are regulated with giveaway in favour of the circulating streams (Figure 2). The B types included two subtypes:

- Type B1 means that the signalized crosswalks can be passed by pedestrians in one step (no gating);
- Type B2 means that the signalized crosswalks can be passed by pedestrians in two steps (gating).

3.3. Type C: fully signalized roundabouts (Direct Control)

In roundabouts with signal control type C circulating traffic streams do not follow the standard rules of "Inside priority". Such signalized roundabouts may act as unsignalized roundabouts at certain times of day (off peak) and signalized roundabouts at other times (peak times).

A variation on the signal controlled roundabouts is to allow traffic in one direction to pass straight through the roundabout. This design has some advantages, but does not allow that the signal is switched off at certain times of day. This special case has not been studied in this project Lyssna.

4. Accessibility / capacity study

The impacts of different types of signal control at a roundabout has been studied by means of computer programs TRANSYT and VISSIM, calibrated with the aid of those in Part 1 completed field measurements (Kusuma, 2009). The analyzed roundabout models for cases A, B and C were based on basic determined data, which is listed below.

4.1. Basic data

Analyses have been carried out with the following assumptions of design and traffic volumes:

- Design: 4 legs roundabout, 20 m inner radius, two lanes everywhere;
- Traffic flow: 800-3200 pcu, the optimization of signal times was elected at 2400 pcu;
- Traffic distribution: 60% in the main road and 40% in the secondary road;
- Traffic movements: 70% straight, 15% right and 15% left;
- Pedestrians: 100 p/h applies to all crosswalks.

4.2. Impacts criteria

A separate study on the impacts criteria has been made where the average delay for pedestrians and for vehicles is proposed as a criterion in the evaluation of different types of signal control of roundabout. The average delays have been measured as mentioned below:

• Vehicle average delay (s/pcu) were measured for three components
  - Whole of the roundabout (including in, out and circulating streams);
  - The approach with crosswalk (main road);
  - The upstream left adjacent approach (secondary road).

• Pedestrian average delay has been measured for fixed time and push-button signal control.

4.3. Calibration of approach capacity in TRANSYT

TRANSYT (TRL, 2009) determines the capacity of yielding approaches by linear module. For one lane of a roundabout the equation in TRANSYT is:

Ca = Co - (A * Vc)

where Ca = capacity, Co = Maximum capacity (when the current conflict is zero) and A = factor for the capacity reduction. While the HCM (TRB, 2000) uses an exponential module with the following function:

$$c_a = \frac{v_c e^{-v_c t_c / 3600}}{1 - e^{-v_c t_f / 3600}}$$

where

c_a = approach capacity (veh/h),
v_c = conflicting circulating traffic (veh/h),
t_c = critical gap (s), and
t_f = follow-up time (s).

The capacity is affected by the critical gap (tc) and follow-up (tf) times as well as the circulating flow rate (Vc). By adjusting the linear of TRANSYT to be near the curve of HCM, it resulted in the following formula:

Ca = 950 - 0.65 Vc

This is resulted in better adaptation to real conditions as in the figure below:

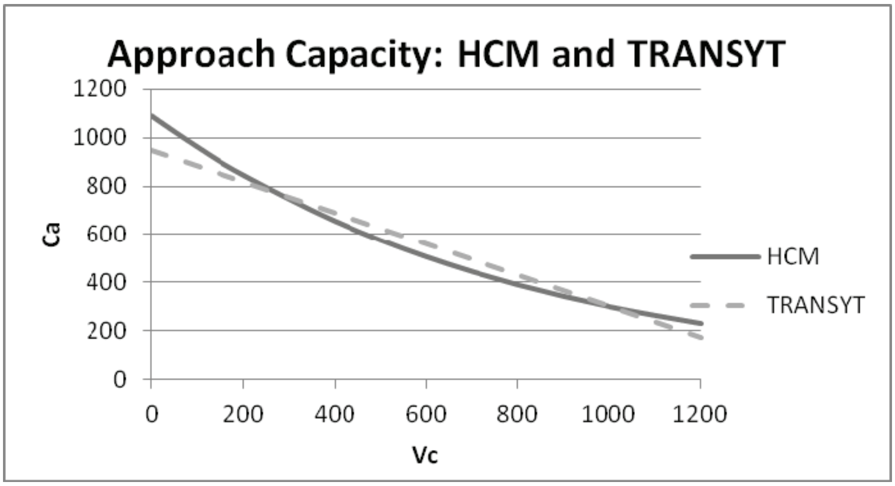

Figure 3 Adjustment of the approach capacity in TRANSYT with HCM

4.4. *TRANSYT runs*

Optimized cycle times results by TRANSYT were about 60 s for all types of signalized roundabouts. Below is an example of the signal timing of type C. 14 s green time allocated to the approaches and the rest to the exits (see Figure 4). Pedestrians pass in two steps (gating).

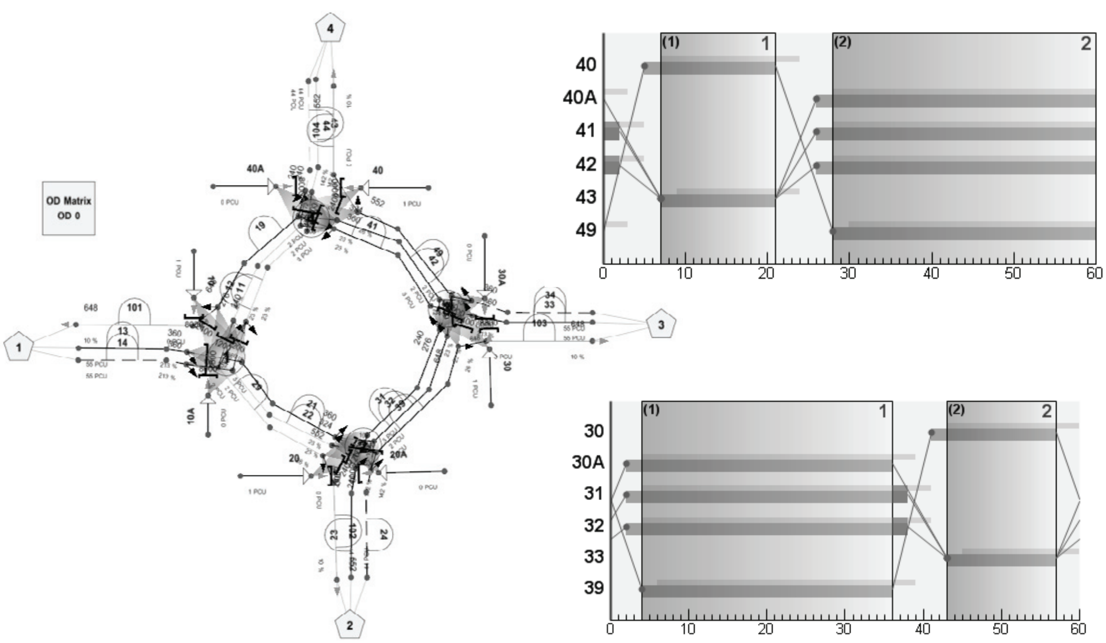

Figure 4: TRANSYT model and signal timing of type C

4.5. VISSIM Simulations

VISSIM runs were used to analyze the relationship between delay and traffic volumes for different types of signal controlled roundabouts. The model was calibrated and validated by using field data (Kusuma, 2009). Conflict Areas module in Vissim has been used instead of priority rules to obtain better model using observational assessment.

Signal control options: With the same basic data that was used in TRANSYT, signal options that have been studied in VISSIM were:

- Unsignalized roundabout as a Reference case;
- Fixed time signal controlled crosswalks;
- Push-button activation for pedestrians;
- Coordination (applies to Type C).

Circulation time 60 seconds has been chosen for all the studied alternatives as a result of TRANSYT runs, which optimized to the traffic volume of 2400 pcu. For the options with type A1 the cycle time is 60 s, green time for the pedestrians was 16 s and for the vehicle was 32 s. In case A2, only 14 s was used for the pedestrians due to shorter crossing. An example of the applications in Vissim from type C is shown below:

Type C (Full signalized roundabout)

For signal coordination the signal times were based on TRANSYT-runs and adjusted by optimizing the simulation results of the VISSIM through many trials (trial and error). The cycle time was 60 s, and green time for the main road approaches was 14 s and for the secondary road approaches 10 s. The remaining green time used for the circulating flows (Figure 5).

The method used is a controller with 10 signal groups where the groups are coordinated with similar conditions as in a junction, i.e. discharge of the main road and secondary road separately with intermediate "emptying" of the circulating streams before and after the approaches. Signal Times Table in Figure 5 is an adjustment of the TRANSYT results.

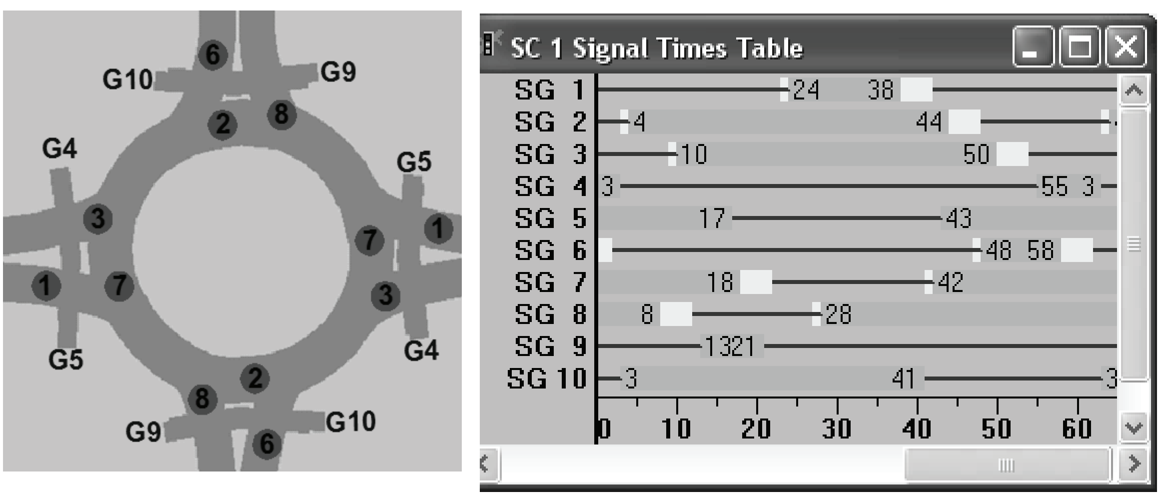

Figure 5 Signal groups and signal times table of full signalized roundabout in Vissim

4.6. Average delay of all types signalized roundabouts (A, B, and C)

Figures 6 & 7 show average delays up to 60 seconds (= one cycle time) and total traffic volume up to 3200 pcu/h to make it easier to compare results of different cases and types.

The graphs below show the comparative relationship between average delay time and total traffic volume for the different types of signal controlled roundabouts. The "Knee" in the delay curve is the point corresponding to the full degree of saturation = 1.0 (Volume to Capacity V/C). At higher flows, the roundabout will be congested and delay increases exponentially, especially for the approach with signal controlled crosswalk.

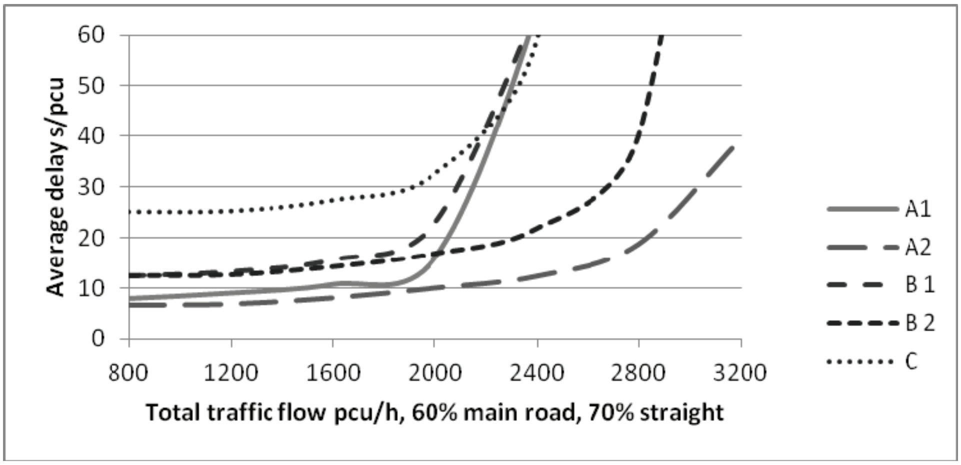

Figure 6 Relationship between traffic volume and average delay in the roundabout for all types of control

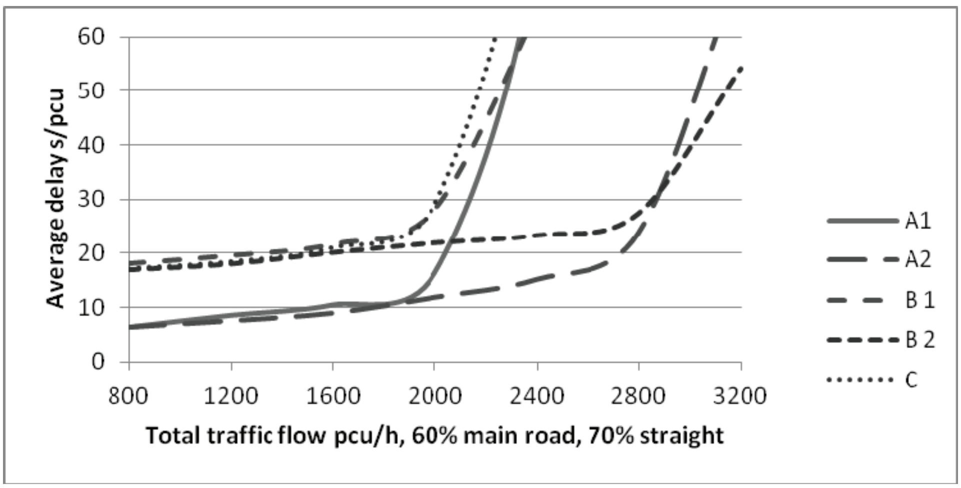

Figure 7 Relationship between traffic volume and average delay time for signal-controlled main approach for all types of signal control

The roughly results from simulation are summarized in Table 1:

Table 1 Simulation capacity and delay results

Roundabout type	Capacity pcu/h (V/C=1)	Pedestrian average delay s/p - main road	Pedestrian average delay s/p - secondary road
A1	2000	13.5	
A2	2800	14	
B1	2000	15	
B2	2800	28	
C	2000	21.5	24.5

5. Traffic safety study

The traffic safety study has been conducted with following work packages:

- Interviews with road authorities focus on function, design and experiences.
- Data analyzes of traffic safety for signalized roundabouts from STRADA (the national administrations data base for accidents).
- Field study of 2 signalized roundabouts.

The number of signalized roundabouts is fairly low in Sweden. The total number is 57. They are normally found in areas with high flow of pedestrians and vehicles. 37 of 57 signalized roundabouts are placed in Stockholm County. In Stockholm the main reason for this solution is capacity for vehicles but in the rest of Sweden the main reason are traffic safety and priority of bus and trams.

The signalization of roundabouts with pedestrian activation shows much different and potentially dangerous behaviour both for pedestrians and vehicles. When the signal is unlit (part-time, off) and "normal" giveaway rules apply, the vehicles show little acceptance for giveaway to pedestrians. This shows a big difference between normal signalization and "unlit" part-time signal.

The two field studies show that unlit part-time signals that have to be activated by pedestrians should be avoided. The analyze of traffic safety data shows that signalized roundabouts does not solve the problem with accidents. It is a big difference in accident rates between Stockholm and the rest of the country. In Stockholm this design has more accidents than the normal baseline. The baseline is given by Swedish Road Administration model for anticipated accidents in junctions (EVA). Perhaps is this difference between Stockholm and the rest of the country an outcome of the much higher volumes of pedestrians in Stockholm, the EVA model doesn't take into account the big differences between the flow of pedestrians in big cites. In the rest of the country the outcome of accidents compares fairly well to the anticipated number. We conclude that when the number of pedestrians is high this solution must be discussed in detail and compared to other solutions.

Table 2 A comparative analyze between accidents from STRADA with anticipated from EVA (the Swedish Road Administration method for anticipated accidents). Acc = accidents, SigRd =signalized roundabouts, SigInt = Sinalized Intersection, Others = outside of Stockholm county

	STRADA						EVA	
	Total Sweden	Total Stockholm	Total Others	Acc/SigRd Sweden	Acc/SigRd Stockholm	Acc/SigRd Others	Rd	SigInt
Death	7	5	2	0.015	0.018	0.007	0.004	0.009
Severe Injured	122	110	12	0.27	0.39	0.043	0.08	0.133
Injured	588	474	114	1.29	1.69	0.41	0.35	0.57

6. Recommendations regarding traffic performance and safety

Recommendations regarding accessibility and safety:

• Alternative (A1) should be avoided from both a capacity and a traffic safety aspect. Use B.
• Alternative (A2) should be placed a minimum of 22 m from the roundabout due to both capacity and a traffic safety aspects.
• Alternative (B2), which has higher capacity than (B1) can be applied if there is a need for signalized crosswalks.
• Alternative (C) can be considered due to capacity constraints at high pedestrians' flow of several approaches.

7. Further research

The project has studied signalized roundabouts from the very limited state of knowledge that existed in Sweden. The following needs for further research were identified:

a) Future studies should be made for several cases, particularly with regard to:

- varying flows for pedestrians;
- different flow distribution;
- compare with the traffic signal at the intersection;
- different signal diagrams and cycle times;
- environment as speed and geometry and number of lanes.

b) Detailed design of signalized roundabout should focus on the situation of vulnerable road users, for example, should gating and offset be studied.

c) Implementation and evaluation of the recommendation in some roundabouts through collaboration with road authorities.

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