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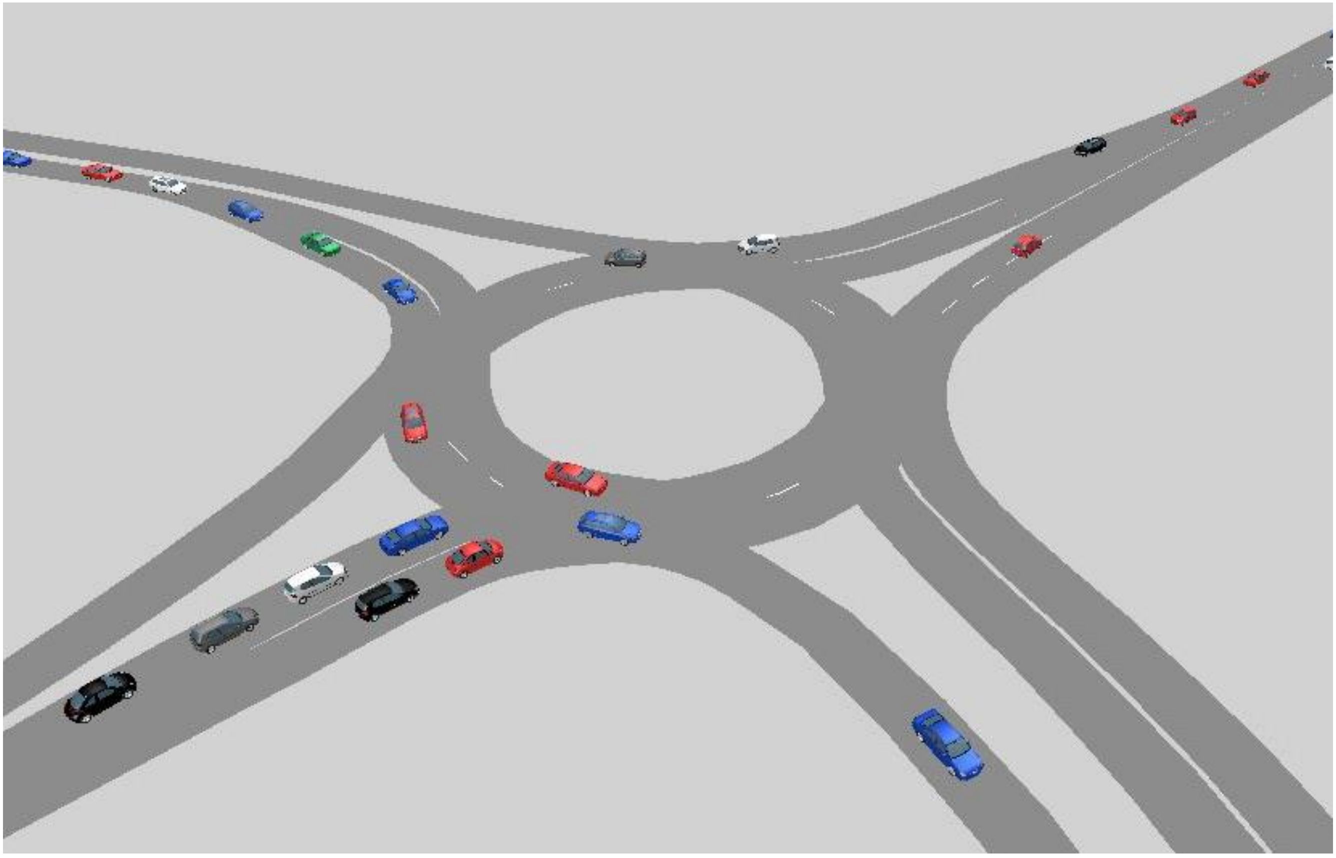

Micro simulation of roundabouts

An analysis of simulation parameters in Vissim

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

MIRIAM BRILL
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Simulation of a roundabout in the micro simulation program Vissim
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ABSTRACT

For the building or upgrading of intersections such as roundabouts it is necessary to provide accurate traffic simulations. One micro simulation program that can be used for the modelling of intersections is Vissim developed by PTV Group which provides two different methods to model the right of way: *priority rules* and *conflict areas.* It also provides default values for parameters describing the interaction of vehicles. This behaviour can however vary in reality depending on the characteristics of the facility. For more accurate traffic simulations it is therefore important to adjust the parameters depending on the given situation.

The aim of the study is to evaluate the correlation between observed data and simulation with default parameters for different types of roundabouts. Furthermore, recommendations for calibrated parameters shall be provided in order to achieve more accurate simulations.

For the comparison of reality and simulation results, suitable existing roundabouts with different characteristics were observed in the area of Gothenburg. For each roundabout two simulations with default parameters were performed first, one with *priority rules* and one with *conflict areas*. Secondly, stepwise tests were performed by altering the parameters. To give recommendations, a calibration of the parameters was performed. When applying the default values, better results are achieved with *priority rules* than with *conflict area*. The latter leads to an underestimation of the capacity. During the testing process the most significant changes could be seen when adjusting the parameters *minimum gap time* for *priority rules* and *safety distance factor* as well as *anticipate route* for *conflict areas.*

The general recommendation based on this study is to apply *conflict area* with adjusted parameters for simple roundabouts with one circulating lane (1/1). It leads to equally good results as *priority rules* and there is less risk of mistakes during the modelling process. The recommendation for complex roundabout with two circulating lanes is to use *priority rules.* For those with one ingoing lane (1/2) default values can be applied. For roundabouts with two ingoing lanes (2/2) it requires adjusted parameters.

Key words: micro simulation, roundabout, Vissim, PTV, conflict areas, priority rules

Mikrosimulering av cirkulationsplatser
En analys av simuleringsparametrar i Vissim

Examensarbete inom masterprogrammet Infrastructure and Environmental Engineering

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SAMMANFATTNING

Inför nybyggnad eller åtgärd av korsningar, så som cirkulationsplatser, är det viktigt att korrekta simuleringar utförs. Ett av simuleringsverktygen som används vid simulering av korsningar är Vissim som är utvecklat av PTV Group. Detta verktyg tillhandahåller två olika metoder för att reglera vem som ska lämna företräde i konfliktsituationer: *Priority rules* och *Conflict areas.* Till dessa metoder finns det standardvärden för de parametrar som beskriver interaktionen mellan fordonen. Detta beteende kan dock variera i verkligheten då detta är beroende av cirkulationsplatsens egenskaper. Det är därför viktigt att justera parametrarna beroende på situationen för att få korrekta resultat.

Syftet med denna studie är att utvärdera korrelationen mellan observerad data och simulerad data med standardvärden för olika typer av cirkulationsplatser. Vidare skall rekommendationer för kallibrering av parametrar tas fram.

För att jämföra verkligheten med simulering valdes lämpliga cirkulationsplatser med olika egenskaper ut i Göteborgsområdet. För varje cirkulationsplats utfördes två simuleringar med standardvärden på parametrarna, först en med *priority rules* sedan en med *conflict areas.* Efter det utfördes flertalet simuleringar där parametrarna för de två metoderna varierades. För att kunna ge rekommendationer utfördes en kalibrering av parametrarna. De simuleringar som utfördes med standardvärden visade att bäst resultat uppnåddes med *priority rules*. *Conflict area* leder till en underskattning av kapaciteten. Under kallibreringen framgick det att parametrarna som resulterade i största skillnaden av resultatet var *minimum gap time* för *priority rules* och *safety distance factor* för *conflict areas*.

Den generella rekommendationen baserad på denna studie är att att använda sig av *conflict area* med justerade parametrar när man simulerar enklare cirkulationsplatser med ett circulerande körfält (1/1). Det ger likvärdigt resultat som *priority rules* och det finns mindre risk för misstag under modelleringsprocessen. För komplexa cirkulationsplatser med två cirkulerande körfält rekommenderas *priority rules.* För de med ett ingående körfält (1/2) bör standardvärden på parametrarna användas. För cirkulationsplatser med två ingående körfält (2/2) bör parametrarna justeras.

Nyckelord: Mikrosimulering, cirkulationsplatser, Vissim, PTV, conflict areas, priority rules

Contents

Preface

In this study an analysis of parameters in the micro simulation program Vissim has been performed with regards to roundabouts. The study was carried out on the initiative of WSP during the spring of 2016.

We would like to thank Björn Öhman and Sebastian Hasselblom for suggesting the interesting topic that became our master thesis. A special thanks to Sebastian for helping us along the way with assistance in Vissim.

The supervisor of this Master’s Thesis was Gunnar Lannér and the examinator was Anders Markstedt both from the department of GeoEnginnering at Chalmers University of Technology.

Finally, thanks are given to the opponents, Johanna Edoff and Elisabeth Åman, for their valuable feedback.

Göteborg June 2016

Miriam Brill & Hanna Persson Brink

Notations

ABBREVIATIONS

AWSC	All-way stop-controlled
CA	Conflict areas
PR	Priority rules
PTV	Planung Transport Verkehr AG
TWSC	Two-way stop-controlled
Vissim	Verkehr in Städten – Simulationsmodell (Traffic in cities – Simulationmodel)
1/1 roundabout	Roundabout with one approaching and one circulating lane
1/2 roundabout	Roundabout with one approaching and two circulating lanes
2/2 roundabout	Roundabout with two approaching and two circulating lanes

UNITS

h	Hour
km	Kilometer
m	Meter
min	Minute
pc	Passenger car
s	Second
veh	Vehicle
%	Percent

1 Introduction

Before building or upgrading of road intersections it is necessary to provide accurate traffic simulations. This is especially important for roundabouts since a great amount has been built in Sweden during the recent years. In only five years, between 2005 and 2010, the number doubled in the whole country. This development can mainly be based on the positive effects of roundabouts to traffic safety (Wedberg, 2013). The reason for this is that there are less traffic flows in conflict with each other than at other non-signalized intersections (Robinson, 2000).

One micro simulation program that can be used for the modelling of intersections is Vissim developed by PTV Group (PTV Group, 2016b). In this program it is possible to model the right of way with two different methods: *Priority rules* or *conflict areas*, which can lead to different simulation results. The latter is recommended by PTV Group (PTV AG, 2011). The program provides default values for parameters describing the interaction of vehicle for both methods. These parameters can however vary in reality depending on the characteristics of the facility. For more accurate traffic simulations it is therefore important to adjust the parameters depending on the situation at the roundabout.

1.1 Aim

The purpose of the study is to evaluate the correlation between observed data and simulation with default parameters in Vissim for different types of roundabouts. Furthermore, recommendations for an adjustment of the parameters shall be provided in order to achieve more accurate simulations.

1.2 Limitations

The limitations of the study are listed below:

- The geographic borders are limited to the area of Gothenburg.
- The study is limited to three roundabouts based on different characteristics.
- No consideration has been taken to pedestrians or cyclist in the simulations.
- Only one adjustment of driving behaviour proposed by WSP was tested in the simulations.
- Since all heavy vehicles were converted into passenger cars no consideration has been taken to heavy vehicles different driving characteristics, such as acceleration and speed within the roundabout.

1.3 Methodology

The following steps have been performed during the study:

- Literature study
- Selection of roundabouts
- Data collection
- Simulation in Vissim
- Testing of parameters
- Calibration

A literature study was performed to give basic knowledge about the subject. It focuses on background information related to the three main topics: traffic, roundabouts and simulations and as well as their relation. It was gathered from scientific books and reports as well as course compendiums and information material about the simulation software.

For later comparison of reality and simulation results, suitable existing roundabouts had to be identified in the area of Gothenburg. The aim was to find roundabouts representing different characteristics. At the chosen roundabouts the traffic flows were observed and recorded in order to obtain required data.

As a part of the preparation for the simulation in Vissim version 7.00-15, models for the chosen roundabouts were set up including geometries, traffic flows, speed limitations and right of way definitions. For each roundabout a simulation with default parameters was performed firstly and secondly several tests were carried out by altering the parameters separately from each other.

Finally a calibration has been performed, where the parameters were also tested in combination in order to give recommendations with the best suitable parameter settings.

2 Literature study

In this chapter the results of the literature study is presented in order to give basic knowledge about the subject.

2.1 Traffic

Traffic is the transportation of goods or passengers along a route by road, rail and air (Slinn, et al., 2005). It usually consists of a mix of different types of traffic modes. These can be classified into public transport and individual transport, as presented in Table 2.1 (Wulfhorst, 2013).

Table 2.1 Transport modes.

Individual transport modes	**Public transport modes**
Truck	Train
Passenger car	Tram
Motorcycle	Bus
Moped	Taxi
Bicycle	
Pedestrian	

Traffic can be described with macroscopic measures such as traffic flow, speed and density as a basis of traffic analysis to understand the traffic stream as a whole. These measures are directly connected to each other with the relation (Mannering & Washburn, 2013):

$$q = uk \qquad (2.1)$$

Where
q = traffic flow
u = speed (space mean speed)
k = traffic density

Microscopic measures on the other hand describe the characteristics of individual pairs of vehicles more closely within a stream and can be related to macroscopic measures. One important microscopic measure is the time headway, h, which is the time between the passages of the front bumpers of two successive vehicles at a designated point. Another measure is the spacing, s, which represents the distance between the front bumpers of two successive vehicles. The relation of time headway and spacing to macroscopic measures are shown below.

Traffic flow, q, is defined as the number of vehicles passing a roadway point, n, during a designated time interval, t, measured in vehicles per unit time (Mannering & Washburn, 2013):

$$q = \frac{n}{t} \quad or \quad q = \frac{n}{\sum_{i=1}^{n} h_i} \qquad (2.2)$$

where
n = number of vehicles passing a roadway point
t = duration of time interval
h_i = elapsed time between arrival of two successive vehicles (time headway)

Speed can be represented as time-mean speed $\bar{u}$, an arithmetic mean of vehicle speeds observed at a designated point.

$$\bar{u}_{t=} \frac{\sum_{i=1}^{n} u_i}{n} \tag{2.3}$$

with
$\bar{u}_t$ = time-mean speed
u_i = speed of the vehicle *i* at a designated point (vehicle spot speed)
n = number of measured vehicle spot speeds

Alternatively, speed can also be represented as space-mean-speed by determining the time spent by a vehicle to travel a designated length of roadway (Mannering & Washburn, 2013).

$$\bar{u}_{s=} \frac{l}{\bar{t}} \tag{2.4}$$

where
$\bar{u}_s$ = space-mean speed
l = length of roadway
$\bar{t}$ = average travel time

Density, *k*, is described either in vehicles per unit distance or in spacing between successive vehicles (measured from front bumper to from bumper):

$$k = \frac{n}{l} \tag{2.5}$$

with
n = number of vehicles at a specified length of roadway at some specified time
l = length of roadway

or

$$k = \frac{n}{\sum_{i=1}^{n} s_i} = \frac{1}{\bar{s}} \tag{2.6}$$

with
s_i = distance between front bumper of vehicles i and front bumper of vehicle i
n = number of measured vehicle spacing
$\bar{s}$ = average spacing distance

2.2 Driving behaviour

The motion of a vehicle is affected by three main components: The driver's characteristics, the vehicle characteristics and the environment. The vehicle's capability, like acceleration and deceleration properties, and the roadway environment presuppose to which extent the driver's actions can be performed. Given these circumstances, the choice of action is strongly dependent on the driver's ability and behaviour (Elefteriadou, 2014).

Humans have varying capabilities when driving a vehicle regarding their vision and perception-reaction time. In order to perceive information presented along a roadway it is important that the driver has a good ability to see well in diverse situations. The quicker a driver can perceive the information the earlier a reaction can be performed (NCHRP, 2012). The reactions are dependent on the driver's personal behaviour and preferences. While some people drive more aggressive others drive more conservative. Thus, choices of speed, acceleration rate and passing decisions can vary amongst drivers. In addition to this, the driving characteristic is also influenced by the familiarity with the roadway facility. Drivers that are familiar with their surroundings, such as commuters, are likely to travel at a higher speed than drivers who are not familiar with the facilities, for example when being on a recreation trip (Elefteriadou, 2014).

The driving behaviour in a situation where more than one vehicle is involved can be described by three different vehicle interactions: Car-following, lane changing and gap acceptance. These are presented further in the following sections.

2.2.1 Car-following model

The car-following model explains the interactions between vehicles in the traffic. If a vehicle is driving without any other vehicle interfering it travels in a speed that is desired by the driver and the situation. If a vehicle is approaching another vehicle it will not be affected by the leading vehicle at first but when it reaches a certain point it will deaccelerate and adjust the speed and distance to the lead car in order to avoid collision. The stages can be seen in Figure 2.1 where the time headway is represented by the horizontal distance between the two trajectories of the vehicles and the space headway is represented by the vertical distance (Elefteriadou, 2014).

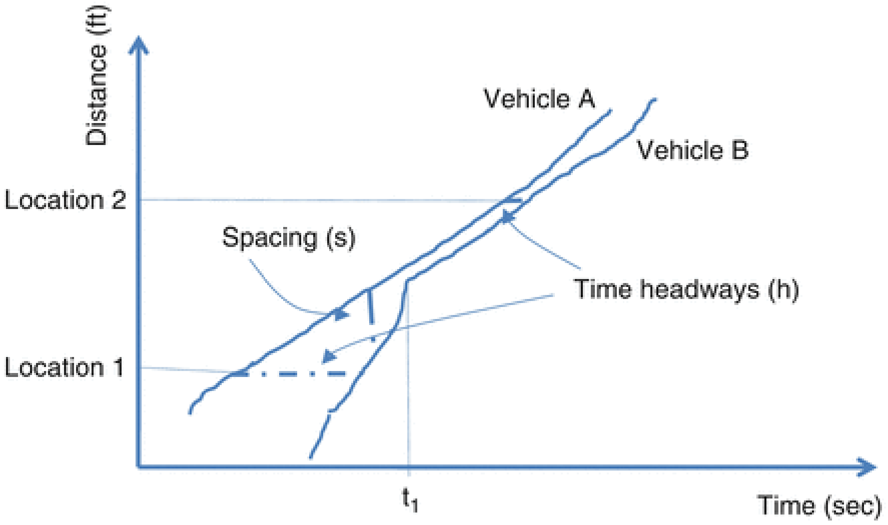


Figure 2.1 Trajectories for two vehicles approaching car-following (Elefteriadou, 2014).

When the following car is in that state of adjusting its driving to the lead car they are in a car-following situation. This will continue until the first car accelerates until it has higher speed than the following car or until the following car overtakes the lead car and has a higher speed *(Elefteriadou, 2014).*

In the 1950s the first car-following models was developed as the traffic researchers wanted to find a better understanding for how the highway capacity is affected. Since then a lot of different models have been developed. Examples of models that are being used today are the Gipps model, MITSIM model and the Wiedemann model, all which are classified as multi-regime models. This means that they have different models that are depending on the conditions in car-following (Elefteriadou, 2014).

The model that is used in the micro simulation program Vissim was created by Rainer Wiedemann in 1974. To create a traffic flow that is heterogeneous the Wiedemann model uses random numbers to simulate the behaviour of different drivers. In this model different thresholds where the driver’s behaviour changes are used (Higgs, et al., 2011).

In Figure 2.2 the thresholds are visualized. In the green area the driver has no influence of any other cars. As it enters the orange area the driver decelerates to adjust to the car in front. Since it still has higher speed than the leading car the distance will continue to decrease and the driver has to reduce the speed even more until it enters a condition of unconscious reactions to the leading vehicle, which is represented by the white area. The black line which starts in the green area, passes through the orange area and ends up in a loop in the white area represents how a vehicle passes through the different stages of car following (PTV AG, 2011).

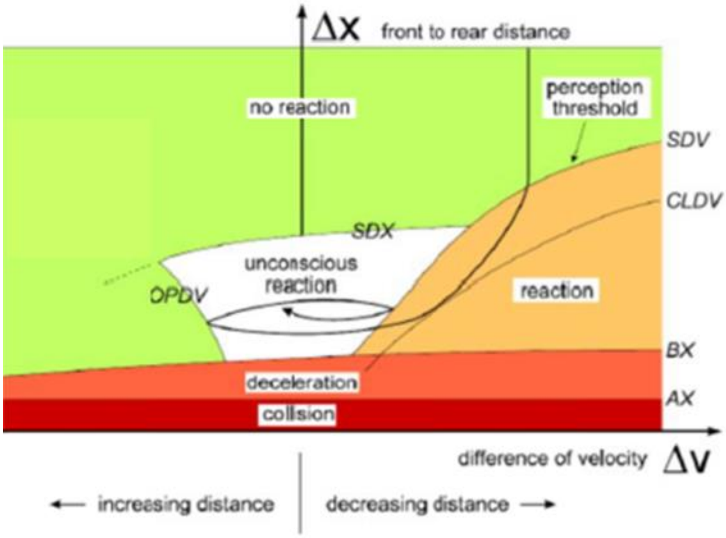


Figure 2.2 Car-following model by Wiedemann (PTV AG, 2011).

2.2.2 Lane changing model

In comparison to the car-following model, the processes of lane changing is more complex since the vehicle is not only affected by the vehicle ahead but also by the vehicle behind. These are also called the lead vehicle and lag vehicle. The intention for a driver to change lane can have different reasons, whereby its urgency has an influence on the drivers behaviour. The process is modelled by including a sequence of four decision-making steps as demonstrated in Figure 2.3 (Elefteriadou, 2014).

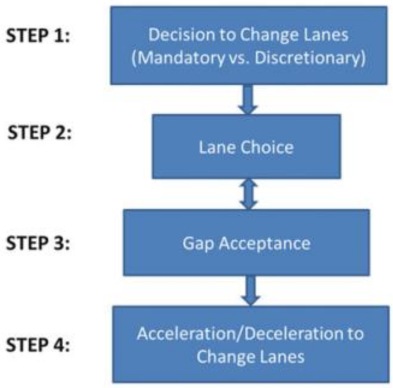


Figure 2.3 Decision-making steps during lane changing process (Elefteriadou, 2014).

As a first step the driver evaluates if a lane change is necessary. In this case, for example when an upcoming turn requires a lane change, it is called a mandatory lane change. Discretionary lane changes on the other hand are performed to gain an advantage such as when passing a slightly slower vehicle ahead to increase the speed and are less imperative. Depending on the driver's behaviour, traffic conditions and driving environment the attempt to carry out a discretionary lane change can differ. As a second step, the driver determines the target lane. In case of a discretionary lane change the choice depends on a set of criteria like queue length or operating speed in the target lane. It is assumed that the driver selects the option that provides the highest utility which is mathematically approached by discrete choice models. In the third step the driver accepts or rejects possible gaps in the target lane by evaluating the gap size according to the gap acceptance process which is described in the respective Section 2.2.3. Step two and three may occur simultaneously in case of a discretionary lane change when two adjacent lanes are suitable. Finally, in the step four, after a decision is taken the driver performs the lane change while adjusting its speed (Elefteriadou, 2014).

Different lane-changing models have been designed such as by Gipps, Krajzewiez or Sparmann (Elefteriadou, 2014). The rule-based lane changing model by Sparmann has been elaborated by observing the driving behaviour of vehicles on a stretch of a two-lane highway (Erlemann, 2007). He distinguishes between changes to a faster lane and changes to a slower lane. The decision for a manoeuvre to the faster lane (left lane) is assumed to be done early in advance in order to avoid breaking when reaching a slower vehicle ahead. A change can then be performed if an adequate traffic safety in the faster lane is given. If the situation is not giving the possibility for a change the driver stops the manoeuvre and adapts the speed of the lead vehicle. Changing to the slower lane (right lane) is usually motivated by the obligation to drive on the right hand side. A change is performed if the traffic situation on the right lane allows the driver's desired speed or if faster, following drivers on the left lane would be affected too much (Detering, 2010).

2.2.3 Gap acceptance

The purpose of gap acceptance models is to determine the number of vehicles that can pass through a conflicting stream or that can change lane. Whether a gap is accepted or rejected depends on the size of the gap. This is defined as the passed time between the passage of the rear bumper of the first vehicle and the front bumper of the successive vehicle. The critical gap defines the minimum gap that a driver is willing to accept. Gaps that are smaller will be rejected. The size of the gap is strongly dependent on the type of manoeuvre such as lane changing or left turn as well as on the driver's behaviour. In long gaps a group of vehicles will enter an intersection with certain headways between each other. This is also called the follow-up time (Troutbeck & Brilon, 2003).

For lane changing processes the driver has to consider both the lead gap, the gap to the lead vehicle in the target lane, as well as the lag gap, the gap to the lag vehicle in the target lane as exemplified in Figure 2.4 (Elefteriadou, 2014).

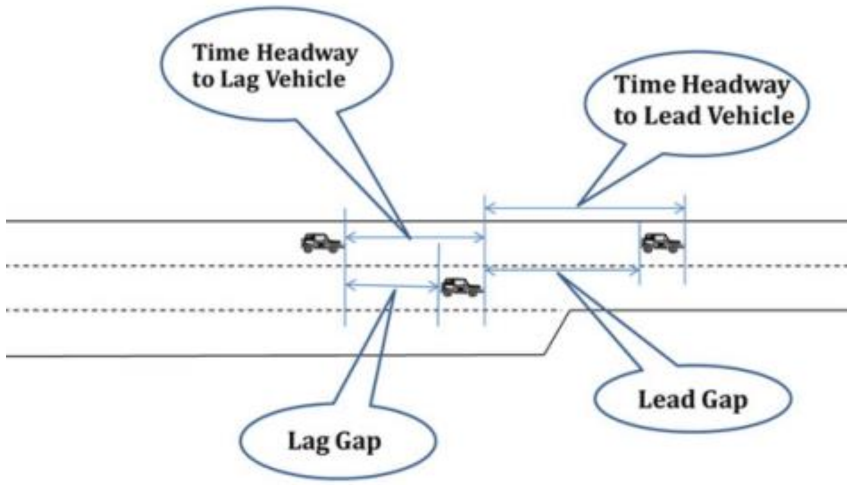


Figure 2.4 Lead gap and lag gap (Elefteriadou, 2014).

In order to analyse the capacity of the intersection some assumptions have to be included in the calculations (Guo & Lin, 2011):

- Base conditions are given which include good weather, good pavement conditions, users are familiar with the facility, traffic flow free of impediments
- Arrival times of minor and major stream vehicles are independent, which means that the headway distribution of the major stream is not influenced by the arrival of vehicles in the minor stream.
- Homogeneous and consistent driver behaviour which means that the threshold for all drivers to accept or reject a gap is identical.

2.3 Intersections

Intersections are defined as the crossings of two or more roadways (Mannering & Washburn, 2013) and are generally divided into signalized and non-signalized junctions.

At signalized junctions the vehicles operate with help of traffic signals whereby traffic streams with green signal are assigned the right of way. Streams with red signal have to stop. Non-signalized intersections on the other hand are controlled by stop or yield signs. Such intersections are either two-way stop-controlled (TWSC) junctions, all-way stop-controlled (AWSC) junctions or roundabouts.

At TWSC intersections, see Figure 2.5, movements from the major roads have priority over movements from the minor road. For the minor streams, it is up to the driver to make a decision about waiting or moving which is depended on the judgement of gap size in the major stream (Elefteriadou, 2014).

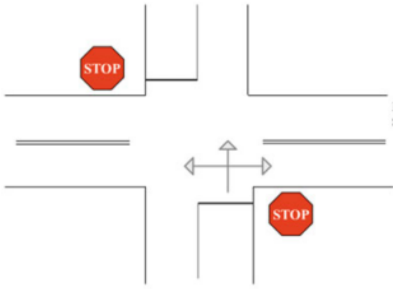


Figure 2.5 Non-signalized intersection: two-way stop-controlled (Elefteriadou, 2014).

At AWSC intersections, visualized in Figure 2.6, movements proceed according to a priority sequence. The driver only needs to observe the movements of the stream with priority position (Elefteriadou, 2014).

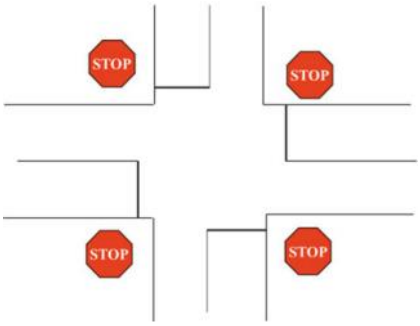


Figure 2.6 Non-signalized intersection: all-way stop-controlled (Elefteriadou, 2014).

Approaching vehicles at roundabouts have to give way to the circulating flow, shown in Figure 2.7 (Elefteriadou, 2014). Roundabouts will be discussed more detailed in the following section.

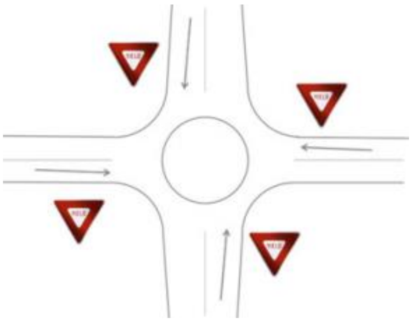
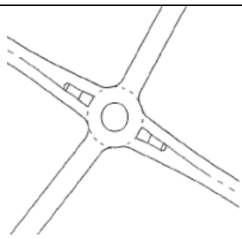
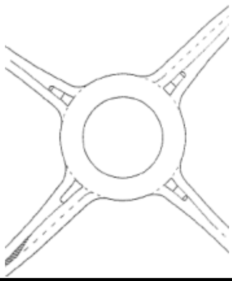
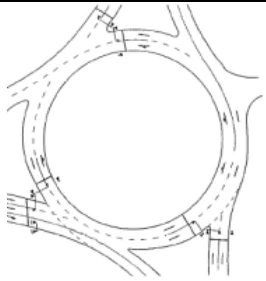


Figure 2.7 Non-signalized intersection: roundabout (Elefteriadou, 2014).

2.3.1 Roundabouts

Roundabouts are circular shaped road junctions where traffic flows into one direction around a central island (Stevenson, 2010). Historically seen, roundabouts have been used all over Europe and America since the 19th century, even before the invention of motorized vehicles. These intersections were architecturally designed with fountains or memorials in the centre around which the traffic was flowing in both directions without any regulations. Later, in the beginning of the 20th century, the one way traffic (anti-clockwise in countries with right-hand traffic) was introduced with the result of higher safety and improved capacities. Roundabouts can have different characteristics for example according to their geometric size and the area in which they are implemented. The typologies are shown in Table 2.2 (Wulfhorst, 2013).

Table 2.2 Typology of roundabouts.

	Mini roundabouts	Small roundabouts	Big roundabouts
Outer diameter [m]	13 - 22	– 60	>60
Area of application	Residential areas, urban and suburban areas	Urban and suburban areas	Rural areas
Example		 	

Roundabouts are suitable where traffic flows are differing strongly over time and where turning flows are high. Further on, they show a high performance regarding their capacity in comparison to non-signalized intersections and in many cases also in comparison to signalized intersections, especially when these operate with more than two phases (Wulfhorst, 2013). Roundabouts also have the advantage of higher safety since the vehicles reduce their speed when approaching. It is safer compared to non-signalized intersection due to less conflict points as illustrated in Figure 2.8. While many different streams at junctions are crossing each other, the conflicting streams at roundabouts are limited to merging (Robinson, 2000).

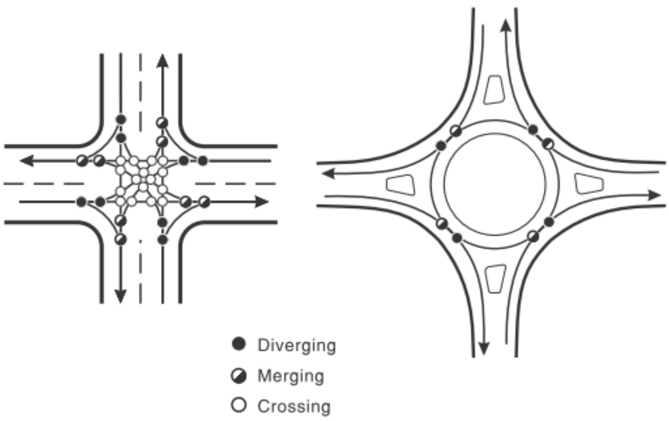


Figure 2.8 Conflict points at intersection and roundabout (Robinson, 2000).

2.3.2 Driving rules

A car that is entering the roundabout should give way to the cars that are already in the roundabout. There are no rules that you have to give signal when entering the roundabout although when a driver wants to switch lane or move sideways it has to indicate. When a car is exiting a roundabout it has to give right turning signal. The driving should be adapted so the exit from the roundabout is done from the right lane, as it is depicted for the left turning vehicle in Figure 2.9. The driver has to be extra observant when exiting the roundabout from the left lane since cars going in the right lane might be continuing within the roundabout (Transportstyrelsen, 2013).

*Figure 2.9 Travelling paths in a roundabout (Nationalföreningen för trafiksäkerhetens främjande, 2016)***.**

2.4 Simulation

Simulations are observations of a model over a period of time (Sokolowski & Banks, 2009) while according to Bratley, Bennet and Schrage (2011) ”a model is a description of some system intended to predict what happens if certain actions are taken” (Bratley, et al., 2011).

Models or simulations are used in order to visualize and understand a system which helps to do investigations before the implementation or modification of the system. This can help to choose correctly between different alternatives and to identify associated problems while it is less expensive than to perform tests on site (Sokolowski & Banks, 2009).

Figure 2.10 represents the approach of setting up a simulation model. The known parameters observed in the real systems are used as an input for the model. Due to possible lack of input parameter estimations are included as input to the simulation. This causes a source of inaccuracy and results in different outputs when comparing the simulated and real system. Therefore, two important steps in the development of a model have to be applied: validation and calibration (Daamen, et al., 2015).

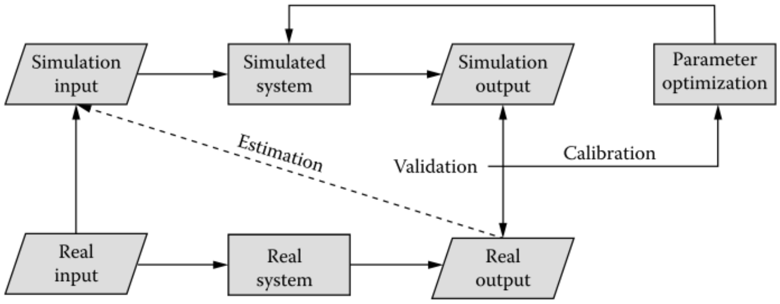


Figure 2.10 Relation between reality and simulation (Daamen, et al., 2015).

In the validation process it is determined how well a simulation represents the real situation by proving its accuracy. To do so, both outputs from real and simulated systems are compared. Since a simulation is a simplified model of a complex system the result can only be an approximation of the actual system and cannot reach the state of an absolutely valid model (Daamen, et al., 2015).

In the calibration the parameters are then adjusted until the difference between real and simulated system reach an adequate correlation. This optimization is an iterative loop process: after the parameter adjustment the system is tested and its output is validated again. As long as the requirements are not met the calibration process will continue (Daamen, et al., 2015).

2.4.1 PTV Vissim

PTV Group (Planung Transport Verkehr AG) provides several logistics and traffic softwares. Amongst these are two simulation programs, one for macroscopic and mesoscopic purposes called Visum and one for microscopic purposes called Vissim (PTV Group, 2016a). PTV Group describes Vissim (Verkehr in Städten – Simulationsmodell) as a "*microscopic, time step and behaviour-based simulation model developed to model urban traffic and public transport operations and flows of pedestrians.*" (PTV AG, 2011). It is a multimodal system that can represent all modes of transport like motorized, rail-based and non-motorized traffic at any kind of junction whether it is signalized or non-signalised (PTV Group, 2016b).

The roadway network in Vissim is built with so called links representing stretches of lanes with homogeneous characteristics. Stretches where the characteristics change or which connect two links are built with so called connectors. As the core of the simulation the traffic flow in Vissim is based on models of the drivers' behaviour. The car-following behaviour is determined by Wiedemann's psycho-physical model which is described in Section 2.2.1 and the lane changing behaviour is simulated using a rule-based model described in Section 2.2.2 (PTV Group, 2016b).

Some important features for the simulation of roundabouts are described in the following sections.

2.4.1.1 Non-signalized intersections

In order to model the right-of-way for two overlapping links at non-signalized intersections in Vissim there are two different modelling techniques: *conflict areas* (*CA*) and *priority rules* (*PR*). PTV Group recommends using *CA* as it is easy to apply and the vehicle behaviour is more intelligent. However, since the techniques are based on different settings, *PR* can be applied when the model does not return the expected results.

When using *CA*, it can be chosen which link has right-of-way and which link has to give way. Furthermore, several properties that affect the calculations in the model can be defined. These are described briefly below (PTV AG, 2011):

- *Visibility* is the maximum distance at which a driver on one link can see vehicles on the other link.

- *Avoid blocking* is a factor between 0 and 1 describing the percentage of vehicles from the major lane that do not enter the conflict area when the possibility to clear it immediately is not given.

- *Observe adjacent lanes* is an option that can be activated. If activated, an incoming vehicle from the minor lane is paying attention to lane changing vehicles on the major lane within the conflict area.

- *Additional stop distance* determines an additional distance from the beginning of the conflict area. It is used when vehicles stop further upstream and thus have a longer traveling way to the conflict area.

- *Front gap* is defined as the minimum time that must pass after the vehicle on the main road has left the conflict area before the vehicle on the minor road can enter the conflict area. It is described visually in Figure 2.11.

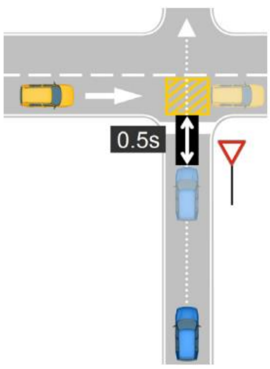


Figure 2.11 Front gap (PTV AG, 2011).

- *Rear gap* is the time that must pass after a vehicle on the minor road has left the conflict area before a vehicle on the major road enters the conflict area. The *rear gap* is sketched in Figure 2.12.

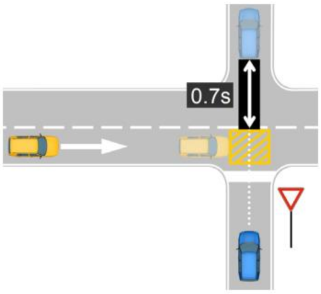


Figure 2.12 Rear gap (PTV AG, 2011).

- *Anticipate route* is a number between 0 and 100 which states the percentage of incoming vehicles from the minor lane that foresee the route of the vehicles on the major lane. Vehicles in the major lane turning at an upstream position will not reach the conflict area.

- *Safety distance factor* is used for merging conflicts to determine the minimum headway of a vehicle from the minor road at the moment when it merges completely into the conflict area. The factor is a value that is multiplied by the normal desired safety distance, as exemplified in Figure 2.13.

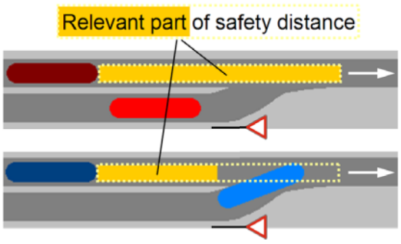


Figure 2.13 Safety distance factor (SDF top = 1.0, SDF bottom = 0.5) (PTV AG, 2011).

When using *PR*, the movements of two conflicting lanes are regulated by a stop line for minor lanes and conflict markers, while the position of conflict markers define the minimum headway and minimum gap time. These are shown visually in Figure 2.14. Other properties that can be defined are maximum speed and look beyond red signals.

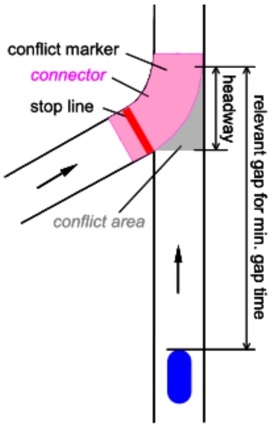


*Figure 2.14 Headway and gap time in priority rules (PTV AG, 2011)***.**

- *Minimum headway* is typically defined by the length of the conflict area between the two lines and regulates that an approaching vehicle from the minor lane stops at the stop line as long as another vehicle is in the conflict area.

- *Gap time* is a determined time interval that is required for a vehicle of the minor lane to merge before a vehicle of the major lane is arriving to the conflict marker.

- *Maximum speed* describes the maximum speed of the approaching vehicles that will be taken into account for headway conditions.

- *Look beyond red signals* is an option that can be activated when headway and gap time are checked also for vehicles upstream of red signals.

2.4.2 Reduced speed areas

Vehicles travel at their desired speed as long as free flow is possible. This is however not realistic in specific sections, such as curves, which makes speed changes necessary. *Reduced speed areas* can be placed on links and connectors and defines a maximum speed. If a vehicle approaches a *reduced speed area*, it lowers its speed in order to reach the defined speed as it arrives to the area (PTV AG, 2011).

2.4.3 Vehicle routes

Vehicles with the same origin can have different destinations for example if a road is diverting. Possible routes are defined by fixed sequences of links and connectors. The vehicles start at the routing decision point and can have multiple destination points. Once a vehicle has passed the start point it will follow one of the defined routes until it has reached the destination point. There are different types of routing decisions. One option is the static routing decision which means that a static percentage is used for each destination that vehicles with the same origin have. The percentages are defined in terms of relative flows. If the equal amount of vehicles with the same origin drive to two different destination the relative flow for both is set to one (PTV AG, 2011).

2.4.4 Data collection points

In order to collect data at a specific segment and during a specific time interval the feature data collection can be used. Markers which are placed at the respective segment measure data about passing vehicles, such as the total number of passed vehicles, its speed, acceleration etc. With help of this tool it is possible to create lists containing desired information (PTV AG, 2011).

3 Description of chosen roundabouts

Before the data collection could be performed suitable roundabouts had to be identified in the area of Gothenburg. The main criterion was the existence of queuing in order to be able to find a relation between the traffic flows in the roundabout. The aim was to find roundabouts representing different characteristics. It was decided to investigate:

- one roundabout with a small diameter, one approaching lane and one circulating lane (1/1).
- one roundabout with a bigger diameter, one approaching lane and two circulating lanes (1/2).
- one roundabout with a bigger diameter, two approaching lanes and two circulating lanes (2/2).

A preselection regarding the geometric characteristics could be done by looking at online map services, while the final selection was taken after on-site visits, where it was possible to observe the queueing situation.

3.1 Roundabout A

The first roundabout is situated in the municipality of Lerum which is approximately 21 km outside of central Gothenburg. Dageborgsleden, Trafikplats Kastenhov and Södra Långvägen intersect at this roundabout. As presented in Figure 3.1 it lies next to the highway E20. All vehicles from Gothenburg that are approaching Lerum exit E20 about 2,7 km south west of the roundabout and the majority of vehicles pass thorough the roundabout. This creates a steady queuing situation during the afternoon and morning peak hour.

Figure 3.1 Map of roundabout A.

The roundabout has an inner diameter of 9 m and an outer diameter of 20 m which can be considered as a mini roundabout. There are three roads that are connected by this roundabout, which all have one ingoing lane and one outgoing. The arm that has been studied in this project was the arm in south-west since the most queuing occurred there with cars coming from the highway.

3.2 Roundabout B

This roundabout is situated close to residential areas in the municipality of Mölndal, south of Gothenburg where Bifrostgatan and Toltorpsgatan intersect. It has a wide circulating lane, see Figure 3.2, which allows two cars to be driving beside each other.

Figure 3.2 Map of roundabout B.

The inner diameter of this roundabout is 39 m and the outer diameter is 57 m. It is thus categorized as a small roundabout but fulfils almost the requirements of a big roundabout. The investigated arm is the one in south-west direction and has one ingoing and one outgoing lane

3.3 Roundabout C

Roundabout C is located in an industrial area in the municipality of Mölndal south of Gothenburg, in direct connection with the west bound exit from highway E6. It forms the junction of Jolengatan, Bifrostgatan and Aminogatan. The inner diameter of this roundabout is 28 m and the outer diameter is 47 m. It can be considered as a small roundabout and has four arms. The layout is portrayed in Figure 3.3.

Figure 3.3 Map of roundabout C.

The studied arm is the west located arm. Each arm of the roundabout has two in going lanes, where the assigned destination of each lane is in accordance to Figure 3.4.

Figure 3.4 Two ingoing lanes in roundabout C.

4 Data collection

The necessary data that had to be collected were approaching flow, circulating flow and exiting flow at one saturated arm of each roundabout. This data was gathered by recording the respective traffic flows with cameras during the afternoon peak hours at the sites. During these hours, the weather condition was around 5 to 15 degrees Celsius without rain for all studied roundabouts. The roadways had pavement in good conditions. The recording time covered approximately two to three hours in total, usually split over several days. All data collected during the video analysis is listed in Appendix I.

The videos have been evaluated by counting approaching flow, circulating flow and exiting flow during time intervals of 20 to 60 seconds in which two conditions constantly had to be given:

- The traffic is not influenced by crossing pedestrians
- There has to be queueing in the lane of approaching flow. Hereby, a queue was defined as a line of more than one car being ready to enter the roundabout.

During the counting it was furthermore noted if there were trucks or busses amongst the vehicles, since they take more space. Trucks and busses were thus set equal to two passenger cars (Li, et al., 2013). Due to the fact that the time intervals differ between 20 and 60 seconds, all measured flows were converted to the hourly based unit passenger cars per hour (pc/h). As a next step, the relations between approaching and its influencing flows were visualized in graphs.

4.1 Roundabout A

In roundabout A the approaching flow is influenced by the circulating and exiting flow. Since the diameter is small and it was observed that not all vehicles give sign before exiting, drivers in the approaching lane have to wait for the exiting vehicles to leave the roundabout before can enter the roundabout. The conflicting flows are illustrated in Figure 4.1.

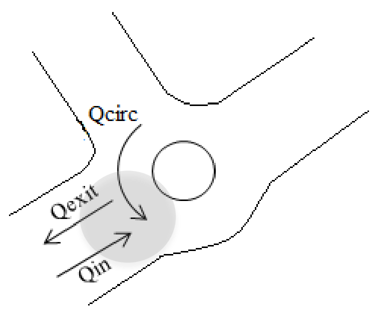


Figure 4.1 Illustration of conflicting flows for roundabout A.

The approaching flow in relation to the respective conflicting flows is depicted in Figure 4.2. The average ingoing flow is 1097 pc/h and the sum of the average circulating flow and average exiting flow is 670 pc/h. The black line shows a linear trend line of the collected data points, which has a slightly negative inclination.

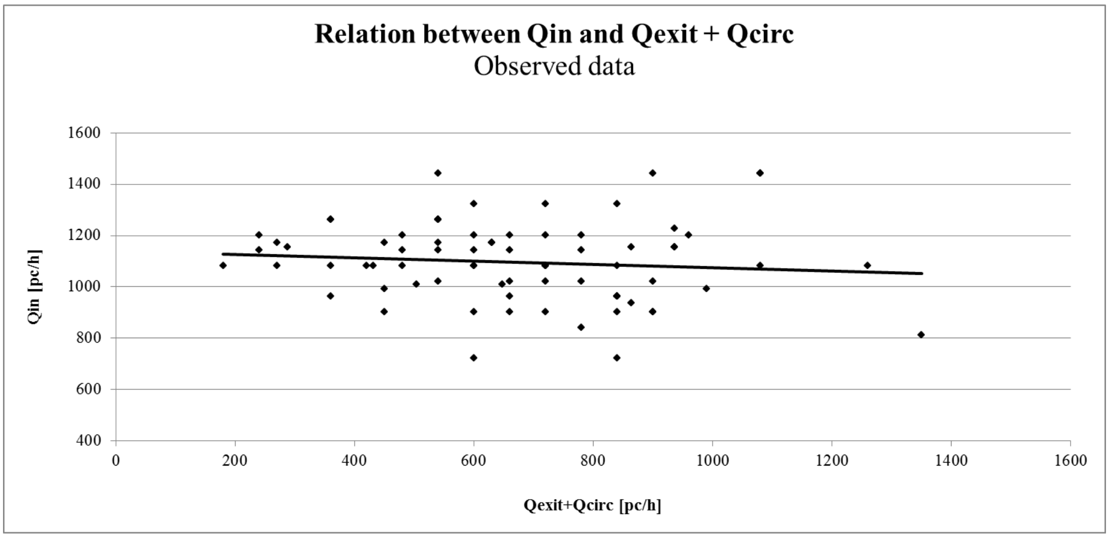


Figure 4.2 Relation between ingoing flow and conflicting flows for roundabout A.

4.2 Roundabout B

In roundabout 2 the drivers on the approaching lane have to wait for both circulating flows as shown in Figure 4.3. It was observed that right turning vehicles from the approaching lane wait for circulating vehicles in the inner lane even though it would be enough space to pass. Due to the large diameter the exiting flow is at distance from the ingoing flow and has thus no influence on the amount of ingoing vehicles. The conflicting flows for roundabout B are demonstrated in Figure 4.3.

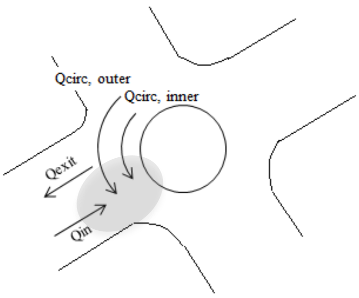


Figure 4.3 Illustration of conflicting flows for roundabout B

Figure 4.4 summarizes the results of approaching flow in relation to the respective conflicting flows for roundabout B, which in this case is the sum of inner and outer circulating flow. The average ingoing flow under queueing conditions is 841 pc/h. The total average circulating flow is 836 pc/h.

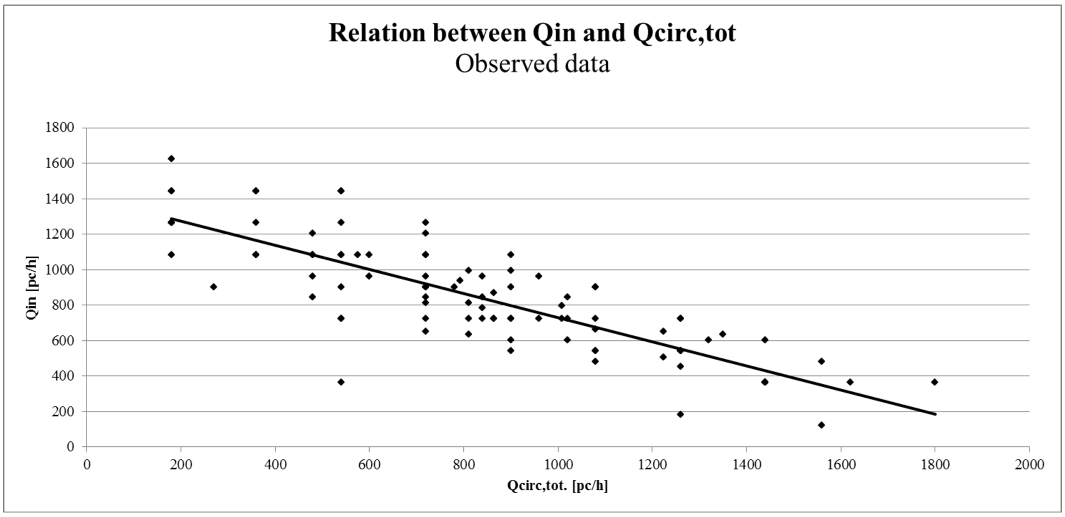


Figure 4.4 Relation between ingoing flow and conflicting flows.

4.3 Roundabout C

In roundabout C there are two approaching lanes. The left lane is dedicated to left turning vehicles which are in conflict with both circulating flows since they aim for the inner circulating lane. The driver is crossing the outer lane and then merging into the inner lane. The right approaching lane is for vehicles going straight or turning right. These are also influenced by both flows. It was observed, that the driver waits for both circulating traffic flows before, no matter if the vehicle is turning right or is going straight forward. This is due to the fact that inner circulating vehicles usually change lane to the outer circulating lane in order to prepare for their exiting maneuver at the next arm. In this way they are blocking both circulating lanes and it is difficult for the ingoing vehicle to estimate the circulating vehicle's behaviour. The conflicting flows are illustrated in Figure 4.5.

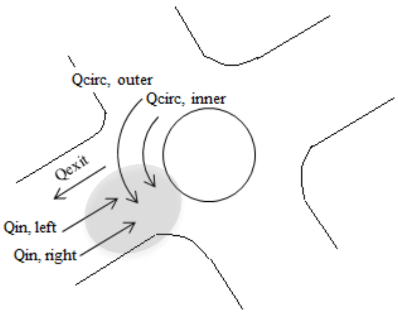


Figure 4.5 Illustration of conflicting flows for roundabout C.

The approaching flows in relation to the sum of inner and outer circulating flow are presented in Figure 4.6 and Figure 4.7. The average ingoing flow of the left lane under queueing conditions is 654 pc/h and the average ingoing flow of the right lane under queueing condition is 744 pc/h. The total average circulating flow is 868 pc/h.

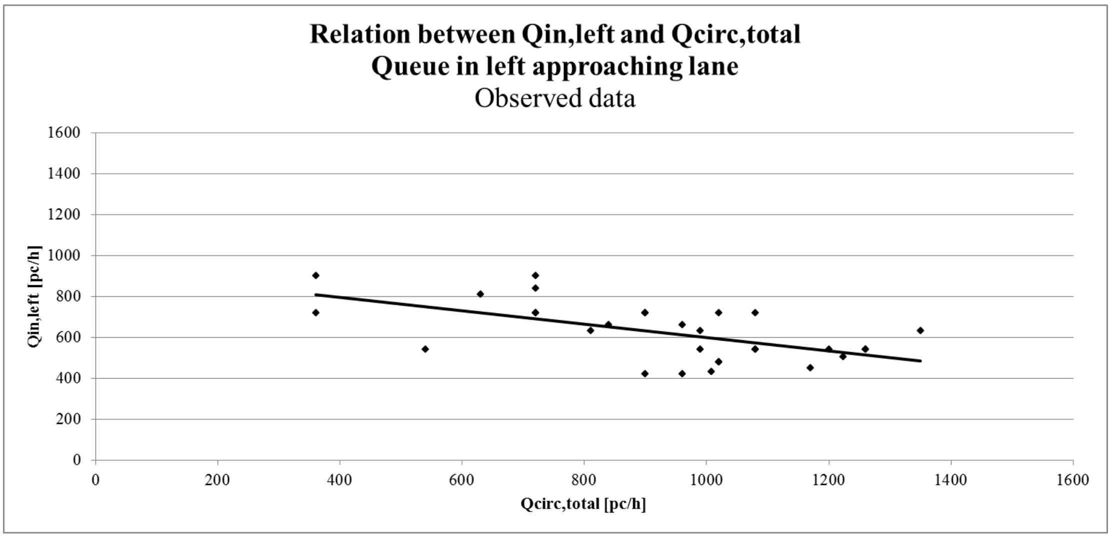


Figure 4.6 Relation between ingoing flow in the left approaching lane and conflicting flows.

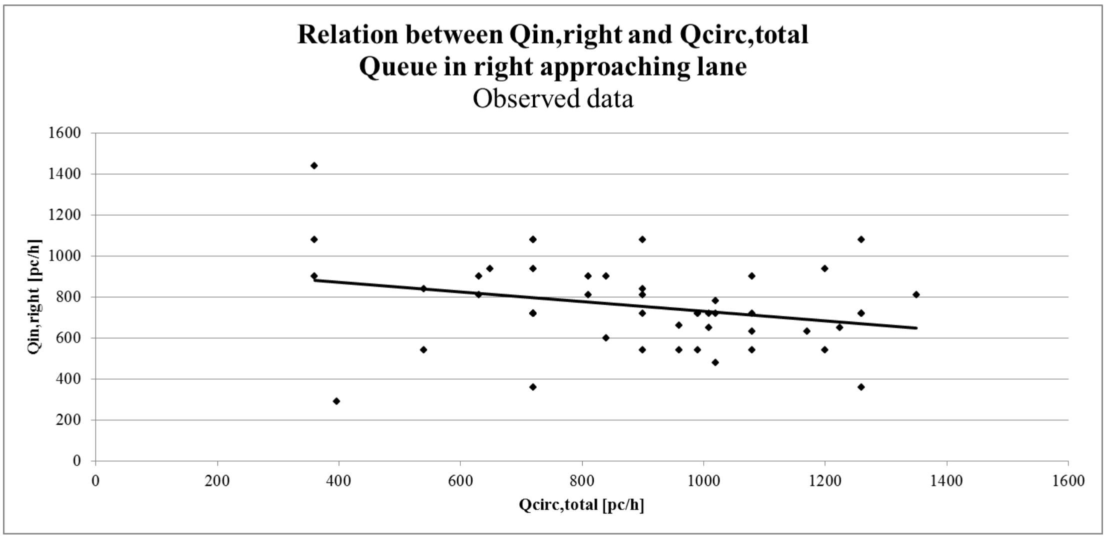


Figure 4.7 Relation between ingoing flow in the right approaching lane and conflicting flows.

5 Simulation in Vissim

The geometry of each roundabout was drawn in Vissim version 7.00-15 by using layout information based on satellite pictures from online map services. The focus lied mainly on the characteristics of the roundabout and less on the surroundings. The continuation of the roads have therefore been simplified.

Priority lanes in the model can be defined either by *conflict areas* (*CA*) or *priority rules* (*PR*). For each roundabout two models are set up, one using *conflict areas* and one using *priority rules*. This gives a total of six different models.

To achieve the same conditions in the simulation as in reality it was important to have queueing in the approaching lane. This means that the input for the ingoing flow must be set to a high number. Input data for all other flows were derived from the measured flow of the video analysis, so that the relative shares between the flows have the same proportions. *Reduced speed areas* were included in the model since vehicles cannot travel at their desired speed inside the roundabout. The space mean speed was derived by estimating the travelling time at a specific stretch in the videos and by applying equation 2.3.

When modelling with *CA* one problem has been observed: In reality all vehicles in the same lane stop in the same position regardless of their destination. To achieve the same behaviour some adjustments had to be made for the more complex roundabouts where several lanes are in conflict with each other. Since the conflict areas do not always align, an *additional stopping distance* was set for the conflict areas where this problem occurred. An example is given in Figure 5.1. Vehicle 1 has entered the roundabout since there were no conflicting cars in the outer circulating lane but had to stop at the conflicting area with the inner circulating lane because of vehicle 3. While vehicle 1 is standing and waiting to drive vehicle 2 appears and is blocked by vehicle 1. If an *additional stopping distance* is applied to the marked conflict area vehicle 1 stops earlier and does not block vehicle 2.

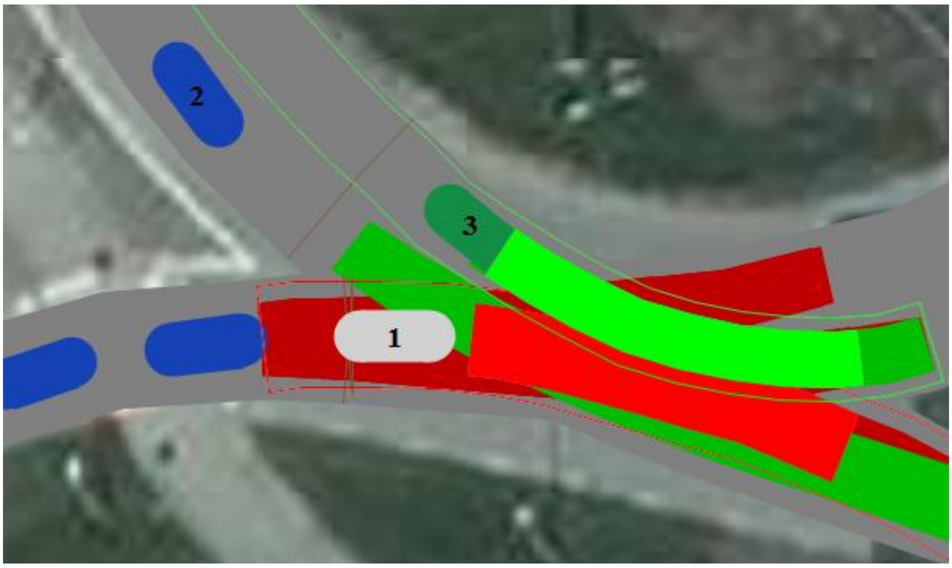


Figure 5.1 Illustration of additional stopping distance

The input data for flows and its respective relative flows for each direction as well as the reduced speed are presented in Appendix II. Roundabout C is simulated with queue in the right approaching lane and with queue in the left approaching lane separately. Therefore, two different relative flows are needed.

The first simulation of each case has been performed with default values for all parameters. As described in Section 2.4.1 there are several adjustable parameters for *conflict areas* and *priority rules*. The default values for the two cases are stated in Table 5.1 and Table 5.2.

Table 5.1 Default parameters for simulation with CA.

Parameters CA	**Default**
Front gap [s]	0.5
Rear gap [s]	0.5
Safety distance factor [-]	1.5
Additional stop distance [m]	0
Observe adjacent lanes	deactivated
Anticipate routes [%]	0
Avoid blocking [%]	100
Visibility [m]	100

Table 5.2 Default parameters for simulation with PR.

Parameters PR	**Default: time gap**	**Default: headway**
Min. gap time [s]	3.0	0.0
Min headway [m]	0.0	5.0
Max. speed [km/h]	180	14
Look beyond red signals	deactivated	deactivated

Furthermore, the driving behaviour in Vissim is based on Wiedemann 74 car-following model with the default values as shown in Table 5.3.

Table 5.3 Default parameters for Wiedemann 74 car-following model.

Parameters Wiedemann 74 car-following model	**Default**
Max. look ahead distance [m]	250
Max. look back distance [m]	150
Temp. lack of attention duration [s]	0
Temp. lack of attention probability [%]	0

In the same way as for the video analysis, a traffic analysis of the simulation was performed. The number of vehicles was automatically counted with the feature data collection point. Flows during intervals of 60 second were recorded and were then used to compare the relations of approaching and its influencing flows with the reality based data. The data collection started after 5 minutes of simulation in order to assure that queue had been forming.

5.1 Roundabout A

For the simulation with *CA* the two merging lanes of ingoing and circulating traffic have a conflict area as displayed in Figure 5.2, while the circulating lane has right of way (marked green).

Figure 5.2 CA settings for roundabout A

The markers for the simulation with *PR* can be seen in Figure 5.3. The red line represents the stop line for ingoing vehicles and the green lines represent the headway marker (downstream) as well as the gap time marker (upstream). The headway marker detects all slow moving traffic travelling at a maximum speed of 14 km/h. It is placed just before the two lanes have merged completely. Vehicles will not enter the roundabout if a slow moving circulating vehicle has not passed the headway marker. The gap time marker detects all vehicles regardless of travelling speed. It defines the minimum gap time that has to be provided for an ingoing car to enter the roundabout. This marker is situated just before the approaching lane connects to the circulating lane.

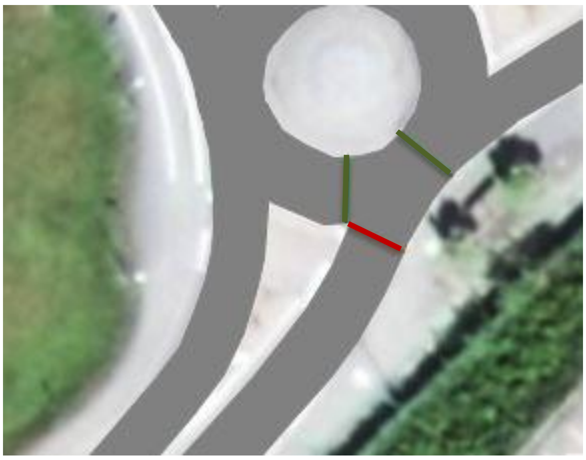


Figure 5.3 PR settings for roundabout A

The results from simulations with *CA* and *PR* applying default values for all parameters are summarized in Figure 5.4. In general it can be seen that results from simulations are less scattered than the ones from observed data. For both simulations the trend line's inclination differs from the observed data. In this way the lines are crossing each other at a certain point. For low conflicting flows the ingoing flow is overestimated and for high conflicting flow the ingoing flow is underestimated. The overestimations and underestimations even each other out to a certain extend. However, *PR* has a closer correlation to observed data than *CA* due to a more similar inclination and the fact that the lines intersect with each other in the middle.

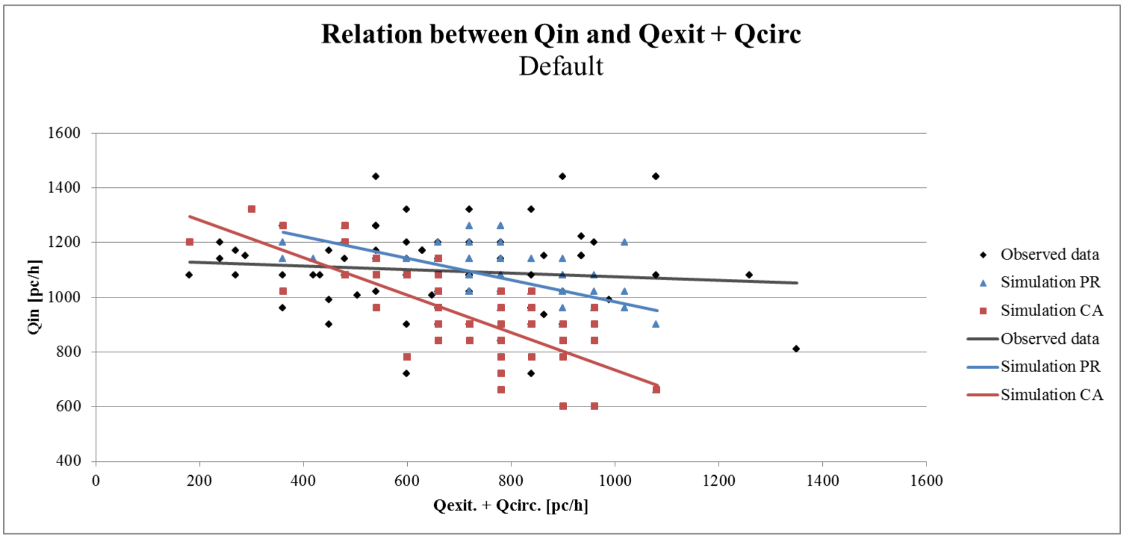


Figure 5.4 Results of default simulation for roundabout A.

5.2 Roundabout B

The conflict areas for roundabout B are displayed in Figure 5.5. The circulating flows have right of way and the approaching lane has to yield.

Figure 5.5 CA settings for roundabout B.

The position of the priority rule markers are illustrated in Figure 5.6. The red line shows the position of the stop line for ingoing vehicles. Since there are two circulating lanes in roundabout B, it is needed to set two headway markers (downstream) as well as two gap time markers (upstream). These are placed in the same way as for roundabout A.

Figure 5.6 PR settings for roundabout B.

Figure 5.7 presents the simulated results for both *CA* and *PR* together with the observed data. It is detected that results from the simulation with *PR* are closest to the observed data.

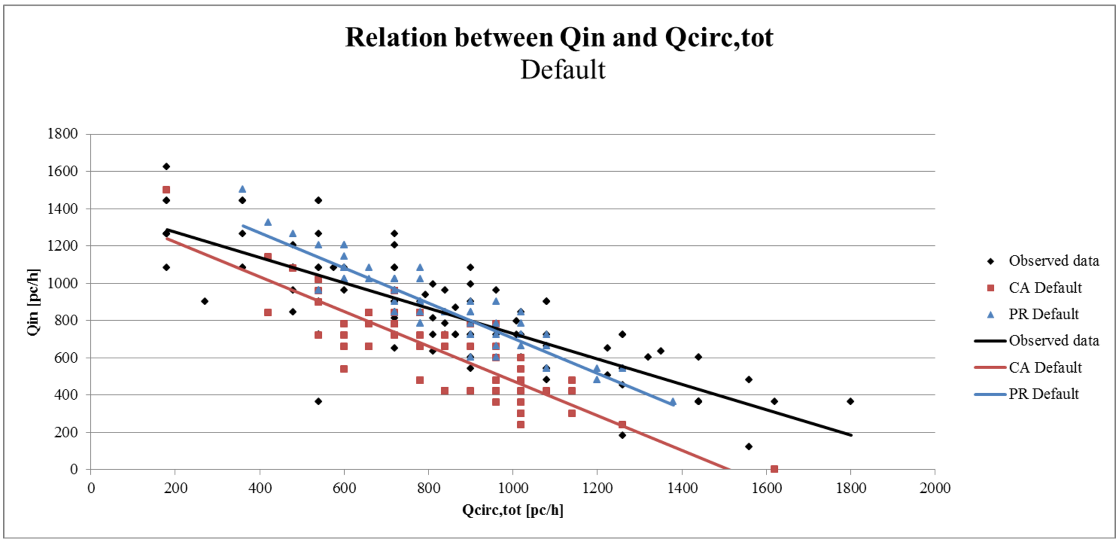


Figure 5.7 Results of default simulation for roundabout B.

5.3 Roundabout C

The conflict areas for roundabout C, where two ingoing lanes are in conflict with the two circulating lanes are defined according to Figure 5.8. As well as for the other roundabouts, the circulating lanes have right of way (marked green).

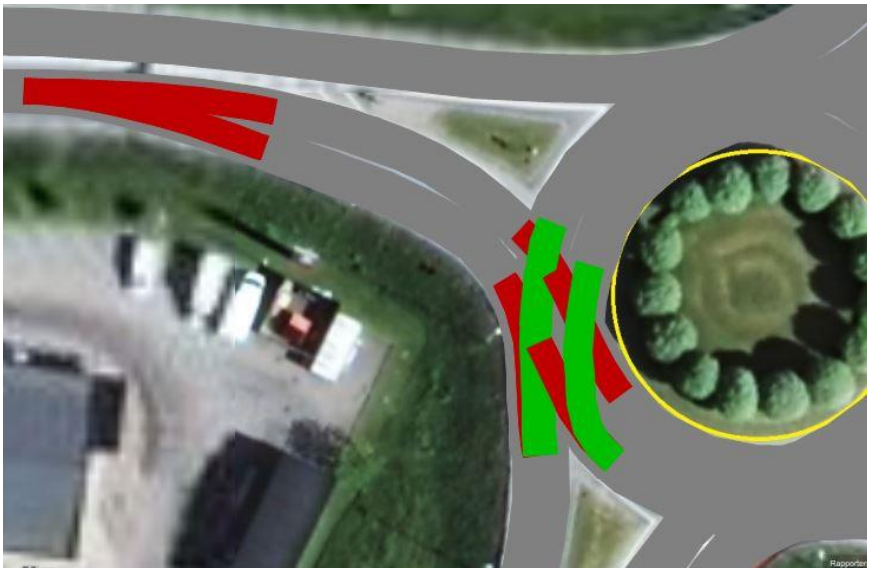


Figure 5.8 CA settings for roundabout C.

For the simulation with *PR*, every approaching lane has one stop line with four markers each as displayed in Figure 5.9. In accordance to roundabout A and B, the lines downstream represent headway markers and the lines upstream represent gap time markers. These are situated differently for left and right approaching lane based on how the lanes are merging.

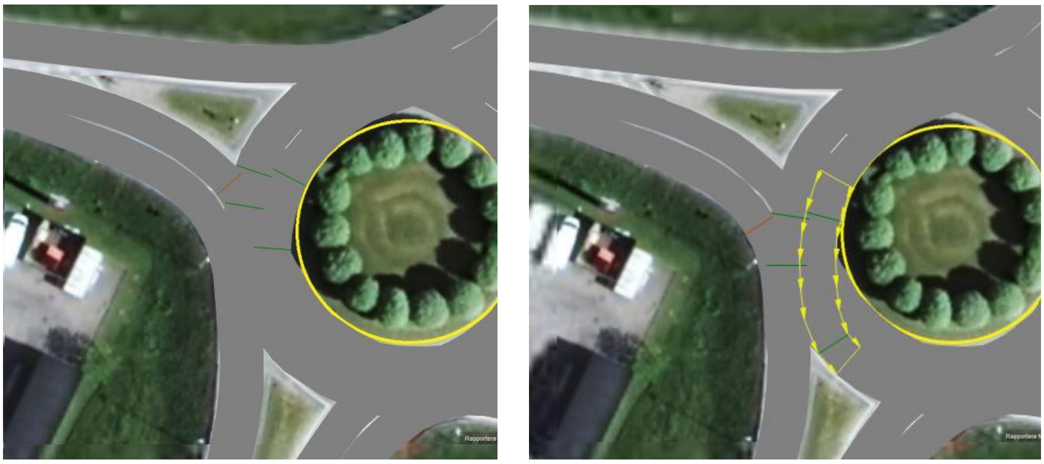


Figure 5.9 PR settings for roundabout C.

The results of the default simulation at roundabout C are displayed in Figure 5.10 and Figure 5.11 for queuing in left lane and right lane respectively. The best correlation for both simulation methods can be seen for the right lane. In general, *PR* simulations give closer results to the observed data than *CA* simulations. However, data points from *CA* simulation are overlapping the observed data points as well.

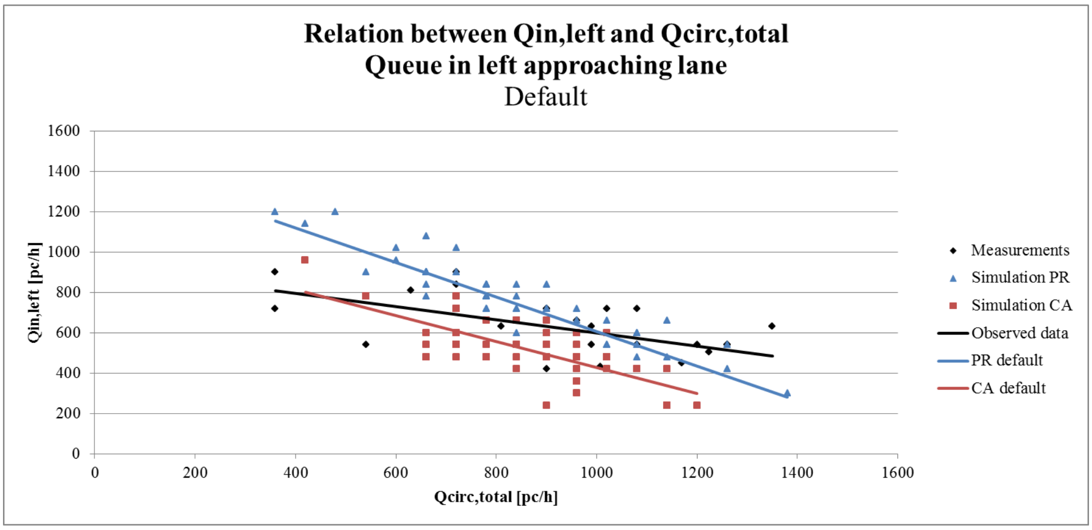


Figure 5.10 Results of default simulation for roundabout C with queue in left lane.

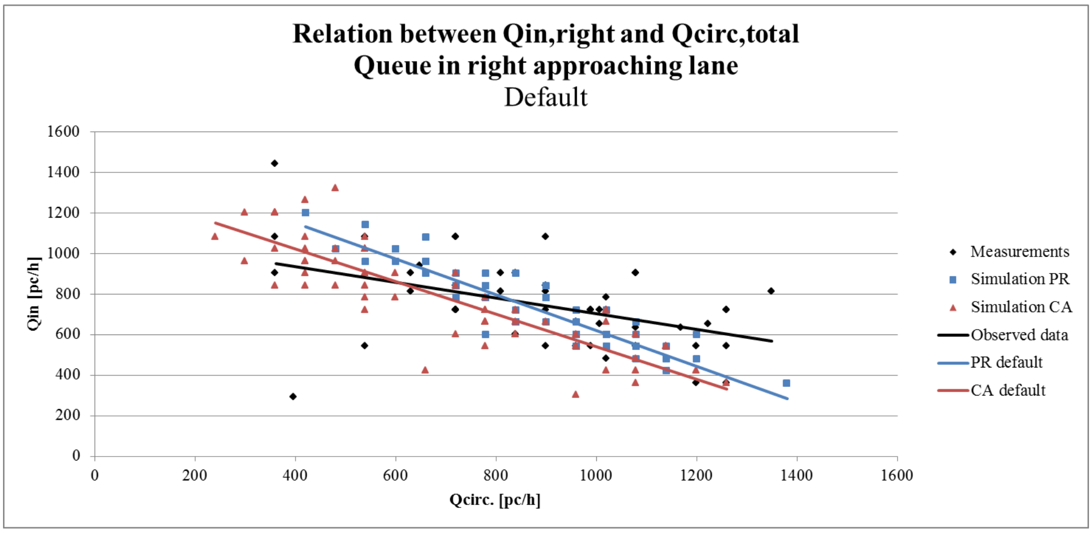


Figure 5.11 Results of default simulation for roundabout C with queue in right lane.

6 Testing of parameters

When testing the parameters for the *CA* models only *anticipate route*, *safety distance factor*, *front gap* and *rear gap* were adjusted due to the following reasons:

- × The visibility at all roundabouts was good. Therefore, the parameter *visibility* has not been changed.
- × *Avoid blocking* is a parameter describing the blocking situation at crossing conflicts caused by vehicles in the major road. This situation cannot occur in a roundabout and therefor this parameter was not of importance.
- × The roundabouts were modelled using single lane links only. It is thus not necessary to activate the parameter *observe adjacent lanes*, since there are no two-lane links.
- × It was observed that vehicles were driving very close to the circulating lane before entering the roundabout. Many of them were even passing the official stop line to reach their waiting position. The parameter *additional stop distance* is therefore not of importance for the testing process but can be of importance when setting up the geometric model which is described further in chapter 5.
- ✓ *Anticipate routes* describes the driving behaviour when observing interacting traffic and is thus of importance for flow adjustments.
- ✓ *Safety distance factor* describes the driving behaviour with regard to gap acceptance and is thus of importance for flow adjustments.
- ✓ *Front gap* and *rear gap* are parameters describing crossing flows. Vehicles entering into the inner lane of a roundabout with two circulating lanes cross the outer circulating lane before merging. Therefore, the parameters might have an influence.

When testing the parameters for the *PR* models *minimum gap time* and *minimum headway* were adjusted due to the following reasons:

- × The parameter *look beyond red signal* is supposed to be activated when vehicles at red signals upstream should be observed as well. Since the focus lies on the roundabout itself and no signalized intersections are included in any of the models this parameter was not of importance.
- × *Maximum speed* defines the maximum speed of vehicles which the PR-markers can detect. Slow moving vehicles should be detected by minimum headway markers. For these markers the *maximum speed* is equal to 14 km/h as suggested by the user manual. Fast moving vehicles should be detected by minimum gap time markers. For these markers the *maximum speed* is equal to 180km/h. For the minimum gap time the aim is to include all vehicles and therefore the speed must be kept high.
- ✓ Vehicles detected by markers for *minimum headway* are the ones moving at slow speed. As mentioned before, all vehicles move at higher speeds than 14 km/h. The hypothesis is, that no or significantly little slow moving traffic

occurs and a change in *minimum headway* might not have an influence on the results. However, in order to validate this assumption the parameter has been evaluated as well.

✓ Since all vehicles regardless of their speed are detected by markers for *minimum gap time.* This parameter can have an influence on the results. It is the parameter with major importance for the testing process.

First the effects of the parameters on the flows were tested. For *CA*, *safety distance factor* and *anticipate routes* were tested seperately. Additionally, *rear gap* and *front gap* were changed to 0.2 seconds one at a time. A similar procedure was performed for *PR* with *minimum time gap* and *minimum headway*. The steps and ranges of how the parameters were tested can be found in Table 6.1 for *CA* and in Table 6.2 for *PR*.

Table 6.1 Parameters to adjust with CA.

Parameters CA	**Test steps**	**From**	**To**
Safety distance factor [-]	0.3	0.6	1.8
Anticipate route [%]	50	0	100
Rear gap [s]	0.3	0.2	0.5
Front gap [s]	0.3	0.2	0.5

Table 6.2 Parameters to adjust with PR.

Parameters PR	**Test steps**	**From**	**To**
Minimum gap time [s]	0.5	2	4
Minimum headway [m]	2	3	7

Apart from the above mentioned parameters also the values for Wiedemann 74 car-following model were adjusted according to

Table 6.3 for both *CA* and *PR* simulations.

Table 6.3 Parameters to adjust in Wiedemann 74 car-following model.

Parameters Wiedemann 74 car-following model	**Adjusted**
Max. look ahead distance [m]	150
Max. look back distance [m]	50
Temp. lack of attention duration [s]	1
Temp. lack of attention probability [%]	5

After the tendency of influence was known, the parameters were adjusted based on the findings for each roundabout with the aim to achieve a result as close as possible to the observed data. This includes the process of validation where simulated values were compared to the measured data from the observations. During the calibration the aim was to match the trend line from the simulations to the trend line that is based on the real data as good as possible.

Finally, a comparison between the results of the roundabouts was performed pointing out the similarities and differences.

6.1 Conflict areas

When simulating with *CA* the parameters *safety distance factor*, *anticipate routes* as well as *rear and front gap* were adjusted. Most significant changes can be seen for adjustment of *safety distance factor*, while changes for the two other parameters have almost no impact. Furthermore, changes of the parameters have most impact for the smallest roundabout (A).

6.1.1 Safety distance factor

The results of the simulations with *CA* with changed values for the parameter *safety distance factor* are shown in Figure 6.1 to Figure 6.4 for all roundabouts.

For roundabout A it can be observed that an increase of *safety distance factor* leads to a decrease of ingoing flow. Such a clear relation can however not be seen for roundabout B and C where the changes do not follow a certain pattern or do not lead to any significant change. In most cases a smaller *safety distance factor* than the default value shows closer results to the observed data. For roundabout A the best correlation can be achieved with 0.9. For roundabout B the values 0.6 and 0.9 show similar results and an improvement compared to the default value. For roundabout C the main change can be observed for the right lane, where a value of 0.6 correlates best to the observed data.

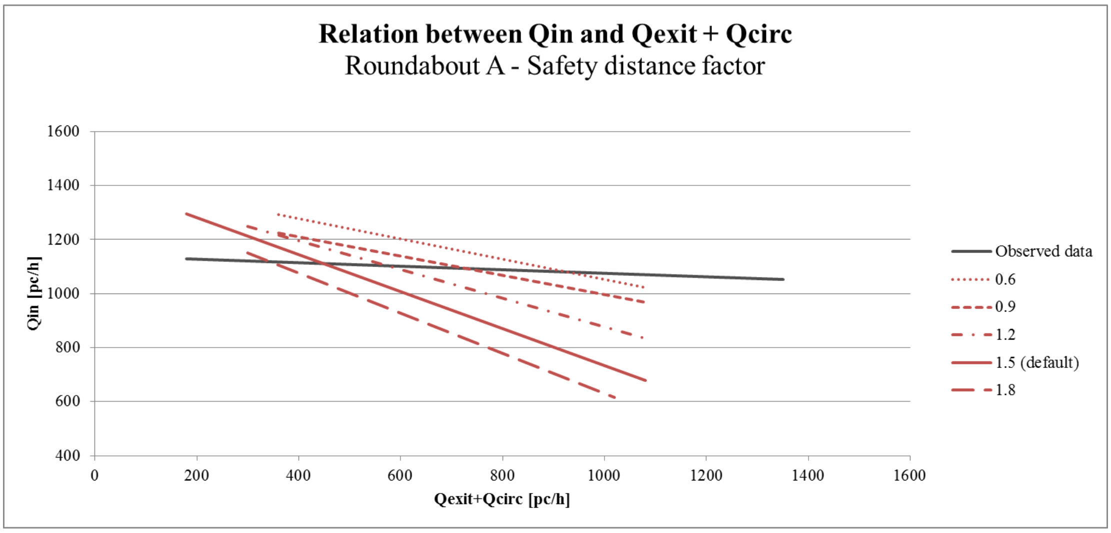


Figure 6.1 Results of CA simulation with adjusted safety distance factor – Roundabout A.

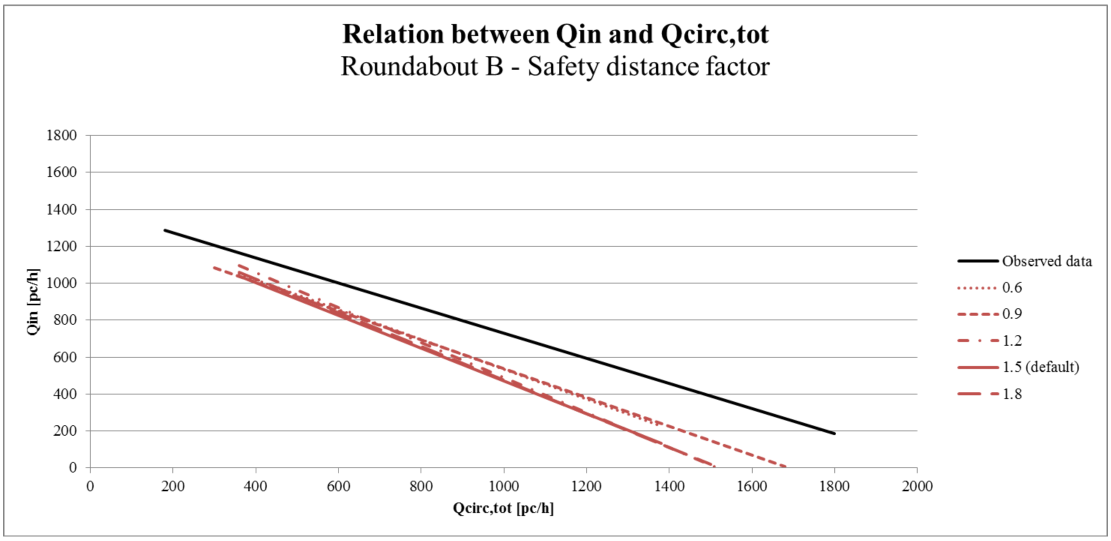


Figure 6.2 Results of CA simulation with adjusted safety distance factor – Roundabout B.

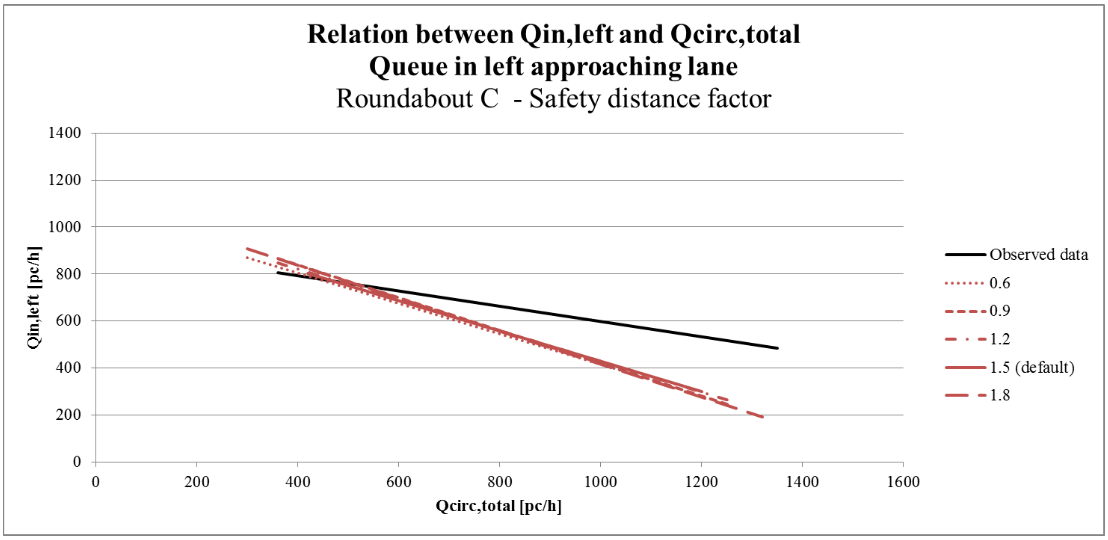


Figure 6.3 Results of CA simulation with adjusted safety distance factor – Roundabout C queue in left lane.

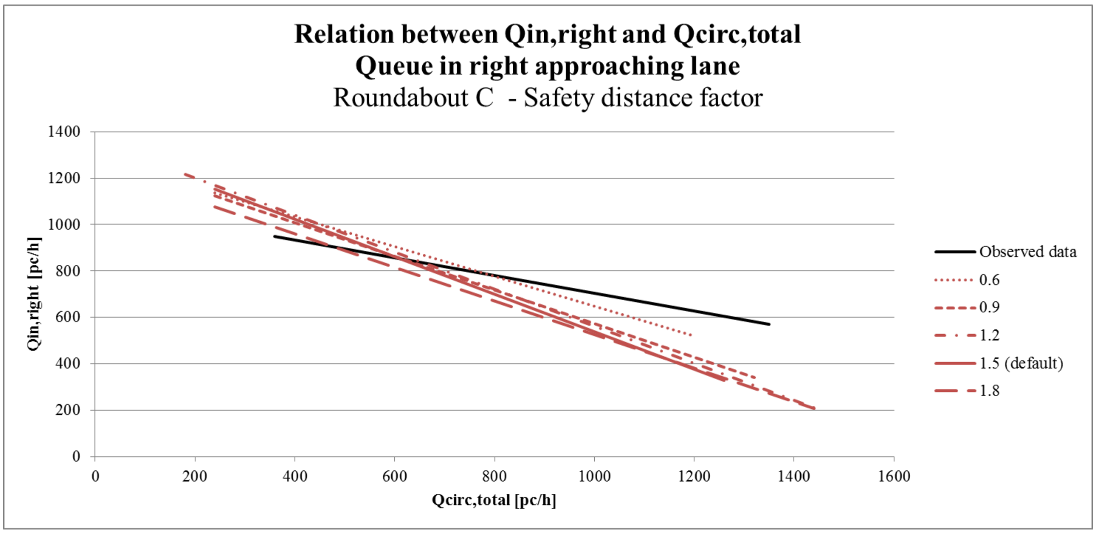


Figure 6.4 Results of CA simulation with adjusted safety distance factor – Roundabout C queue in right lane.

6.1.2 Anticipate route

The results for all roundabouts of the simulations with *CA* with changed values for the parameter *anticipate route* are shown in Figure 6.5 to Figure 6.8. The results for roundabout A show an almost linear trend between the increase of *anticipate route* and the increase of ingoing flow. According to Figure 6.5 an increase to 50 % gives an increase of 150 pc/h of the ingoing flow. The same effect is occurring for a further increase to 100%. The best correlation is observed with 70 %. For roundabout B and C no obvious trend or significant change can be observed, as seen in Figure 6.6 to Figure 6.8.

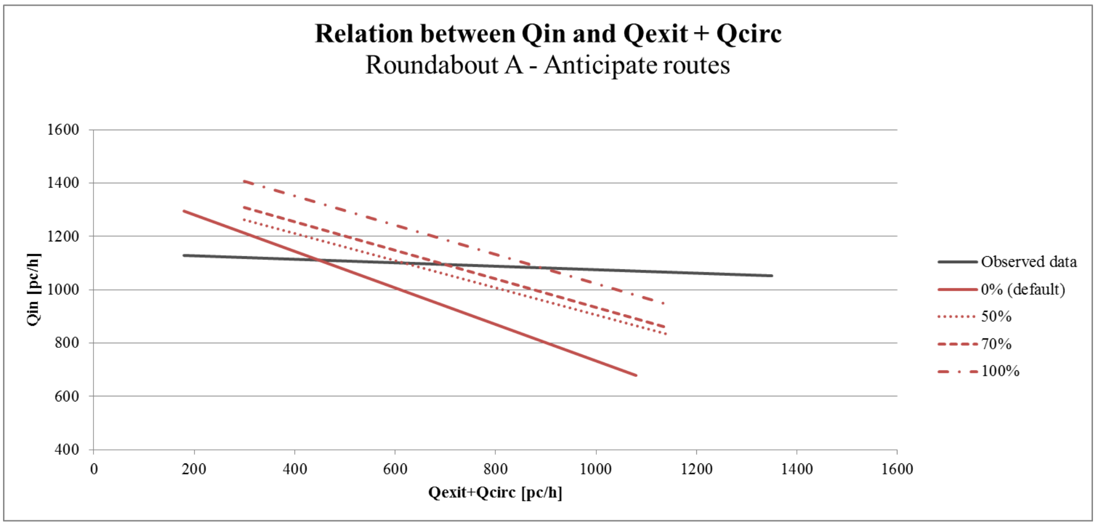


Figure 6.5 Results of CA simulation with adjusted anticipate routes – Roundabout A.

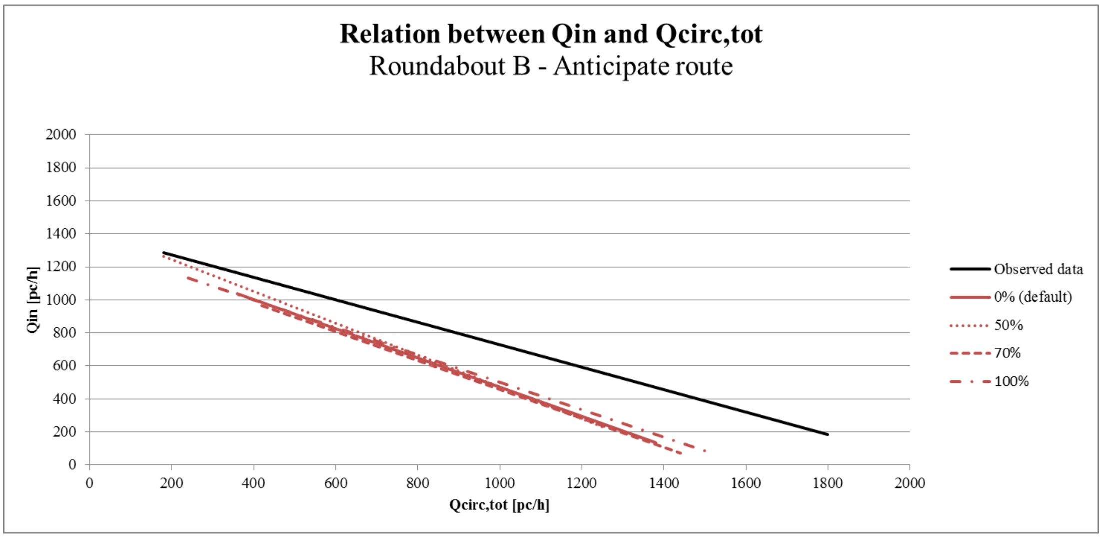


Figure 6.6 Results of CA simulation with adjusted anticipate routes - Roundabout B.

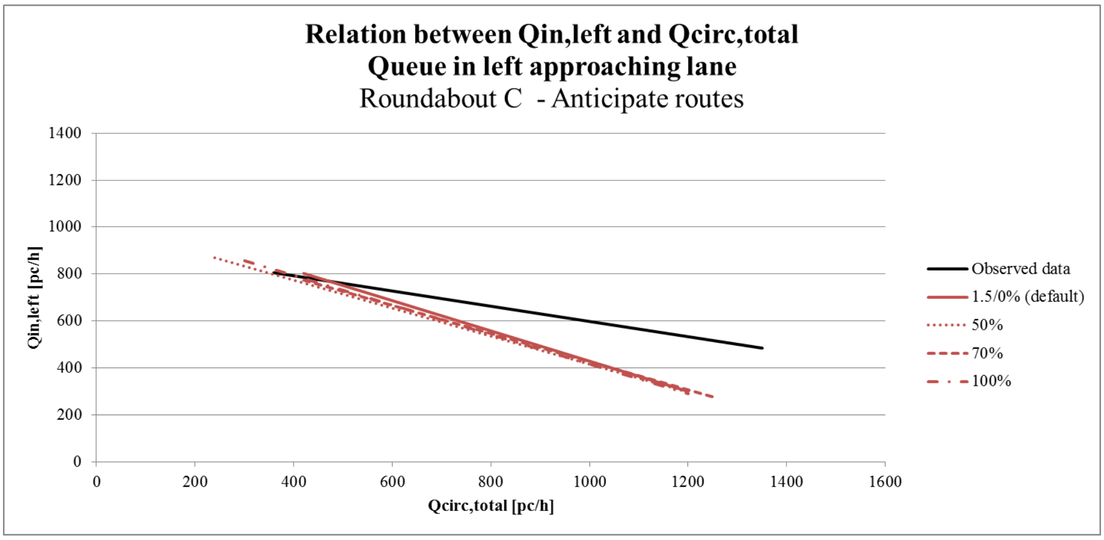


Figure 6.7 Results of CA simulation with adjusted anticipate routes – Roundabout C queue in left lane.

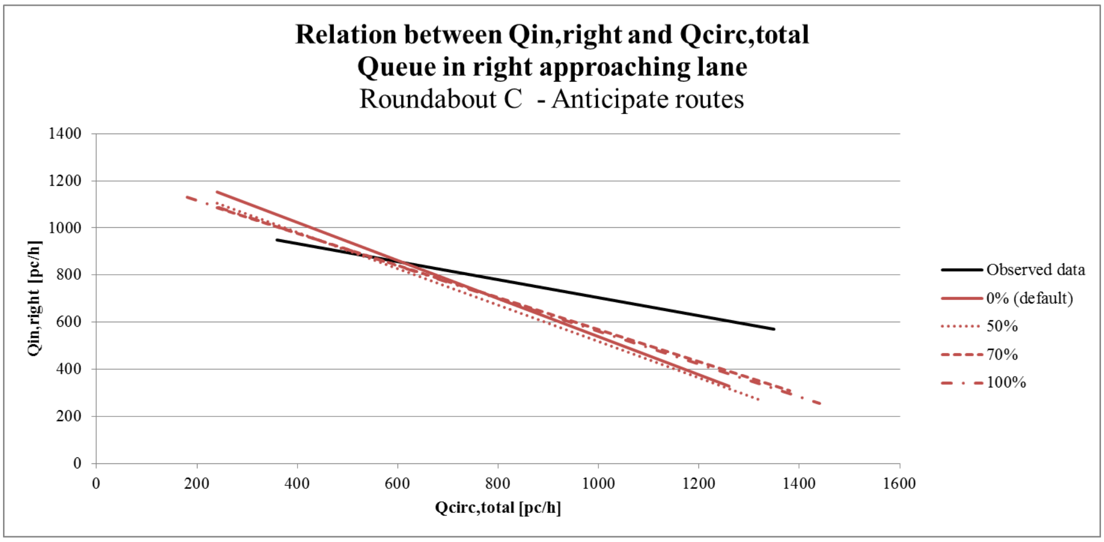


Figure 6.8 Results of CA simulation with adjusted anticipate routes – Roundabout C queue in right lane.

6.1.3 Rear gap and front gap

This investigation is only done for roundabouts where crossing flows occur, i.e. roundabouts with two circulating lanes. Since roundabout A only consists of one circulating lane no crossing conflicts occur between ingoing and circulating flows and it has thus not been studied for this parameter. Roundabout B and C show no significant change, neither for *rear gap* nor for *front gap*. Since the results for both cases are similar only results for roundabout B are presented, see Figure 6.9. Results for roundabout C can be found in Appendix III.

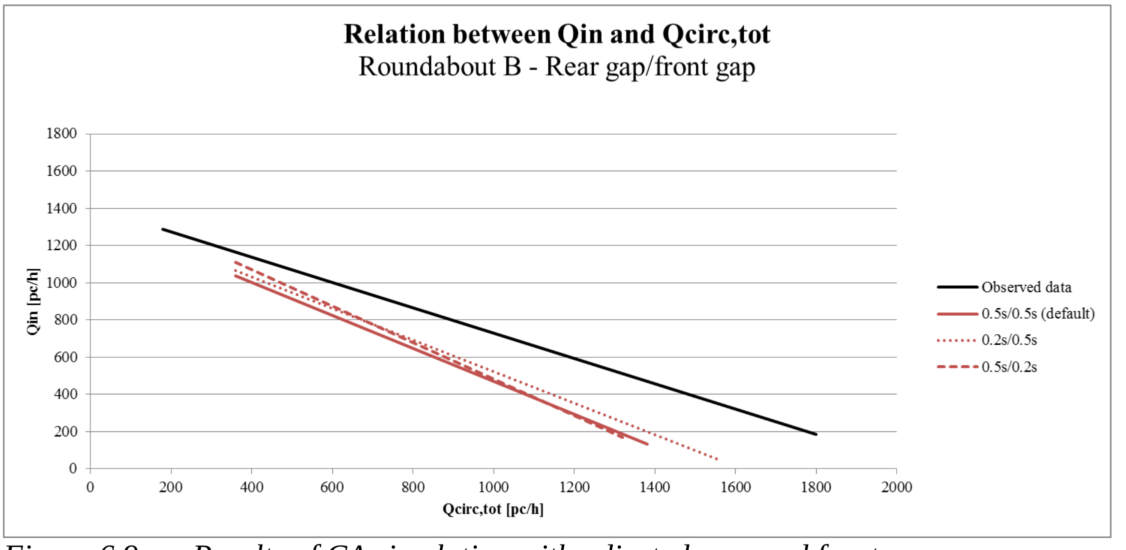


Figure 6.9 *Results of CA simulation with adjusted rear and front gap - Roundabout B*

6.2 Priority rules

When simulating with *PR* the parameters *minimum gap time* and *minimum headway* were adjusted. The greatest impact is observed for *minimum gap time*.

6.2.1 Minimum gap time

The results for all roundabouts of the simulations with *PR* with changed values for the parameter *minimum gap time* are illustrated in Figure 6.10 to Figure 6.13. An increase of the parameter leads to a decrease of ingoing flow. This trend can clearly be seen in the results for all cases. Overall, the default value of 3.0 seconds gives well correlating results as the respective trend lines intersect with the trend line of observed data in the middle of the line. One exception is the left lane of roundabout C, where a *gap time* of 3.5/3.6 seconds matches better, see Figure 6.12.

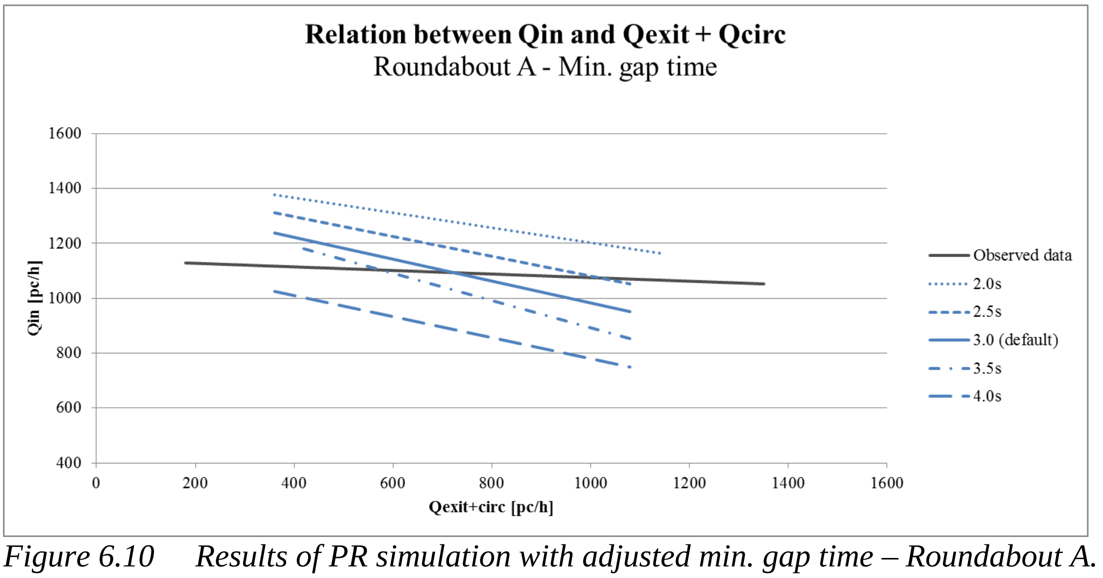


Figure 6.10 *Results of PR simulation with adjusted min. gap time – Roundabout A.*

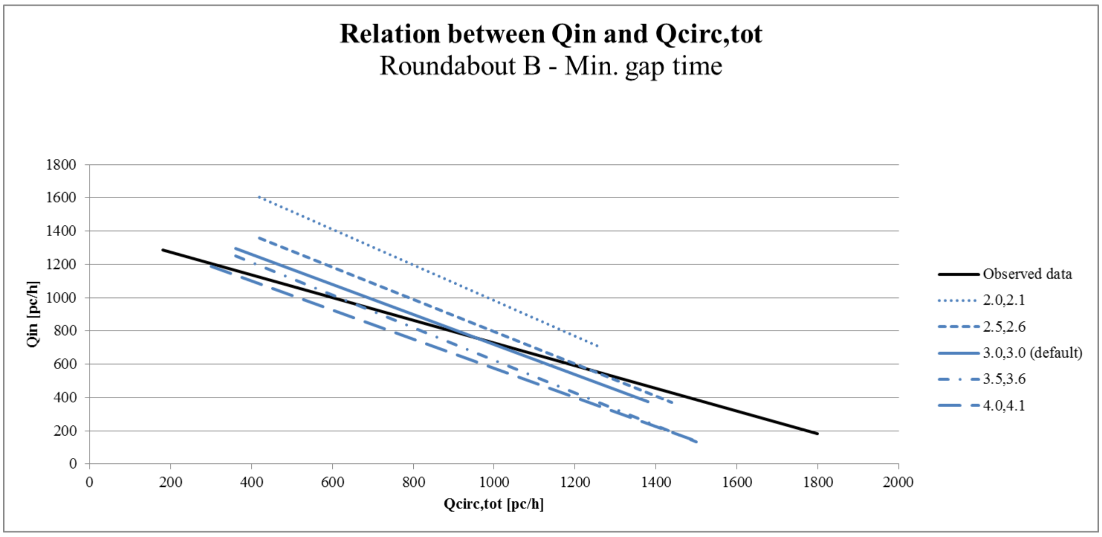


Figure 6.11 Results of PR simulation with adjusted min. gap time – Roundabout B.

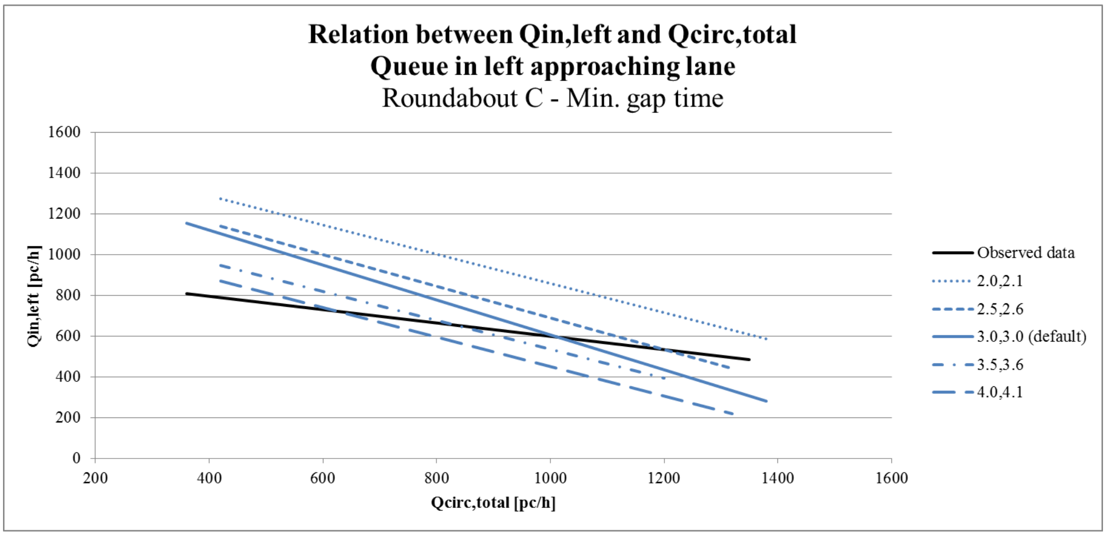


Figure 6.12 Results of PR simulation with adjusted min. gap time – Roundabout C queue in left lane.

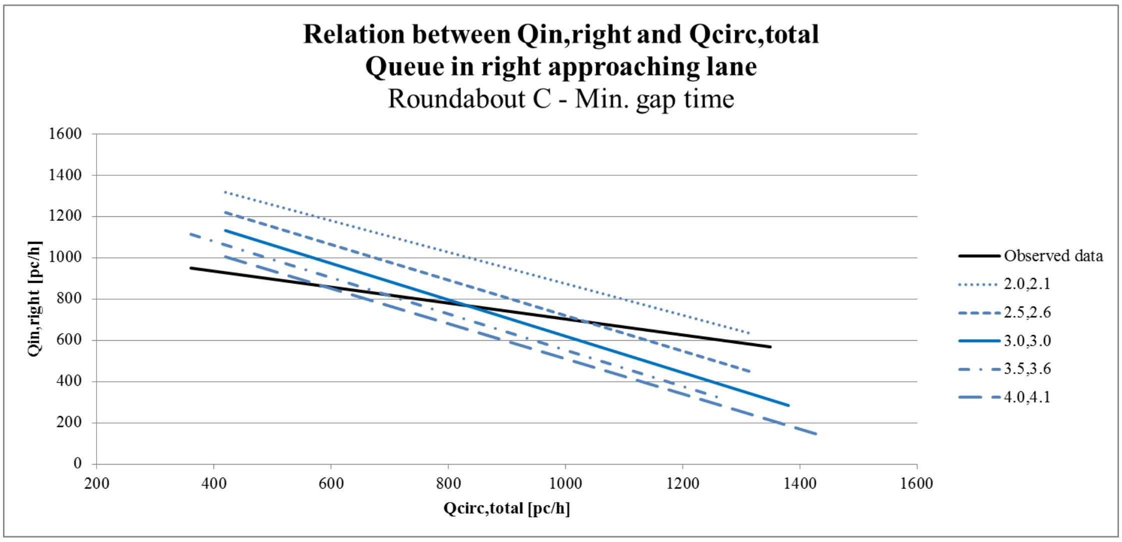


Figure 6.13 Results of PR simulation with adjusted min. gap time – Roundabout C queue in right lane.

6.2.2 Minimum headway

The results for all roundabouts show no significant changes when adjusting *minimum headway*. Since the results for all cases are similar only results for roundabout A are presented in Figure 6.14. Results for roundabout B and C can be found in Appendix III.

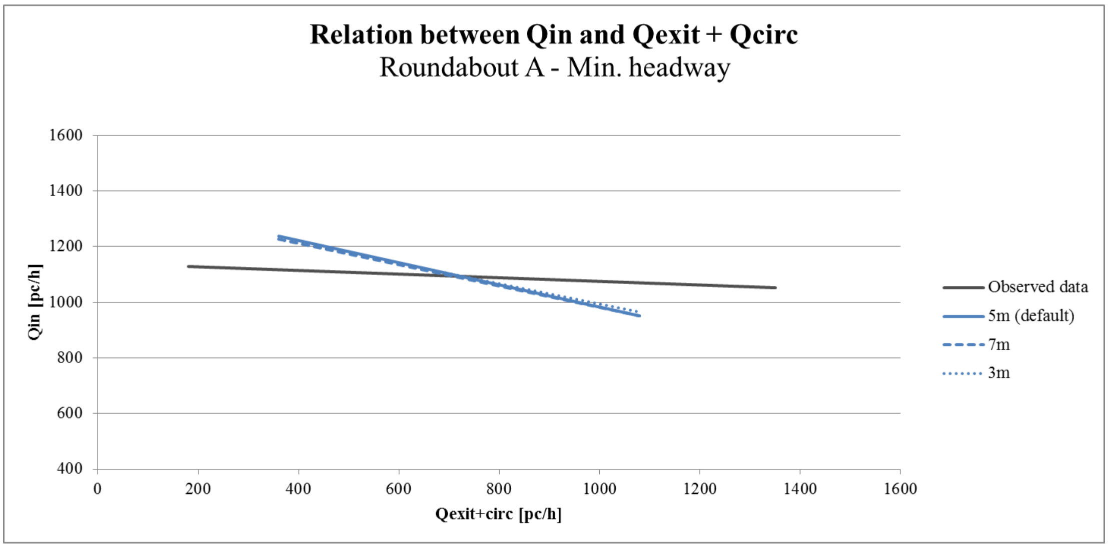


Figure 6.14 Results of PR simulation with adjusted min. headway – Roundabout A.

6.3 Driving behaviour

The results for all roundabouts show no significant change when adjusting the *driving behaviour*. Since the results for all cases are similar only results for roundabout B are presented in Figure 6.15. Results for roundabout A and C can be found in Appendix III.

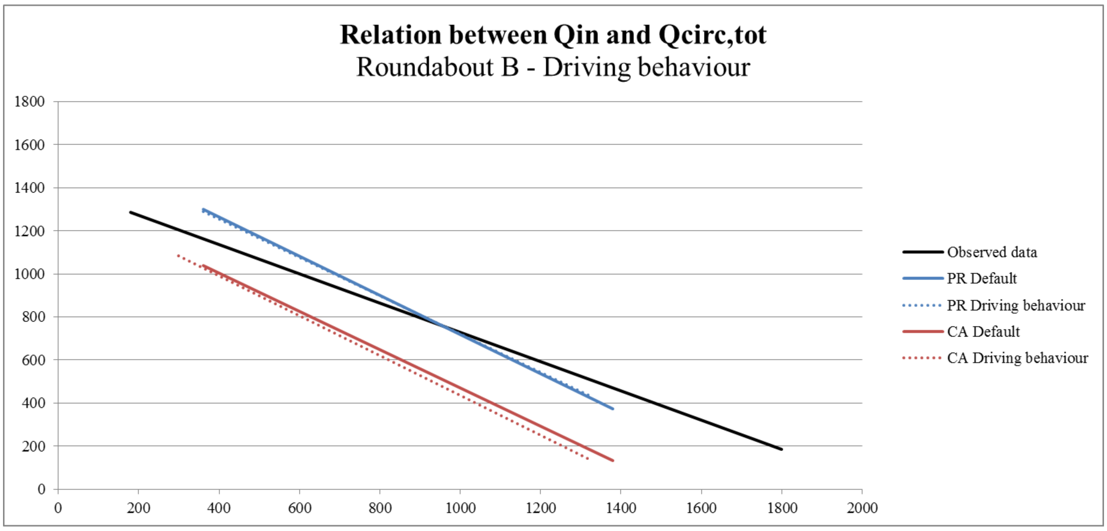


Figure 6.15 Results of PR and CA simulation with adjusted driving behaviour - Roundabout B.

7 Calibration & Recommendations

While Chapter 6 presents the effects of the parameters separately this chapter investigates the effects when adjusting several parameters in combination in order to achieve most suitable results. This is done as an iterative process where the simulation of each case is repeated while adjusting the parameters until an acceptable result can be observed, also called calibration. The recommendations provided in this chapter are for the specific characteristics of the three investigated roundabouts with their respective flows. For similar roundabouts with different flow relations the parameters settings might have to be adjusted.

For *driving behaviour* the default values are kept in all cases since no changes were noticed when testing it separately. During all calibration with *PR* adjustments of *minimum headway* were neglected due to the fact that travelling speeds lower than 14km/h do not occur. It is thus kept at the default value of 5m.

7.1 Roundabout A

When simulating a roundabout with the characteristics of roundabout A with *conflict areas* the best correlating result, see Figure 7.1, can be achieve with the parameter setting in Table 7.1.

Table 7.1 Recommended parameter settings of CA simulation for Roundabout A.

Parameter CA	
Safety distance factor [-]	1.0
Anticipate routes [%]	0 (default)
Rear gap / Front gap [s]	0.5 / 0.5 (default)

The trend line with a *safety distance factor* of 1.0 intersects with the trend line of observed data where the average circulating and exiting flow approximately occurs. This is at 670 passenger cars per hour. This means that all overestimations and all underestimations even each other out. For *rear and front gap* the default values are kept since no crossing flows occur in roundabout A.

When simulating a roundabout with the characteristics of roundabout A with *priority rules* the best correlating results, see Figure 7.1, can be achieve with parameter settings according to Table 7.2.

Table 7.2 Recommended parameter settings of PR simulation for Roundabout A.

Parameter PR	
Min. gap time [s]	3.1
Min. headway [m]	5 (default)

The intersection point of the trend lines of observed data and recommendation is closest to the conflicting flow of 670 passenger cars per hours. Further on, an adjustment of *minimum headway* is not of importance for roundabout A as there are no crossing flows.

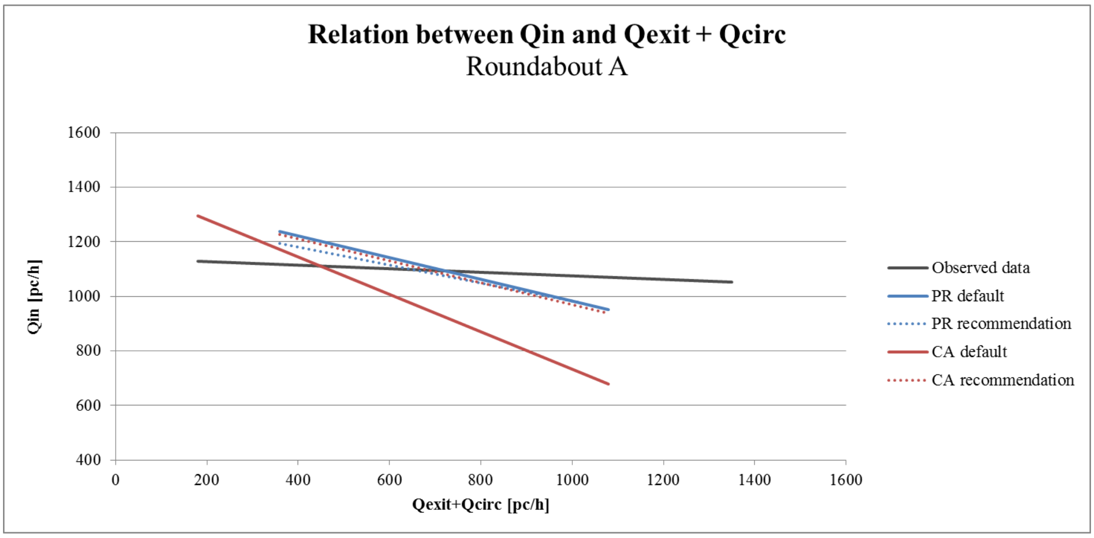


Figure 7.1 Results of simulation with calibrated parameters for Roundabout A.

7.2 Roundabout B

The best result when simulating roundabouts with similar characteristics as roundabout B with *CA* is achieved with the parameters presented in Table 7.3. Figure 7.2 illustrates the respective results.

Table 7.3 Recommended parameter settings of CA simulation for Roundabout B.

Parameter CA	
Safety distance factor [-]	0.9
Anticipate routes [%]	0 (default)
Rear gap / Front gap [s]	0.2 / 0.5

Since the *safety distance factor* at 0.9 gives closest correlation to the observed data it was chosen for the recommendation. Although *rear gap* did not show an effect separately, in combination with other parameters it gave an effect on the result.

The best results, shown in Figure 7.2, when simulating roundabouts with similar characteristics as roundabout B with *PR* is achieved with the default values as stated in Table 7.4. The intersection point of these lines is closest as possible to an average circulating flow of 840 pc/h.

Table 7.4 Recommended parameter settings of PR simulation for Roundabout B.

Parameter PR	
Min. gap time [s]	3.0 (default)
Min. headway [m]	5 (default)

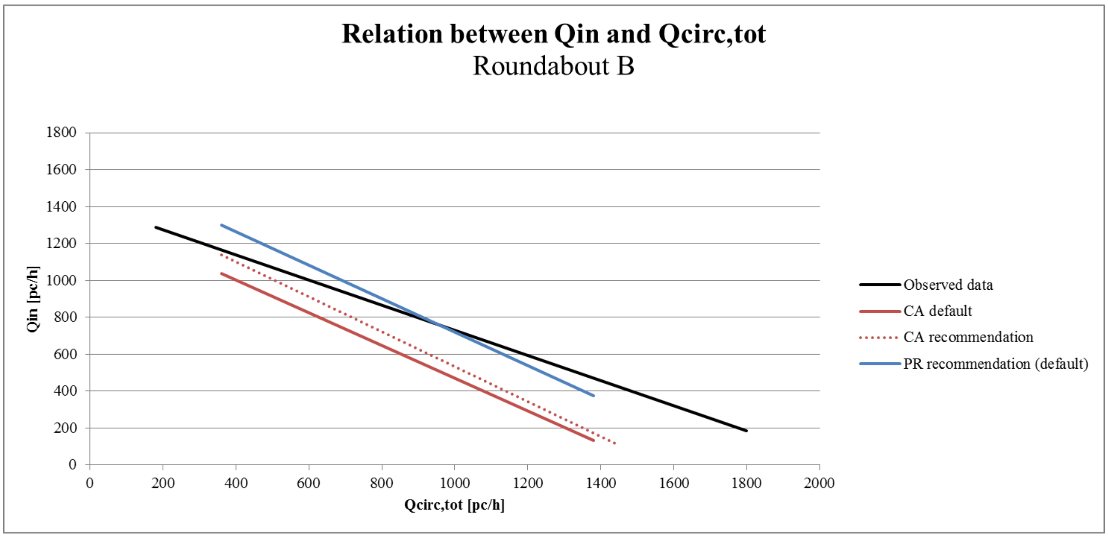


Figure 7.2 Results of simulation with calibrated parameters for Roundabout B.

7.3 Roundabout C

The recommended parameters for roundabouts with characteristics similar to roundabout C are listed in Table 7.5. The results are depicted in Figure 7.3 for the left lane and in Figure 7.4 for the right lane.

Table 7.5 Recommended parameter settings of CA simulation for Roundabout C.

Parameter CA	
Safety distance factor [-]	0.6
Anticipate routes [%]	0 (default)
Rear gap / Front gap [s]	0.5 / 0.5 (default)

While no changes towards better results can be achieved with *conflict areas* for the left lane it is possible for the right lane. Therefore, the best possible adjustments for the right lane are taken for the recommendation. For *rear and front gap* the default value is kept as no significant changes were observed when adjusting this parameter.

When simulating roundabout C with *PR* it is recommended to apply the parameters summarized in Table 7.6 which lead to results as shown in Figure 7.3 and Figure 7.4.

Table 7.6 Recommended parameter settings of PR simulation for Roundabout C.

Parameter PR	**Left lane**	**Right lane**
Min. gap time [sec]	3.4/3.5	2.8/2.9
Min. headway [m]	5 (default)	5 (default)

For the left approaching lane a longer gap time is needed. The *minimum gap times* have been chosen individually for each lane depending on the best results for each lane. It was aimed that the trend lines cross the trend line of observed data at a total circulating flow as close as possible to 870 passenger cars per hour which corresponds to the average flow.

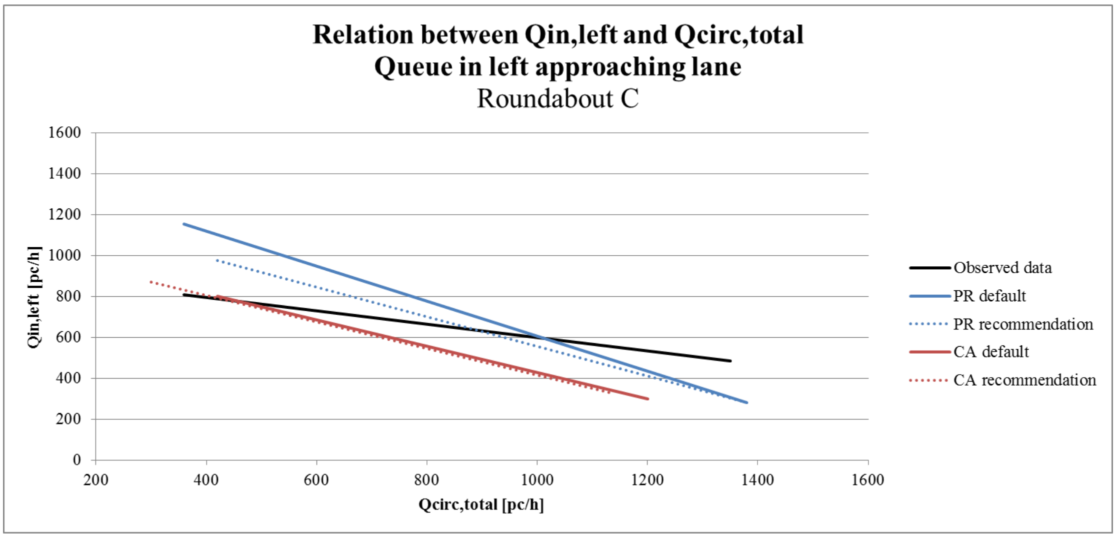


Figure 7.3 Results of simulation with calibrated parameters for Roundabout C – queue in left lane.

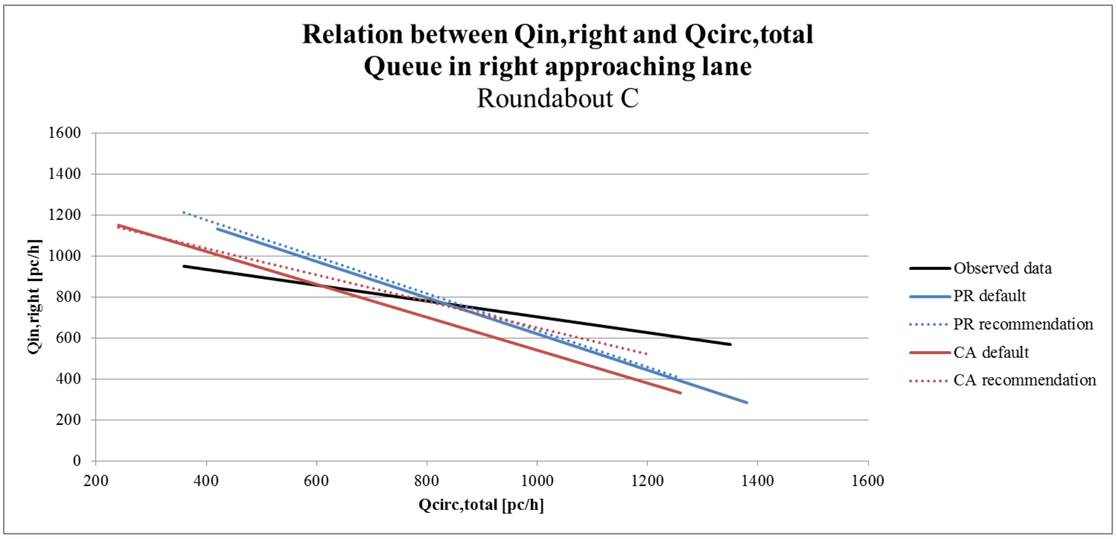


Figure 7.4 Results of simulation with calibrated parameters for Roundabout C – queue in right lane.

8 Discussion and conclusion

Overall, the study shows that when simulating with default values for all parameters, *priority rules* give better result than *conflict areas*. The latter leads to an underestimation of the capacity. This counts for all types of roundabouts.

During the testing process the most significant changes could be seen when adjusting the parameters *minimum gap time* for *priority rules* and *safety distance factor* as well as *anticipate route* for *conflict areas.* Although several of the parameters did not have an effect on the results when tested separately, in combination with other parameters they could show an effect.

When adjusting the *safety distance factor* a linear pattern was observed in the results for roundabout A. However, this pattern does not account for the other roundabouts. A reason for this random behaviour of the results might be due to the complexity of roundabout B and C since they have more than one circulating lane. Mainly values in the range of 0.6 to 1.0, which are lower than the default value, show good correlation to the observed data.

Changes of the parameter *anticipate routes* have a bigger influence on the simulation of smaller roundabouts. This might be due to the fact that interacting flows lie close to each other. It makes the observation of other vehicles more important than in larger roundabouts. If for example a circulating vehicle shows signal to exit the roundabout the driver in the ingoing lane would wait given an *anticipate route* of zero percent. With a higher *anticipate route* the driver could enter as soon as registering the signal given by the circulating vehicle. In a big roundabout the distance between the exiting lane and the ingoing lane is longer than the necessary headway. The driver in the ingoing lane only has to look at vehicles that are circulating since they are the only ones who will block the accepted gap. The exiting vehicles will drive out of the roundabout before reaching and blocking the accepted gap. When the circulating vehicle is blocking the accepted gap it will definitely reach the ingoing vehicle. This means that the *anticipate route* will not make any difference since there is no other choice of route that the vehicle can make.

The reason for the non-existing changes of the result when altering the *rear gap* can be explained by the fact that the drivers choose the biggest defined gap. If for example a certain rear gap gives an acceptable gap of 10 m and at the same time a certain SDF gives an acceptable gap of 12 m the gap that the drivers require will be determined by the higher value of these, in this case 12 m. Although *rear and front gap* did not show an effect separately, in combination with other parameters they gave an effect on the results for roundabout B and C. For roundabout B the effect on the result is positive which is why it is used in the recommendations. For roundabout C it did not have a positive effect which means that the default value is preferred.

An increase of *minimum gap time* leads in all cases to a decrease of capacity. This is due to the fact that fewer gaps, only the ones with long gap times, can be accepted by the drivers and thus fewer vehicles can enter the roundabout. The default duration of 3.0 seconds gives good results for all cases, except for the left approaching lane of roundabout C. Longer gap times are needed for the latter because of the complex entering manoeuvre into the inner circulating lane whereby the outer circulating lane has to be crossed first.

Priority rule markers that define the *minimum headway* only detect slow moving vehicles. When changing *minimum headway* no significant changes were noticed due to the fact that driving speeds of less than 14 km/h do not occur. The *reduced speed areas* are set to 20 to 45 km/h, which is the speed that the drivers aim for.

The changes in *driving behaviour* include a decrease of visual distance to the front and back as well an increase of lack of attention. As the roundabouts describe a small area the drivers do not need a long visual distance in order to observe all necessary traffic. In addition to this, only one percent of the drivers have a lack of attention. This is very little and has thus almost no influence.

Based on the observation mentioned above the general recommendation is to apply *conflict area* with adjusted parameters for simple roundabouts (A). It leads to equally good results as *priority rules* but there is less risk of mistakes during the modelling process. The recommendation for complex roundabouts is to use *priority rules*. For roundabouts with one ingoing lane (B) default values can be applied. For roundabouts with two ingoing lanes (C) it requires adjusted parameters.

The study shows that a model is a representation of reality that is minimised in its complexity through assumptions and simplifications. Thus, exact equal results cannot be achieved. One simplification of the gap acceptance model in Vissim is that all drivers behave homogenous. It might not be realistic as drivers do not behave identically. More aggressive drivers for example accept smaller gaps than less aggressive drivers. Another assumption is that good weather and good pavement conditions are given. Further on, the familiarity of drivers with the facility and the absence of impediments are assumed. These conditions are not considered to be valid all the time in reality. Throughout the study most basic conditions were given although it is estimated that not all drivers are familiar with the roundabout. One example that has been observed is vehicles driven by students of driving schools.

As the study is limited to the area of Gothenburg, and the driving behaviour of its citizens, the recommendations might not be applicable to all cities. There might be more or less aggressive behaviour in other places.

The roundabouts are situated in different parts of the city where there might be a difference in behaviour depending on how good the drivers know the area. For example, the exact same type of roundabout used by commuter could lead to a higher capacity than if used by tourists.

The results of the data collection might have been influenced by the setup during the observation. The cameras were place visible for all drivers, whose attention could have been disturbed. The driving behaviour might thus have been affected. It was however technically not possible to place the cameras unnoticeable for the drivers.

It was challenging to find roundabouts where both requirements are fulfilled continuously. The time frame of this study additionally limited the amount of collected data. Therefore roundabouts where the requirements are given temporarily had to be chosen and traffic could only be counted in short and varying time intervals of 20 to 60 seconds. By converting those intervals into a common unit of 60 seconds, small errors might have been multiplied. If for example a time interval of 30 seconds was observed, it has then been multiplied by two. In this way it is assumed that the last 30 seconds behave identically to the first 30 seconds, which may not be the case. This error is then magnified with the factor 60 by converting it to the common unit of "passenger cars / hour".

Finally, it is important to remember that the given recommendations of parameters are calibrated in order to suit the investigated types of roundabouts with their respective flows. The parameters can therefore differ for roundabouts with other characteristics or other flows. In this case, Chapter 6 (Testing of parameters) can be used as a guidance to adjust the parameter settings for a specific flow.

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Appendix I

The flows in pc/h are calculated by the following formula:

$$\frac{Q\ [veh/t]}{t\ [sec/t]} * 3600\ [\frac{sec}{hour}] = x\ [\frac{veh}{hour}]$$

Data collected at roundabout A

	time interval t	Q_{in}	$Q_{in,}$ (HGV/bus)	Q_{circ}	$Q_{circ,}$ (HGV/bus)	Q_{exit}	$Q_{exit,}$ (HGV/bus)	Q_{in}	Q_{circ}	Q_{exit}	Q_{circ} + Q_{exit}
	$[mm:ss]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$
1	00:50	17	0	1	0	12	0	1224	72	864	936
2	00:20	6	0	0	0	6	0	1080	0	1080	1080
3	01:00	16	1	0	0	11	0	1020	0	660	660
4	01:00	19	0	2	0	8	0	1140	120	480	600
5	01:00	16	0	2	0	9	0	960	120	540	660
6	00:30	11	0	1	0	6	0	1320	120	720	840
7	00:50	14	0	3	0	4	0	1008	216	288	504
8	00:20	6	0	0	0	1	1	1080	0	360	360
9	01:00	20	0	2	0	10	1	1200	120	660	780
10	01:00	16	0	1	0	12	1	960	60	780	840
11	01:00	16	0	4	0	10	0	960	240	600	840
12	00:20	6	0	1	0	0	0	1080	180	0	180
13	00:20	7	0	0	0	3	0	1260	0	540	540
14	00:20	7	0	0	0	3	0	1260	0	540	540
15	00:30	10	0	1	0	1	0	1200	120	120	240
16	00:20	5	0	2	0	3	0	900	360	540	900
17	00:40	10	1	3	0	8	0	990	270	720	990
18	01:00	17	0	2	0	7	0	1020	120	420	540
19	00:50	16	0	1	0	11	0	1152	72	792	864
20	01:00	15	0	5	0	9	0	900	300	540	840
21	00:20	8	0	0	0	3	0	1440	0	540	540
22	00:50	16	0	0	0	4	0	1152	0	288	288
23	01:00	14	0	3	0	10	0	840	180	600	780
24	01:00	17	0	1	0	12	0	1020	60	720	780
25	00:30	10	0	0	0	6	0	1200	0	720	720
26	00:20	5	0	0	0	4	0	900	0	720	720
27	01:00	18	0	2	0	6	0	1080	120	360	480
28	00:30	6	0	1	0	6	0	720	120	720	840
29	01:00	18	0	4	0	3	0	1080	240	180	420
30	00:30	11	0	1	0	4	0	1320	120	480	600
31	01:00	17	0	2	0	10	0	1020	120	600	720
32	00:30	8	0	1	0	2	0	960	120	240	360

33	00:50	15	0	2	0	8	0	1080	144	576	720
34	00:50	15	0	1	0	5	0	1080	72	360	432
35	00:40	14	0	0	0	4	0	1260	0	360	360
36	00:40	13	0	1	0	4	0	1170	90	360	450
37	00:20	6	0	1	0	6	0	1080	180	1080	1260
38	00:40	10	0	1	0	4	0	900	90	360	450
39	00:30	9	0	1	0	5	0	1080	120	600	720
40	00:50	14	0	3	0	6	0	1008	216	432	648
41	00:40	12	0	1	0	2	0	1080	90	180	270
42	00:50	13	0	0	0	12	0	936	0	864	864
43	01:00	20	0	2	0	9	0	1200	120	540	660
44	00:40	11	0	2	0	3	0	990	180	270	450
45	01:00	18	0	2	0	10	0	1080	120	600	720
46	01:00	15	0	2	0	13	0	900	120	780	900
47	00:30	8	0	1	0	6	0	960	120	720	840
48	00:40	9	0	5	0	10	0	810	450	900	1350
49	01:00	17	0	4	0	11	0	1020	240	660	900
50	01:00	15	0	3	0	7	0	900	180	420	600
51	01:00	18	0	3	0	7	0	1080	180	420	600
52	00:40	13	0	1	0	2	0	1170	90	180	270
53	01:00	15	0	4	0	7	0	900	240	420	660
54	01:00	19	0	1	0	7	0	1140	60	420	480
55	00:50	16	0	1	0	12	0	1152	72	864	936
56	01:00	18	0	1	0	9	0	1080	60	540	600
57	00:40	13	0	1	0	6	0	1170	90	540	630
58	01:00	19	0	2	0	7	0	1140	120	420	540
59	00:20	7	0	1	0	1	0	1260	180	180	360
60	00:40	13	0	1	0	5	0	1170	90	450	540
61	01:00	18	0	1	0	13	0	1080	60	780	840
62	00:50	16	0	3	0	10	0	1152	216	720	936
63	00:30	10	0	2	0	3	0	1200	240	360	600
64	00:30	6	0	3	0	2	0	720	360	240	600
65	00:40	15	1	0	0	12	0	1440	0	1080	1080
66	01:00	19	1	0	0	8	0	1200	0	480	480
67	00:40	13	0	2	0	5	0	1170	180	450	630
68	00:20	7	0	0	0	3	0	1260	0	540	540
69	01:00	19	0	0	0	4	0	1140	0	240	240
70	00:20	7	1	1	0	4	0	1440	180	720	900
71	00:30	11	0	0	0	6	0	1320	0	720	720
72	00:30	10	0	0	0	8	0	1200	0	960	960
73	00:20	8	0	0	0	6	0	1440	0	1080	1080
74	01:00	19	0	0	0	11	0	1140	0	660	660
75	01:00	19	0	0	0	12	1	1140	0	780	780
Average								1097	114	556	670

Data collected at roundabout B

	time interval t	Q_{in}	Q_{in} (HGV/bus)	$Q_{circ, outer}$	$Q_{circ, outer}$ (HGV/bus)	$Q_{circ, inner}$	$Q_{circ, inner}$ (HGV/bus)	Q_{exit}	Q_{in}	$Q_{circ, outer}$	$Q_{circ, inner}$	$Q_{circ, total}$
	$[mm:ss]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$
1	01:00	13	0	6	0	8	0	9	780	360	480	840
2	00:50	13	2	4	0	4	0	6	1080	288	288	576
3	00:40	11	1	2	0	4	0	11	1080	180	360	540
4	00:20	5	0	4	0	1	0	3	900	720	180	900
5	00:30	8	0	5	0	0	0	4	960	600	0	600
6	00:50	10	0	9	0	5	0	11	720	648	360	1008
7	00:20	7	0	2	0	1	0	3	1260	360	180	540
8	00:20	3	0	2	0	3	0	1	540	360	540	900
9	00:30	5	0	6	0	5	0	6	600	720	600	1320
10	00:40	8	0	5	0	4	0	4	720	450	360	810
11	00:20	7	0	2	0	2	0	6	1260	360	360	720
12	00:50	13	0	5	0	6	0	6	936	360	432	792
13	00:30	8	0	3	0	3	0	6	960	360	360	720
14	00:40	11	0	5	0	5	0	9	990	450	450	900
15	00:50	9	0	3	0	7	0	6	648	216	504	720
16	00:30	10	0	3	0	1	0	3	1200	360	120	480
17	00:30	7	0	4	0	2	0	7	840	480	240	720
18	00:30	9	0	3	0	1	0	4	1080	360	120	480
19	00:20	9	0	0	0	1	0	1	1620	0	180	180
20	00:30	8	0	3	0	1	0	4	960	360	120	480
21	00:30	9	0	1	0	2	0	5	1080	120	240	360

22	00:20	7	0	0	0	1	0	1	1260	0	180	180
23	00:20	2	0	2	0	6	0	2	360	360	1080	1440
24	00:20	4	0	4	0	3	0	1	720	720	540	1260
25	00:40	8	0	4	0	6	0	4	720	360	540	900
26	00:20	4	0	0	0	3	0	7	720	0	540	540
27	00:20	8	0	2	0	1	0	2	1440	360	180	540
28	01:00	10	0	5	0	10	0	12	600	300	600	900
29	00:20	5	0	2	0	4	0	4	900	360	720	1080
30	00:20	8	0	2	0	1	0	0	1440	360	180	540
31	00:20	2	0	6	0	4	0	2	360	1080	720	1800
32	00:30	1	0	3	0	10	0	6	120	360	1200	1560
33	00:20	7	0	0	0	1	0	1	1260	0	180	180
34	00:20	8	0	1	0	0	0	6	1440	180	0	180
35	01:00	9	0	7	1	10	0	14	540	480	600	1080
36	00:20	5	0	2	0	1	0	4	900	360	180	540
37	00:40	5	0	4	0	10	0	2	450	360	900	1260
38	00:30	9	0	3	0	2	0	7	1080	360	240	600
39	00:20	2	0	4	0	4	0	4	360	720	720	1440
40	00:30	6	0	5	0	3	0	1	720	600	360	960
41	00:20	4	0	0	0	6	0	1	720	0	1080	1080
42	00:50	10	0	5	0	7	0	4	720	360	504	864
43	00:20	3	0	5	0	2	0	4	540	900	360	1260
44	00:20	3	0	4	0	2	0	5	540	720	360	1080
45	00:20	2	0	1	0	7	0	0	360	180	1260	1440
46	00:20	3	0	0	0	7	0	4	540	0	1260	1260
47	00:30	9	0	1	0	3	0	11	1080	120	360	480

48	00:50	7	0	7	0	10	0	10	504	504	720	1224
49	00:40	11	0	4	0	5	0	6	990	360	450	810
50	00:40	10	0	4	0	4	0	5	900	360	360	720
51	00:50	11	0	5	0	9	0	9	792	360	648	1008
52	00:30	10	0	1	0	5	0	6	1200	120	600	720
53	00:20	1	0	2	0	5	0	3	180	360	900	1260
54	00:20	2	0	6	0	3	0	0	360	1080	540	1620
55	00:40	9	0	4	0	4	0	8	810	360	360	720
56	00:30	8	0	3	0	4	0	4	960	360	480	840
57	00:20	6	0	2	0	3	0	2	1080	360	540	900
58	00:30	4	0	6	0	3	0	6	480	720	360	1080
59	01:00	12	0	10	0	7	0	10	720	600	420	1020
60	01:00	14	0	6	0	11	0	13	840	360	660	1020
61	00:40	9	0	4	0	5	0	6	810	360	450	810
62	00:20	7	0	0	0	1	0	4	1260	0	180	180
63	00:20	5	0	2	0	2	0	3	900	360	360	720
64	00:20	7	0	1	0	1	0	6	1260	180	180	360
65	01:00	10	0	5	0	12	0	8	600	300	720	1020
66	00:20	6	0	1	0	1	0	4	1080	180	180	360
67	00:30	5	0	7	0	5	0	4	600	840	600	1440
68	00:20	4	0	1	0	3	0	5	720	180	540	720
69	00:50	8	1	5	0	12	0	11	648	360	864	1224
70	00:30	8	0	1	0	7	0	5	960	120	840	960
71	00:40	8	0	7	0	7	0	8	720	630	630	1260
72	00:20	6	0	1	0	0	0	2	1080	180	0	180
73	00:20	8	0	1	0	1	0	3	1440	180	180	360

74	00:20	3	0	4	0	3	0	3	540	720	540	1260
75	00:30	4	0	5	0	8	0	7	480	600	960	1560
76	00:40	7	0	4	0	5	0	9	630	360	450	810
77	00:50	12	0	3	0	9	0	10	864	216	648	864
78	01:00	15	0	5	0	7	0	13	900	300	420	720
79	00:30	7	0	4	0	3	0	3	840	480	360	840
80	00:40	8	0	5	0	5	0	9	720	450	450	900
81	00:40	7	0	8	0	7	0	8	630	720	630	1350
82	00:30	7	0	2	0	2	0	4	840	240	240	480
83	00:20	2	0	3	0	5	0	3	360	540	900	1440
84	00:20	8	0	1	0	1	0	0	1440	180	180	360
85	01:00	15	0	9	0	4	0	10	900	540	240	780
86	01:00	12	0	2	0	7	0	9	720	120	420	540
87	00:50	10	0	3	0	9	0	7	720	216	648	864
88	00:40	12	0	4	0	2	0	10	1080	360	180	540
89	01:00	10	1	6	0	12	0	15	660	360	720	1080
90	00:40	10	0	0	0	3	0	3	900	0	270	270
91	00:20	5	0	2	0	4	0	3	900	360	720	1080
92	00:30	9	0	1	0	5	0	3	1080	120	600	720
93	00:30	6	0	3	0	4	0	3	720	360	480	840
94	00:20	2	0	1	0	2	0	4	360	180	360	540
95	00:20	7	0	0	0	1	0	2	1260	0	180	180
96	00:20	2	0	4	0	4	0	0	360	720	720	1440
97	00:20	8	0	1	0	0	0	5	1440	180	0	180
98	00:30	9	0	3	0	3	0	3	1080	360	360	720
Average									841	369	467	836

Data collected at roundabout C

	Queue left	Queue right	Time interval t	$Q_{in,left}$	$Q_{in,left}$ (HGV/bus)	$Q_{in,right}$	$Q_{in,right}$ (HGV/bus)	$Q_{circ,inner}$	$Q_{circ,inner}$ (HGV/bus)	$Q_{circ,outer}$	$Q_{circ,outer}$ (HGV/bus)	$Q_{in,left}$	$Q_{in,right}$	$Q_{circ,inner}$	$Q_{circ,outer}$	$Q_{circ,total}$
	[yes=1]	*[yes=1]*	$[mm:ss]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{veh}{t}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$	$[\frac{pc}{h}]$
1	1	1	01:00	8	0	12	0	6	0	11	0	480	720	360	660	1020
2	1	1	00:50	6	0	9	0	8	0	6	0	432	648	576	432	1008
3	1	1	00:20	3	0	2	0	3	0	4	0	540	360	540	720	1260
4	1	1	00:40	7	0	8	0	7	0	4	0	630	720	630	360	990
5	1	1	00:20	4	0	4	0	4	0	1	0	720	720	720	180	900
6	1	1	01:00	11	0	14	1	10	0	4	0	660	900	600	240	840
7	1	1	00:40	9	0	9	0	6	0	1	0	810	810	540	90	630
8	1	1	00:30	7	0	9	0	5	0	1	0	840	1080	600	120	720
9	1	1	00:40	8	0	9	0	4	0	5	1	720	810	360	540	900
10	1	1	00:40	7	0	9	0	8	0	6	1	630	810	720	630	1350
11	1	1	01:00	7	0	9	0	14	0	2	0	420	540	840	120	960
12	1	1	00:20	4	0	4	1	3	0	3	0	720	900	540	540	1080
13	1	1	00:20	3	0	3	0	4	0	2	0	540	540	720	360	1080
14	1	1	00:30	6	0	6	0	2	0	4	0	720	720	240	480	720
15	1	1	00:50	7	0	9	0	10	0	6	1	504	648	720	504	1224
16	1	1	00:20	3	0	3	0	2	0	1	0	540	540	360	180	540
17	1	1	01:00	8	0	8	0	10	0	6	1	480	480	600	420	1020
18	1	1	00:20	5	0	4	0	1	0	3	0	900	720	180	540	720
19	1	1	00:40	6	0	6	0	3	0	8	0	540	540	270	720	990
20	1	1	00:40	6	0	7	0	9	0	3	0	540	630	810	270	1080

21	1	1	00:30	6	0	6	0	3	0	3	0	720	720	360	360	720
22	1	1	00:40	5	0	6	1	11	0	2	0	450	630	990	180	1170
23	1	1	01:00	12	0	13	0	12	0	5	0	720	780	720	300	1020
24	1	1	01:00	11	0	11	0	10	0	6	0	660	660	600	360	960
25	1	1	00:20	4	0	6	0	1	0	1	0	720	1080	180	180	360
26	0	1	01:00	4	0	10	0	9	0	5	0	240	600	540	300	840
27	0	1	00:20	3	0	4	0	1	0	3	0	540	720	180	540	720
28	1	0	00:50	7	0	6	0	10	0	6	0	504	432	720	432	1152
29	1	0	00:20	3	0	3	0	5	0	2	0	540	540	900	360	1260
30	0	1	00:40	4	0	8	0	8	0	3	0	360	720	720	270	990
31	0	1	00:50	2	0	10	0	9	0	5	0	144	720	648	360	1008
32	1	0	00:20	4	0	3	0	3	0	2	0	720	540	540	360	900
33	0	1	00:20	2	0	6	0	3	0	2	0	360	1080	540	360	900
34	1	0	00:20	3	0	3	0	4	0	2	0	540	540	720	360	1080
35	1	0	00:50	11	0	3	0	5	0	6	0	792	216	360	432	792
36	0	1	00:20	3	0	6	0	2	0	2	0	540	1080	360	360	720
37	1	0	00:20	4	0	2	0	2	0	3	1	720	360	360	720	1080
38	0	1	01:40	5	0	8	0	9	0	2	0	180	288	324	72	396
39	0	1	00:20	2	0	4	0	5	0	2	0	360	720	900	360	1260
40	0	1	00:20	1	0	4	0	6	0	1	0	180	720	1080	180	1260
41	1	0	00:20	5	0	4	0	2	0	2	0	900	720	360	360	720
42	1	0	00:20	4	0	4	0	4	0	0	0	720	720	720	0	720
43	1	1	01:00	9	0	8	1	14	0	6	0	540	540	840	360	1200
44	1	1	00:40	7	0	10	0	5	0	4	0	630	900	450	360	810
45	1	0	00:30	3	0	5	1	4	0	3	0	360	720	480	360	840
46	1	0	01:00	8	0	9	0	13	0	3	0	480	540	780	180	960

47	1	0	01:00	11	0	13	0	12	0	2	0	660	780	720	120	840
48	1	0	01:00	14	0	5	2	2	0	5	0	840	420	120	300	420
49	1	0	00:20	7	0	0	0	0	0	2	0	1260	0	0	360	360
50	0	1	00:20	3	0	8	0	2	0	0	0	540	1440	360	0	360
51	1	0	00:40	6	0	5	0	7	0	3	0	540	450	630	270	900
52	0	1	00:40	3	0	9	0	6	0	3	0	270	810	540	270	810
53	1	0	00:20	3	0	3	0	2	0	2	0	540	540	360	360	720
54	0	1	01:00	13	0	12	2	7	0	8	0	780	840	420	480	900
55	0	1	00:30	2	0	3	0	8	0	2	0	240	360	960	240	1200
56	1	0	00:40	9	0	4	0	2	0	5	0	810	360	180	450	630
57	0	1	00:50	4	0	13	0	9	0	0	0	288	936	648	0	648
58	0	1	00:40	7	0	8	0	6	0	2	0	630	720	540	180	720
59	1	0	01:00	10	1	8	0	11	0	5	0	660	480	660	300	960
60	1	0	01:00	8	0	5	0	11	0	4	0	480	300	660	240	900
61	0	1	00:30	5	0	7	0	2	0	4	0	600	840	240	480	720
62	1	0	00:30	9	0	3	0	3	0	0	0	1080	360	360	0	360
63	0	1	00:20	1	0	5	0	2	0	4	0	180	900	360	720	1080
64	1	0	01:00	10	0	5	0	9	0	7	2	600	300	540	540	1080
65	1	0	01:00	6	0	5	0	12	0	8	0	360	300	720	480	1200
66	1	0	01:00	10	0	7	0	11	1	3	0	600	420	720	180	900
67	1	0	00:40	10	0	5	1	4	0	1	0	900	540	360	90	450
68	0	1	00:20	0	0	6	0	1	0	2	0	0	1080	180	360	540
69	0	1	00:40	7	0	10	0	3	0	4	0	630	900	270	360	630
70	1	0	00:40	11	0	4	0	3	0	2	0	990	360	270	180	450
71	1	1	00:20	3	0	3	0	3	0	4	0	540	540	540	720	1260
72	1	0	01:00	13	0	4	0	7	0	6	0	780	240	420	360	780

73	1	0	01:00	11	0	4	0	11	0	5	0	660	240	660	300	960
74	1	1	00:20	5	0	5	0	1	0	1	0	900	900	180	180	360
75	1	0	00:30	5	0	6	0	6	0	3	0	600	720	720	360	1080
76	1	1	01:00	7	0	9	0	9	0	6	0	420	540	540	360	900
Average												584	641	529	340	868

Appendix II

Input data

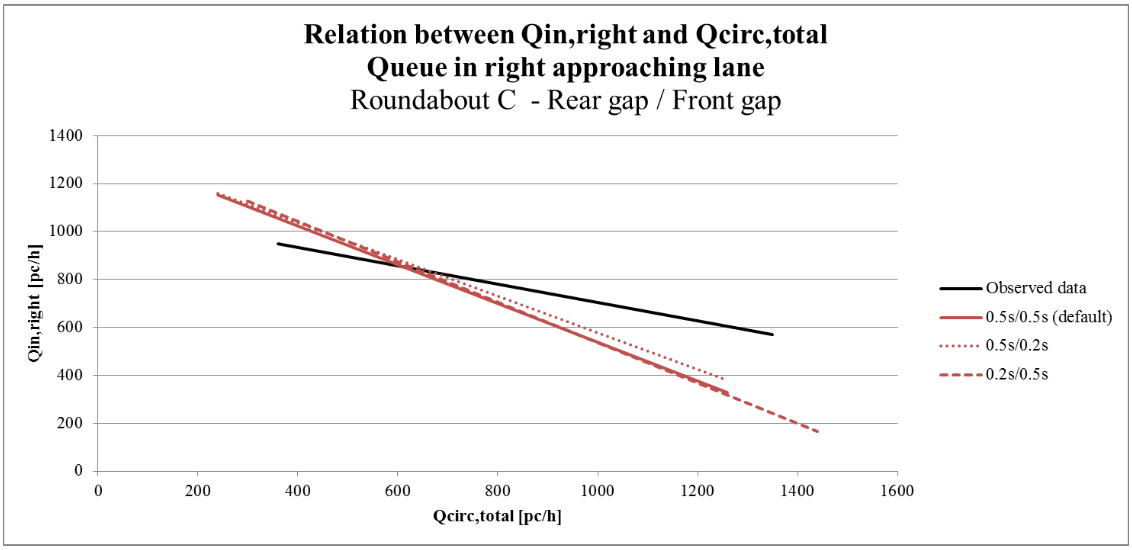
Roundabout A			
Flows	Qin, north	Qin, east	Qin, west
Total [pc/h]	403	378	1400
RF Left	0.45	-	1
RF Straight	-	2.78	1
RF Right	1	1	-
Reduced speed (km/h)	20		

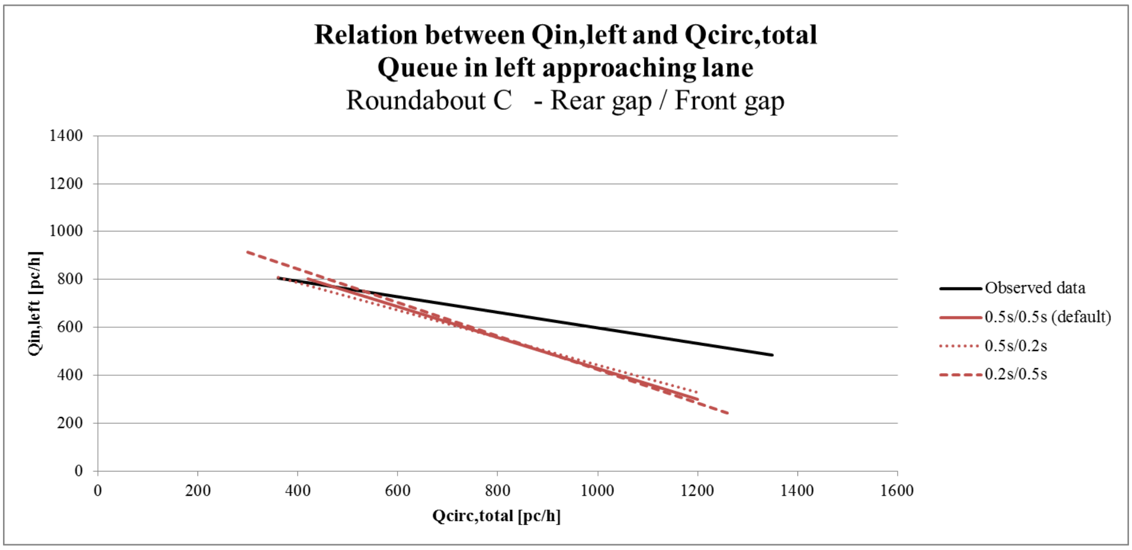
Roundabout B				
Flows	Qin, north	Qin, east	Qin, south	Qin, west
Total [pc/h]	842	475	390	800
RF Left	0.97	1.85	1.9	1
RF Straight	2.46	1.9	1	1
RF Right	1	1	1	1
Reduced speed (km/h)	45			

Roundabout C				
Flows	Qin, north	Qin, east	Qin, south	Qin, west
Total [pc/h]	932	502	437	1100
RF Left	2.23	1.65	2.37	0 / 1 (queue left / right)
RF Straight	0.7	2.37	1	1 / 0
RF Right	1	1	1	1 / 0
Reduced speed [km/h]	25			

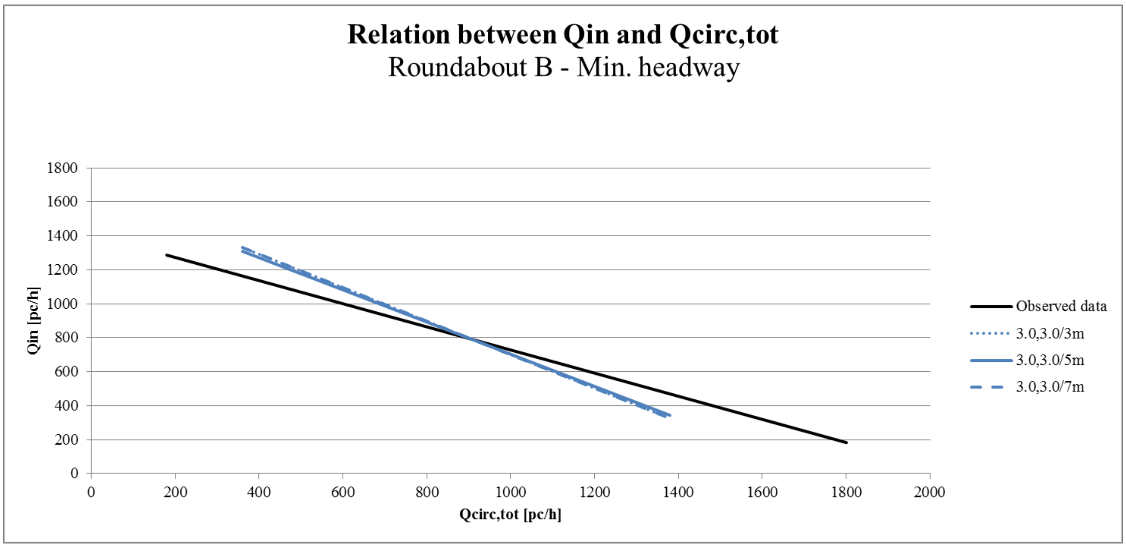
Appendix III

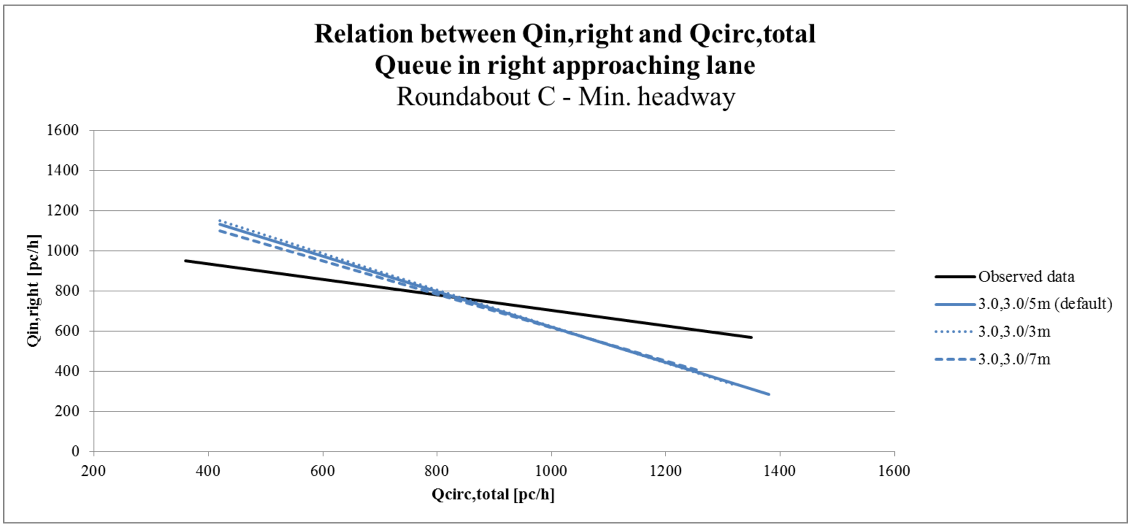
Results of CA simulation with adjusted rear and front gap

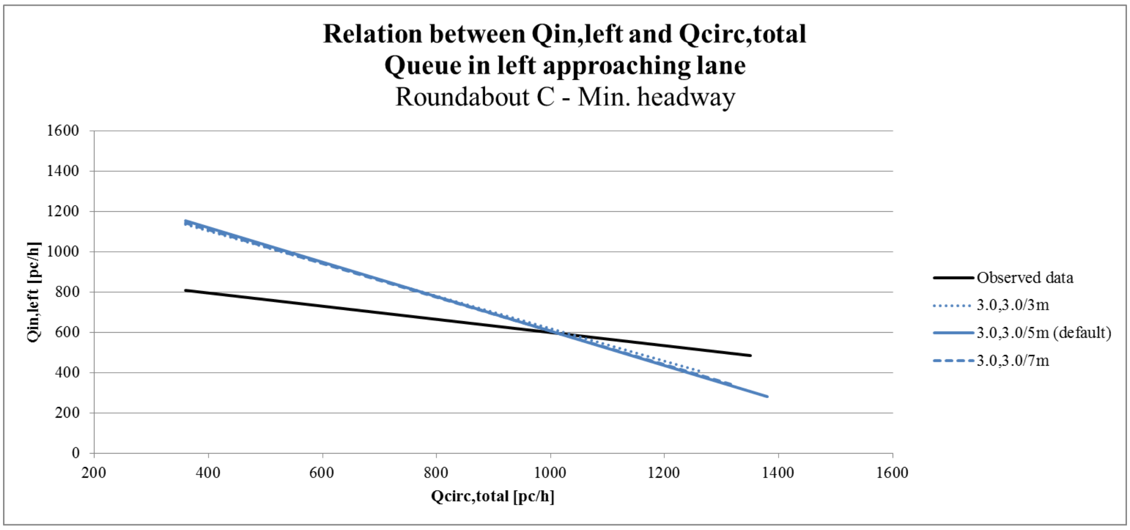




Results of PR simulation with adjusted minimum headway







Results of PR simulation with adjusted minimum headway