

CAPACITY OF SINGLE-LANE ROUNDABOUTS WITH SLOW TRAFFIC

Martijn A. M. de Leeuw

Research Engineer

Hein Botma

Research Engineer

Piet H.L. Bovy

Professor of Transportation Planning and Engineering

Scientific Director of Research School TRAIL

Delft University of Technology

Faculty of Civil Engineering and Geosciences

Transportation and Traffic Engineering Section

PO Box 5048, 2600 GA Delft, The Netherlands

Phone 31.15.278 40 31, Fax 31.15.278 31 79

Email: H.Botma@CT.TUdelft.NL

1 INTRODUCTION

Until recently no satisfying method was available in the Netherlands to weigh one junction type against another, such as to choose between a signalized intersection and a roundabout. To remedy this situation the Dutch consultant Goudappel Coffeng has started a project to develop software (Junction Explorer) to do this in a consistent way. The purpose of this decision support system is to estimate values for capacity, delay, emissions, safety and required space for different junction types. The function of the Junction Explorer is to help decision-makers and designers in their task.

This paper deals with the development and calibration of a method to determine the capacity and the resulting delay of single-lane and two-lane roundabouts. The model developed is suitable for both types of roundabouts but could so far only be calibrated for the single-lane type, due to a lack of sufficiently saturated cases of two-lane types. The paper is therefore limited to single-lane roundabouts.

In 1998 new Dutch design recommendations for roundabouts were published, CROW (1). These recommendations include right-of-way for cyclists on roundabouts in built-up areas. The influence of cyclists on capacity cannot be neglected in The Netherlands; therefore the model presented in this paper explicitly takes into account the influence of cyclists. The operational aspects of the recommendations from CROW were based on this model.

Set up of the study

The development of the model has been carried out in the following steps:

- Literature survey
- Development of new model as a combination of existing models
- Extension and adjusting of existing models
- Field study to determine capacity and delay and to validate the approach
- Calibration of the model by adjusting parameters

The paper will describe the development of the analytical model relations and the calibration of the model. For a more detailed account of this work, see De Leeuw (2).

2 ROUNDABOUT CAPACITY ESTIMATION METHODS

Dutch State of the Art

In the Netherlands single-lane roundabouts are generally accepted as a good solution for junctions. The discussion focused on the rule for cyclists, in or out priority; see Botma (3). The recent recommendation of CROW (1) is to give cyclists priority in built-up areas and no priority in rural areas.

It is preferred to accommodate cyclists with a separate bicycle path and not just a bicycle lane at the outside of the roundabout. The first design is safer, as is also concluded in a recent NCHRP study, Jacquemart (4). Moreover, it has a slightly higher capacity, as will be shown in this paper, but on the other hand it requires more space.

At present, only one capacity calculation method in the Netherlands, Van Arem & Traag (5), is available that takes into account the influence of cyclists on capacity. However, this method results in too low capacity values. For single-lane roundabouts also the PC-program 'The Roundabout Explorer', Van Arem (6), is available. This program gives credible values for the capacity, but is not meant to handle roundabouts with slow traffic having priority.

Concise Overview of methods

To determine the capacity of a roundabout, several methods can be used:

- Rule of thumb
One rule of thumb for instance is that a single-lane roundabout can handle an AADT of 20,000 to 25,000 vehicles.
- Use of analytical relations:
 - Use of one formula per entry.
These formulae suppose a macroscopic relation between the capacity of an entry and the volumes of the conflicting traffic streams. For each entry the capacity has to be determined separately.
 - Use of a graph.
For some general cases graphs can be deduced from the formulae and so the determination of the capacity is simplified.
 - Use of a computer program that combines analytical relations.
A computer program simplifies the use of analytical formulae and can give an overview of all entries. Especially in the case of oversaturation of the roundabout, the sizes of the conflicting streams are dependent on the capacities of the other entries. Therefore an iterative calculation procedure is needed.
- Use of a microscopic simulation model.
In a microscopic simulation model movements of each vehicle are calculated and it is possible to take a lot of details of the traffic operation into account. On the other hand the development and the calibration require much time and effort.

The last two possibilities were explored but it turned out that the analytical approach was more appropriate than the development of a micro simulation model. However, the preliminary simulation models have had some influence on the analytical model development; they have given more insight into blocking back effects on a roundabout.

Yielding Situations

On a single-lane roundabout without slow traffic, motor vehicles have to yield only one traffic stream: the motor vehicles on the circular roadway. In reality another influence is present: sometimes vehicles on the entry are waiting for vehicles using the exit of the same leg. This pseudo conflict reduces the capacity of the entry. The conflict between the entering and circulating flow, included the pseudo conflict, is called the main conflict.

The presence of cyclists with right-of-way reduces the capacity of the roundabout for the motor vehicles. A motor vehicle using the roundabout meets the bicycles two times, at the entry and the exit and in both cases it has to yield them. Motor vehicles yielding cyclists at the entry are queuing on the entry and do not influence any other traffic stream. However, motor vehicles yielding cyclists at the exit are queuing on the roundabout itself and possibly block other traffic streams.

The layout of a roundabout is important for the capacity reduction. In the Netherlands three types of roundabouts are common:

- Mixed flow; i.e. no special facility is present for cyclists. The dimensions of the roundabout are small, forcing vehicles and bicycles to stay behind each other.
- Cycle lane; i.e. the outer portion of the roundabout is reserved for bicycles. Between the legs of the roundabout, small curbs separate bicycles and cars.
- Cycle path; i.e. the cyclists are riding at a separate cycle path, which is positioned approximately 5 m out of the main part of the roundabout. This alternative is preferable, because safety and capacity are significantly better than with a cycle lane.

3 A NEW MODEL FOR ROUNDABOUT CAPACITY

Three points have guided the development of the model:

- the influence of slow traffic must be fully taken into account, it should not be a simple correction term;
- the roundabout must be modeled as an entity, i.e. not per leg and not only the most used leg, but the interaction between the processes at all parts of the system must be included;
- to use existing models for parts of the roundabout process as much as possible and only modify or extend them if necessary.

Model Specifications

Required Types

The objective is to develop models for several types of roundabouts, viz.:

- one-lane roundabout (no cyclists or cyclists have no right-of-way);
- one-lane roundabout with cycle lane (cyclists have right-of-way);
- one-lane roundabout with cycle path (cyclists have right-of-way);
- two-lane roundabout with single-lane entries and exits;
- two-lane roundabout with two-lane entries and exits.

We will limit this paper to single-lane types.

It is not a requirement that the model can handle roundabouts with mixed flow. This type is only used at a maximum AADT of 6000 vehicles and then capacity is not a problem.

Required Input

Because the capacity of an entry is based on the volumes of the conflicting streams, the OD-matrix for motor vehicles (in pcu/h) is the most important input. When cyclists and pedestrians have right-of-way, their OD-matrix is needed too.

The dimensions of a roundabout have influence on capacity too and therefore the following geometric properties are input for the model:

- Inscribed circle diameter
- Central island diameter
- Entry radii
- Exit radii
- Entry widths
- Exit widths

- Splitter island widths

Required Output

The model has to present per entry the following output:

- Volume
- Capacity
- Average delay
- Average number of waiting vehicles

A general assumption is that cyclists with no right-of-way do not have any influence on motor vehicles. This might not be true for very high volumes of cyclists and minor car volumes. However, these situations are considered too scarce to justify extra investigations.

Structure of the Model

The main purpose of the model is to estimate capacity and average delay per entry. The average delay depends on the values of volume and capacity of the entry and therefore the capacity calculation has to be carried out first.

Reason for iterative calculation: In the calculation of capacity the roundabout is modeled as a combination of a number of T-junctions. One of the factors influencing capacity is the volume of the circular roadway. When no entry is oversaturated, the volume of the circular roadway can easily be calculated as the sum of some OD-pairs. In case one entry is oversaturated, the circulating flow for the other entries becomes less because the limitation due to the oversaturated entry has to be taken into account. If one or more entries are oversaturated, the calculation of capacity has to be repeated until the calculation of the circulating volume is in conformity with the calculated capacities, see Figure 1.

So far, the described structure is traditional. To take into account the influence of cyclists with right-of-way on capacity, the model structure is extended in two respects:

- Influence of cyclists at the entry
At the entry the crossing cyclists will reduce capacity, because motor vehicles have to yield them. The cyclists that use the entry themselves do not have any influence. Two situations are possible: the cyclists have their own cycle lane at the roundabout, or they have a separated cycle path. In the latter case space is available for one car between the cycle path and the roundabout. This will increase capacity (compared to a cycle lane) because a driver does not have to wait for a simultaneous gap in both conflicting flows.
- Influence cyclists at the next exit
This point has been mentioned earlier in the section 'Yielding Situations'. In the model it is chosen to take into account the blocking back effect of the first downstream exit. Motor vehicles yielding cyclists or pedestrians at the exit are waiting on the roundabout itself. In theory it is possible that also the second and third downstream exit influence the entry. However, with practical volumes (to 500 bic/h crossing) this is very unlikely to happen.

The structure of the model, with the two procedures added, is presented in Figure 1 and consists of four submodels:

- Capacity as a result of the main conflict;
- Reduction caused by cyclists crossing the downstream exit;
- Reduction caused by cyclists crossing the entry;
- Delay and queue length.

For each submodel a choice is made from existing models. In some cases adjustments were needed.

Submodel Main Conflict

Several models for the capacity of an entry of a roundabout have been developed; some based on gap-acceptance and others on experimental macroscopic relations. In this section three models are discussed which are most suitable for the situation in the Netherlands: the model of Brilon and of Bovy, both based on macroscopic relations, and the model of Tanner, based on gap-acceptance.

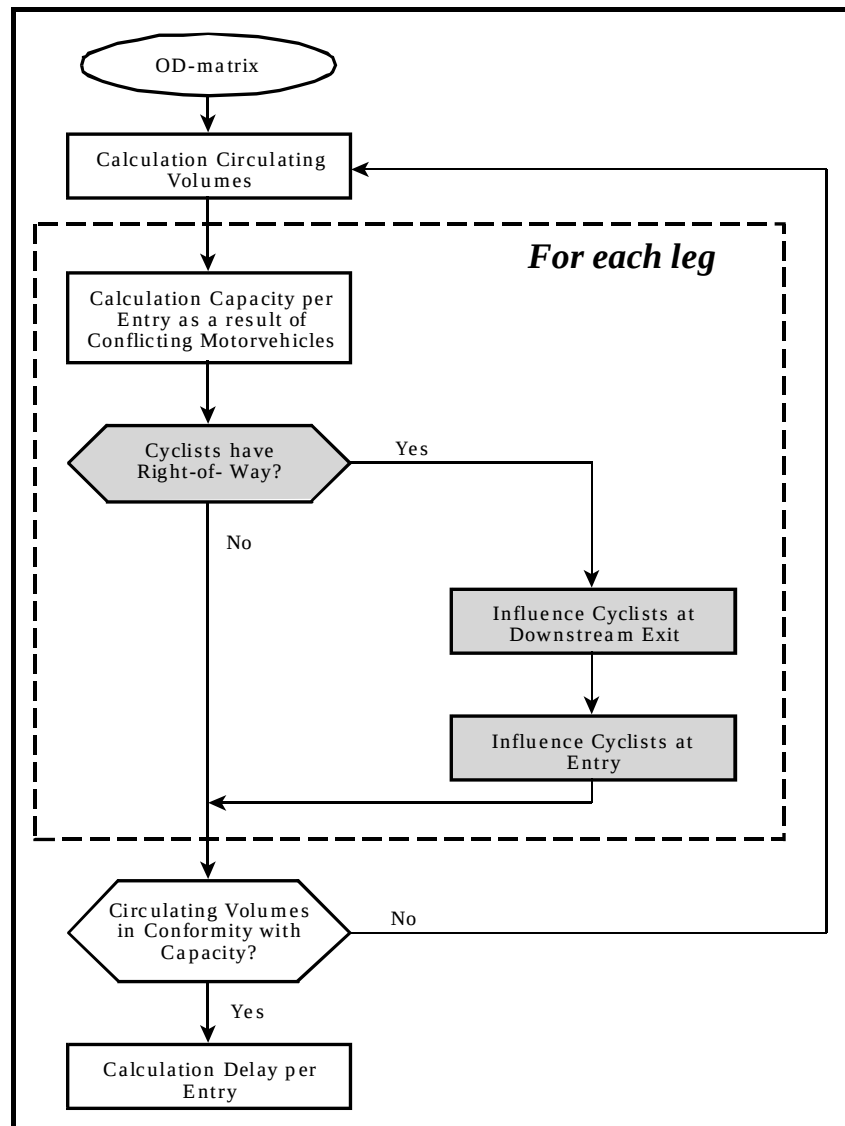


Figure 1 Extended model with new elements indicated

- Brilon's model (7) has a linear relation between the conflicting stream and the capacity of the entry. As conflicting stream only the circulating flow is taken into account, because in Germany no empirical evidence for the pseudo conflict has been found.
- Bovy's model (8) also has a linear relation between the conflicting stream and the capacity of the entry. However, Bovy takes also into account the outgoing volume at the same leg. This outgoing volume is partly added to the circulating flow. The influence of the outgoing stream depends on several geometric variables of which the most important is the width of the splitter island.
- The last model is of Tanner, see e.g. Van Arem (6), and is used in the Dutch Roundabout Explorer. This formula is based on gap-acceptance and supposes random arrivals of the circulating vehicles.

To model the traffic stream realistic, Tanner sets all headways less than a fixed minimum headway equal to this minimum headway.

Figure 2 shows a graphical comparison of these models.

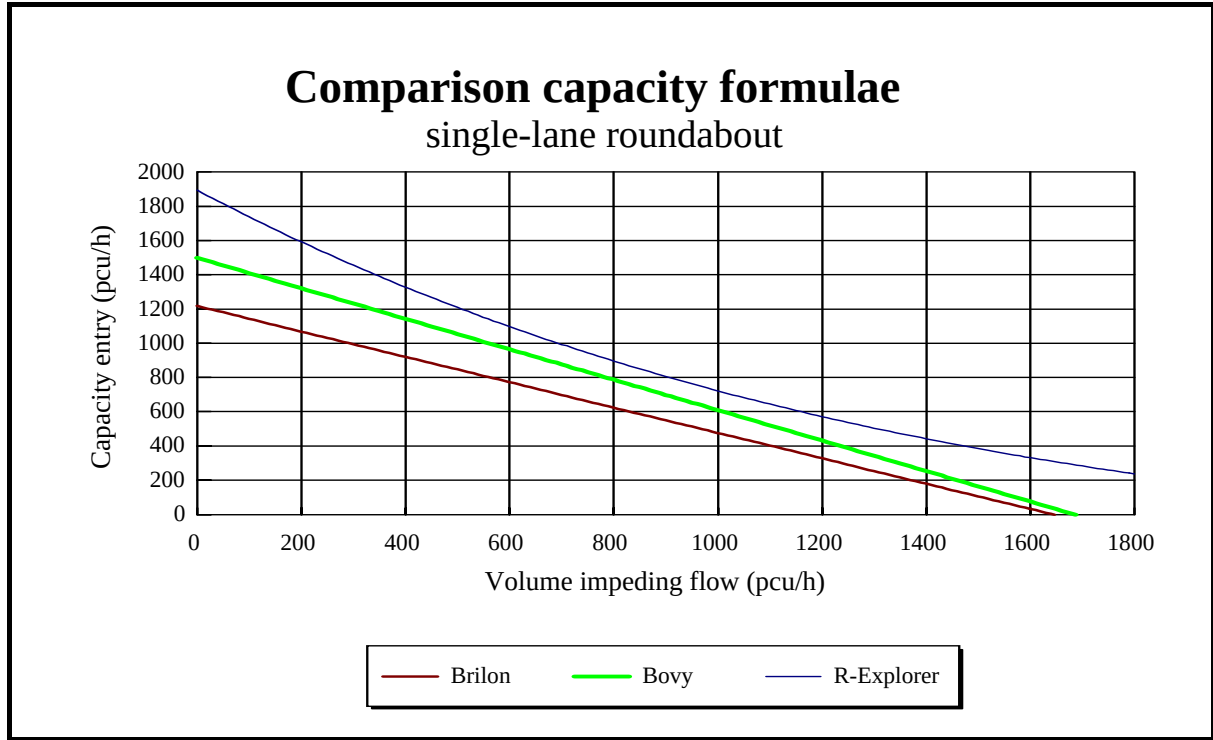


Figure 2 Comparison of existing capacity formulae for single-lane roundabouts

Bovy's model is chosen for the new model for two reasons:

- Field studies in the Netherlands have proven the influence of outgoing traffic; Van Arem & Traag (5);
- No evidence for a non-linear relation between conflicting volume and capacity of the entry has been found. On the contrary, a linear relation is supported by the 'limited priority' merge theory of Troutbeck & Kako (9). The linearity is caused by minor stream vehicles forcing gaps in cases of high circulating flows and cooperating vehicles in the main stream.

The model of Bovy for the entry capacity, C_{entry} [pcu/h], is:

$$C_{\text{entry}} = \frac{1}{\gamma} \left[1500 - \left(\frac{8}{9} \right) (\beta Q_{\text{circ}} + \alpha Q_{\text{exit}}) \right] \quad (1)$$

With: γ Influence number of lanes entry one-lane: 1.0 two-lane: 0.6-0.7
 β Influence number of lanes roundabout one-lane: 0.9-1.0 two-lane: 0.6-0.8
 Q_{circ} Circulating volume [pcu/h]
 α Influence outgoing traffic
 Q_{exit} Volume outgoing traffic [pcu/h]

The method of Bovy has three free parameters: α , β , and γ , and two fixed parameters. The first is the value of 1500, representing the capacity of a single-lane entry with no conflicting flows. The second is the value of 8/9, representing the slope of the relation between entry capacity and impeding flow. In the calibration of the new model, these two values are updated if necessary.

The determination of parameter α , the influence of outgoing traffic at the same leg, is dependent on the distance b between the conflict points of exit and entry. In the original method b was read from a drawing of the roundabout and parameter α was read from a graph, see Figure 3. Because the new model must finally become a part of a computer program, the determination of the distance b had to be automated. By using standard geometric rules, the distance b can be derived from the standard dimensions of the roundabout; see De Leeuw (2).

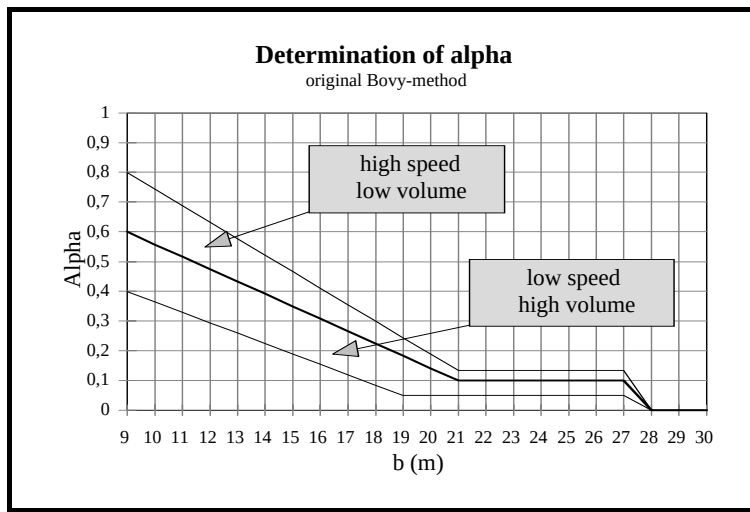


Figure 3 Determination of pseudo conflict parameter, α , from distance between conflict points, b

The method of Bovy takes also into account the expectation of the drivers and supposes this to be dependent on the relative size of the outgoing volume and the speed; see Figure 3. Again, the graph of Bovy has to be represented by a heuristic formula. In the new model no information concerning speed is available, so the variation of α depends on volumes only, in the following way.

Multiplying the middle line by respectively 2/3 and 4/3 approximates the lower and the upper bound of the graph. The conditions low and high volumes are represented by the ratio of volume

and capacity at the exit. The variation of α represents the expectation of the drivers at the entry and therefore also the exiting proportion of the total flow on the roundabout is used. This results in the following formula for the parameter α :

$$\alpha = \alpha_0 \left(1 - \frac{1}{3} - \frac{2}{3} \sqrt{\frac{Q_{exit}}{C_{exit}} \frac{Q_{exit}}{Q_{total}}} \right) \quad \text{with} \quad Q_{total} = Q_{circ} + Q_{exit} \quad (2)$$

With:

α_0	Nominal (middle) value of α
Q_{exit}	Volume exiting flow [pcu/h]
C_{exit}	Capacity exit [constant in pcu/h]
Q_{circ}	Volume circulating flow [pcu/h]

Submodel Reduction Downstream Exit

For the capacity reduction caused by cyclists crossing the downstream exit, the method of Marlow & Maycock, see Semmens (10), for crossing pedestrians is used.

We will not repeat the details of the procedure but only point out the additions. In the method the probability the exit is blocked is determined via an intermediate variate, the virtual V/C-ratio, x . This is determined as a function of:

- Volume of crossing cyclists (V);
- Time required by cyclists to cross the exit (t_{cross});
- Minimum follow-up time of exiting vehicles (t_f).

Marlow & Maycock present a table with blocking chances based on this virtual V/C-ratio. For the new model this table is represented by a function, leading to the 'reduction factor for the exit', F_{exit} :

$$F_{\text{exit}} = 1 - p_{\text{blocking}} = 1 - [x^{N+1} - 0.14x] \quad (3)$$

With: x Virtual V/C-ratio
 N Space between roundabout and cycle facility expressed in number of cars
 p_{blocking} Chance of exiting vehicles blocking the roundabout

This method is extended with the so-called pseudo conflict due to cyclists. Field observations showed that not only the crossing bicycles at the exit, but also the exiting bicycles contributed to the impeding volume. On narrow roundabouts exiting drivers are not able to see in time whether circulating cyclists will continue or exit the roundabout. Therefore a proportion, δ , of the exiting cyclists, q_{exit} , is added to the circulating bicycle flow, q_{circ} , leading to the impeding volume of cyclist, q_c .

Submodel Reduction Entry

Cycle lane: The reduction of capacity caused by crossing cyclists is modeled by the formula of Siegloch, based on gap-acceptance, and presents the chance that the entry is not blocked by crossing cyclists. The formula supposes random arrivals of slow traffic. This seems a realistic assumption, because in general slow traffic does not platoon so much as motor vehicles. The chance that the entry is not blocked by crossing cyclists, p_{entry} , is:

$$p_{\text{entry}} = e^{-q_{\text{circ}} t_0} \quad \text{with} \quad t_0 = t_{\text{cr}} - 0.5 t_f \quad (4)$$

with: q_{circ} Volume circulating cyclists [bic/s]
 t_{cr} Critical gap to cyclists [s]
 t_f Minimum follow-up time entry traffic [s]

Consequently in case of a cycle lane the capacity of the entry, $C_{\text{entry,clane}}$ [pcu/h], is:

$$C_{\text{entry,clane}} = C_{\text{entry,h}} F_{\text{exit}} p_{\text{entry}} \quad (5)$$

With: $C_{\text{entry,h}}$ Capacity of the entry due to the main conflict [pcu/h]
 F_{exit} Reduction factor caused by downstream exit
 p_{entry} Probability exit is not blocked by cyclists

Cycle path: The capacity increase caused by the extra space between cycle path and roundabout can be modeled using a model of Brilon (11), describing the process at two-stage priority intersections. At the entry of a roundabout the motor vehicles also have to yield the conflicting flows in two phases. At first the vehicles are yielding the crossing cyclists, then they can use the space of five meters between the conflicting flows, and then they are yielding the circulating motor vehicles. For this case Brilon gives the following formula for the capacity of the entry in case of a cycle path, $C_{\text{entry,path}}$ [pcu/h]:

$$C_{\text{entry,path}} = \frac{C_{\text{entry,bic}} C_{\text{entry,w}} - C_{\text{entry,clane}}^2}{C_{\text{entry,bic}} + C_{\text{entry,w}} - 2 C_{\text{entry,clane}}} \text{ with } C_{\text{entry,bic}} = p_{\text{entry}} 1500 \text{ and } C_{\text{entry,w}} = C_{\text{entry,h}} F_{\text{exit}} \quad (6)$$

With: $C_{\text{entry,bic}}$ Capacity of the entry due to crossing cyclists only [pcu/h]
 $C_{\text{entry,w}}$ Capacity of the entry without crossing cyclists [pcu/h]
 $C_{\text{entry,clane}}$ Capacity of the entry in case of a cycle lane [pcu/h]

Submodel Delay

Only queuing delay is considered, no geometric delay. For the calculation of queues and delays a choice was made from the methods of: Brilon (12); Akçelik and Troutbeck (13) and Kimber & Hollis, see also Brilon (12). The latter was chosen because the experiences in the Netherlands with this model are rather good, not because the other methods failed.

In the method the queue length and the delay follow from the V/C-ratio over a given time period and the queue length at the beginning of the period. First the queue length is calculated and after that the delay, by integrating the queue length over the time period.

The new model considers sequential periods and presents the average delay for vehicles arriving in the actual period. Therefore an extra calculation is needed for the vehicles in the queue at the end of each period. The total delay of these vehicles in the following periods is added to the actual period. The total delay of vehicles, already present at the start of the actual period, is subtracted from the delay of the actual period.

4 CALIBRATION

The new model has several parameters, of which some are new. In principle one could determine the values of some parameters by microscopic field studies, for instance observation and analysis of the gap-acceptance processes. We have chosen to use the indirect way, i.e. to compare the output of the model (mainly capacity and delay) with the same variables of the field study. In this way one prevents the discussion about the validity of capacities derived from undersaturated situations.

Observations

To measure the capacity of an entry in the field, it has to be saturated. In the Netherlands it is a problem to find roundabouts which are regularly saturated. Two different single-lane roundabouts were

chosen for the field study, viz.:

- I. Type single-lane with cyclists having right-of-way on cycle lane, site Alphen aan de Rijn;
- II. Type single-lane with cyclists having right-of-way on cycle path, site Hilversum.

At both roundabouts traffic at two entries was observed. The main objective of the calibration is to determine the capacity in reality. This is done by counting the entering vehicles on the entries in saturated periods. In the model the capacity is depending mainly on the conflicting flows, so these had to be counted. The measurements were carried out by Goudappel Coffeng using two video cameras.

For each vehicle the exact entering time is read out from the tapes. The periods of saturation are determined separately, resulting in a data set consisting of 35 periods of 5 minutes and 18 periods of 1 minute. On both roundabouts also the delay of each vehicle on one entry is calculated. This is done by determining for each vehicle the passing-time at a point upstream of the entry. Together with the time of entering the roundabout, this results in a travel-time between these points. The delay is defined by this travel time minus a representative free flow travel time. All delay which vehicles experience on the roundabout itself is neglected, including the delay due to acceleration from the stop line. The acquired data set consisted of 46 periods of 5 minutes.

Estimation of Parameters

Based on the measurements the parameters of the model were changed manually. From the deviations between model and reality it was mostly clear which part of the model was not totally correct and which parameters had to be changed. The eventual parameter values are presented in Table 1. It turned out that no parameters of the delay submodel needed adjustment.

TABLE 1 Calibration Results

Submodel	Parameter		Value
Main conflict	Pseudo conflict (α)		According to calculation, not changed
	Influence number of circular lanes (β)	One-lane roundabout	1
	Influence number of entering lanes (γ)	One lane entry	1
	Slope		9/9
	Free-flow capacity one lane		1500 pcu/h
Bicyclists entry	Critical gap (t_{cr})		3.5 s
Bicyclists exit	Crossing-time (t_{cross})		3.2 s
	Space (N)	cycle track	1.0 pcu
		cycle lane	0.3 pcu

Free-flow capacity exit (3600/t _f)		1500 pcu/h
Influence exiting bicyclists (δ)	cyclelane	0,25
	cycletrack	0

The pcu-values for motorcycles (0.8) and other vehicles, not being a truck (mainly tractors with $\text{pcu}=2.0$) are taken from the literature. The pcu-value for light and heavy trucks are adapted in the calibration, because these parameters have much influence on the outcomes of the model. In general the pcu-value for trucks is different for circulating and entering traffic streams. CROW (1) recommends a pcu-value of 2.0 for circulating trucks and a value of 4.0 for entering trucks. The calibration shows that there is a difference between these two values, but much smaller than according to the recommendation. For a single truck, either circulating or entering, a pcu-value of 2 was found. For an articulated truck a pcu-value of 2.5 for entering and 2.75 for circulating was found.

Calibration Results

Figure 4 presents an illustration of a calibration result. It can be concluded that the method of Van Arem and Traag has a large bias; the Roundabout Explorer has still a bias but it is much smaller; and finally, the new model predicts the capacity quite accurately.

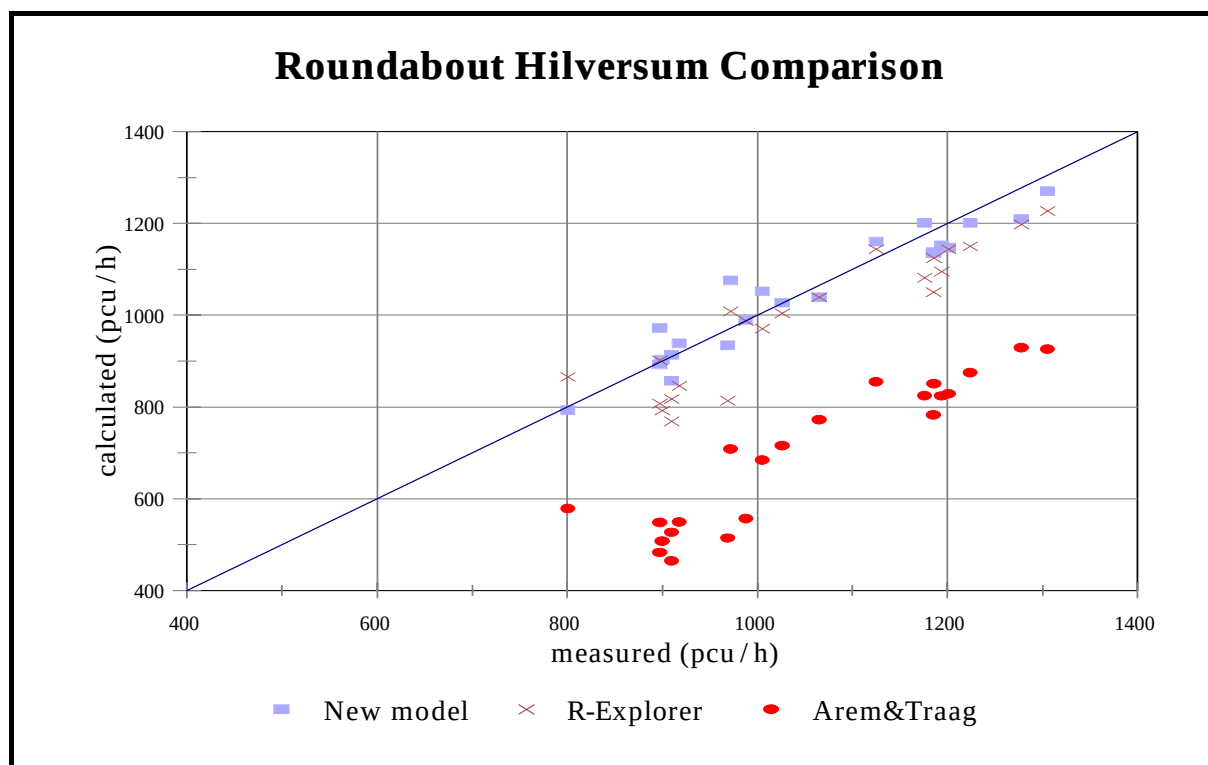


Figure 4 Comparison between model predictions and observations

5 EXAMPLES OF MODEL RESULTS

Meaning of Reserve Capacity

Because the model presents the capacity per entry, the results must be interpreted carefully. For instance, at a four-legged roundabout with a symmetric demand pattern, the model presents for each entry a reserve capacity of, say, 200 pcu/h. The value of the reserve capacity is valid for one entry, given the other traffic flows. Increasing the entering volume of one entry will decrease the capacity of some other entries, so the reserve capacity of the whole roundabout is not equal to 800 pcu/h. The only way to determine the capacity of the whole roundabout is to increase the OD-matrix in little steps until one traffic stream reaches capacity.

Roundabout Dimensions

In the development of the model the dimensions of the roundabout have got relatively little attention. The only explicit influence of geometric properties is in the calculation of the impeding volume according to Bovy's procedure. The reason for this is that in the Netherlands there is a strong tendency to use standardized dimensions. In the next examples the following dimensions are used: central island diameter of 21.0 m; inscribed circle diameter of 32.0 m; entry radius of 12 m; exit radius of 15 m; width of entry 4 m; width of exit of 4.5 m; and finally width of splitter island of 2.5 m.

Effect of Position Bicycle Facility on One Entry

To illustrate the effect of the bicycle facility, either a bicycle lane or a separate cycle path, the entry capacity graph according to the model is calculated. To simplify the example the influence of the downstream exit is neglected. At the entry a relatively large amount of bicycles is crossing (500 bic/h).

The result is depicted in Figure 5 and two trivial points can be noticed. The point where the impeding flow of motor vehicles is equal to zero and the point where it is equal to its maximum value of 1500 pcu/h. If no conflicting motor vehicles are present, the position of the cycle facility is not important any more. On the other hand, if no vehicle can enter the roundabout because of the circulating conflicting motor vehicles, the number of cyclists is not important either. For intermediate impeding flows the effect of the separate cycle path on entry capacity can be as large as 25 %.

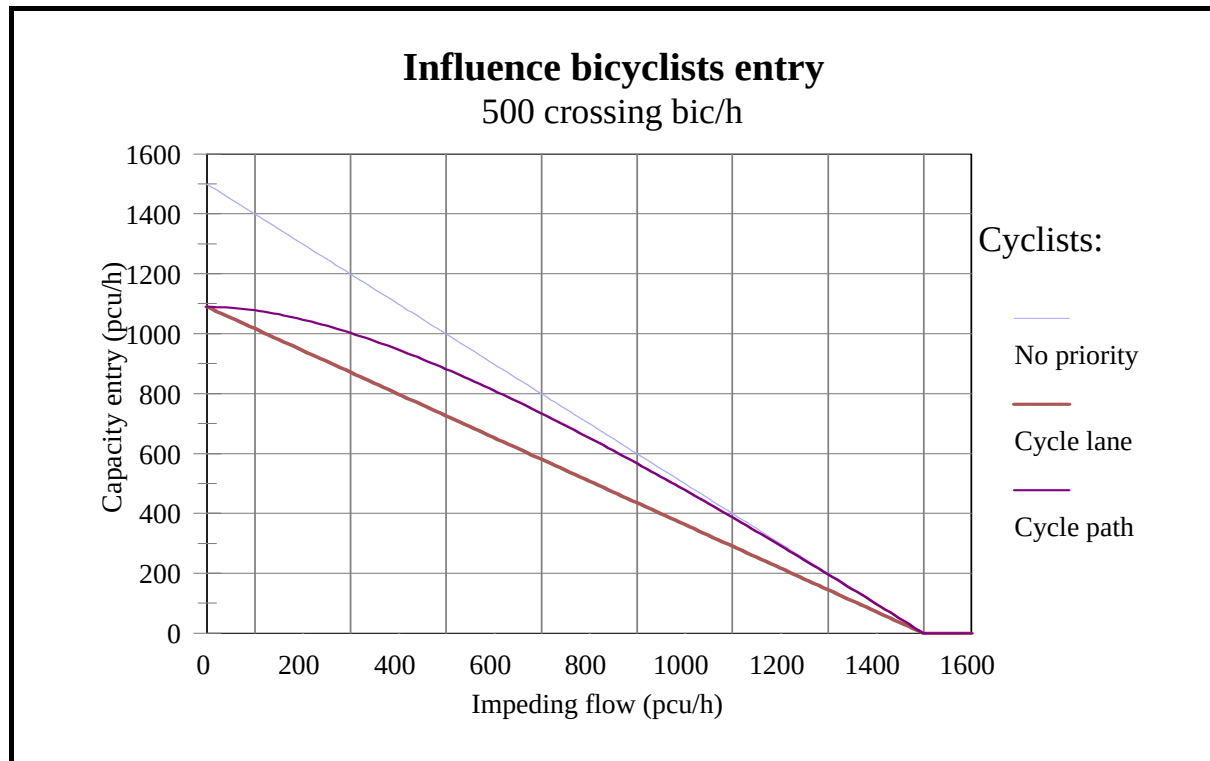


Figure 5 Influence facility for cyclists

Effect of proportions going left, straight ahead, and right

Starting point for the following cases is a four-legged roundabout with a symmetric OD-matrix, i.e. from all legs comes the same amount of traffic and the proportions going in the three directions are the same for all entries. The proportions as such are varied. In the first five cases, no cyclists are present.

1. A quarter of the traffic is going left, a quarter right and the other half is going straight ahead, denoted as a vector $\{\frac{1}{4} ; \frac{1}{2} ; \frac{1}{4}\}$. According to the model the capacity per entry is 680 pcu/h and so the total capacity of the roundabout is 2720 pcu/h. With this symmetric OD-matrix, the value of 680 pcu/h is valid for all cases for which the proportions of left and right going traffic are the same. Also the two following extreme cases result in a capacity of 680 pcu/h:
2. All traffic straight ahead, i.e. the destination vector is $\{0 ; 1 ; 0\}$.
3. Fifty percent is going left, fifty percent right, no traffic going straight ahead, i.e. $\{\frac{1}{2} ; 0 ; \frac{1}{2}\}$.
4. All traffic is going left. This is the most negative situation for traffic performance because every vehicle passes two entries during circulating, resulting in a low value for capacity of 465 pcu/h per entry; the total capacity of the roundabout is 1860 pcu/h.
5. All traffic is going right. This is the most favorable situation for traffic performance and it gives the highest value for capacity. Note that in this case the free-flow capacity of an entry (1500 pcu/h) can not be reached because the pseudo conflict of exiting motor vehicles prevents this. The capacity per entry is 1310 pcu/h, and the total capacity is 5240 pcu/h.

The cases with all traffic turning left and all traffic turning right give respectively the lower and the upper bound of the capacity. More representative are the cases with an intermediate capacity value of 680 pcu/h. For this case now two situations with cyclists added will be discussed:

6. Suppose 300 cyclists enter the roundabout per entry, 100 going left, 100 going right and 100 going straight ahead. The cyclists reduce the capacity per entry from 680 pcu/h to 658 pcu/h on a cycle path and to 576 pcu/h on a cycle lane.
Note that if one expresses the capacity in number of vehicles (car + bic), the total throughput of the roundabout with a cycle path equals $4 \cdot (658 + 300) = 3832$ veh/h.
7. Suppose next the amount of cyclists doubles to 600 bic/h per entry. Then the cyclists reduce the capacity per entry to 598 pcu/h on a cycle path and to 480 pcu/h on a cycle lane.

In the last case the capacity of the roundabout equals still $4 \cdot 480 = 1920$ pcu/h. Assuming this is the peak hour load and that the share of the peak hour is 10% of AADT, it turns out that an AADT of 19,200 vehicles can be accommodated. This is a little less than according to the Dutch rule of thumb mentioned earlier, but it should be added that the bicycle volumes used are rather high, even in the Netherlands.

Comparison with the example in the concept of HCM 2000

Finally a comparison is made with the example of a roundabout calculation in the concept of the new HCM. The HCM presents three sets of outcomes with different combinations of the parameters values for follow-up time and critical gap. Summing the capacities of the four entries, this results in capacities of 2721, 3029 and 3398 veh/h for respectively the pessimistic, the middle and the optimistic scenario. Our model finds a capacity very close to the middle scenario with 3050 veh/h. Details per leg are given in Table 2 and then differences with the HCM example are larger.

TABLE 2 Example Problem 6 of HCM 2000 with New Model

	Volume (pcu/h)	Cap (pcu/h)	Cap HCM Middle Scenario (pcu/h)	V/C	Mean Delay (s)	Queue at End of Period (pcu)
EB	660	913	871	0,72	13,2	2,5
WB	609	770	770	0.79	19.3	3,4
NB	427	619	644	0.69	17.4	2,1
SB	500	748	744	0.67	13.7	1,9
Sum	2196	3050	3029			

6 FINAL REMARKS

The model developed can be used as a tool to analyze the traffic operation of single-lane roundabouts, taking fully into account the effect of cyclists with priority. The effect of the cyclists at the entry and the exit has been accounted for in a coherent way. The calibration has shown that the model can predict real capacities and delays with sufficiently accuracy. However, it is recommended to carry out more validating field studies.

The model can be used as an element of the general software package that is under development and meant to compare different intersection solutions.

As far as the effect of slow traffic on the operation of a roundabout has been taken into account, this has been only worked out for the bicycle mode. However, the same structure and calculation procedures can be used for pedestrians. The parameter values for pedestrians will certainly differ from those for cyclists.

At the moment the development of a microscopic simulation model, for traffic operation at a roundabout with fast and slow traffic, does not seem to be urgent. This could be different if the entering cars have a special pattern, e.g. coming from a signalized intersection at a short distance. And also pedestrians can be rather platooned in urban areas, as shown by Virkler (14). The same could be true for cyclists but certainly the platoons of both slow modes will not arrive at the roundabout at the same time.

The Origin-Destination matrix is an important input of the model, if not the most important. Unfortunately often the errors in predicted OD-matrices are large. For the roundabout with slow traffic one needs even two or three OD-matrices, one for fast and one or two for slow traffic. This is a direct consequence if one wants to take account of slow traffic in a more quantitative way, and this tendency is certainly also present in the new HCM. Hence more attention should be paid to the estimation of design volumes, peak hour factors, origin-destination patterns, route choice, etc. of slow traffic.

Further studies are needed for the points:

- The model has been calibrated for single-lane roundabouts, but should preferably be validated with observations from other sites.
- Some extra research seems to be needed concerning the pcu values of trucks. Possibly it will be needed to have separate values for single and articulated trucks.
- The effects of deviating geometrical designs deserve more study.

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