Effects of OD Flows on Roundabout Entry Capacity

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ABSTRACT

Roundabouts are normally considered as a series of T-intersections, each intersection regarded as being independent of the other intersections. Based on recent research on Swedish roundabouts a new capacity model for two-lane roundabouts was suggested. By use of this model it was found that changes of the OD flows gave significant changes of the roundabout entry capacity. The model was compared with the OD model proposed by Akcelik. It was found that the effect of the OD flows on the roundabout entry capacity, predicted by the Akcelik model, can be divided in two parts, one depending on the degree of saturation and one depending on the OD flows. The effect of the OD flows will then be reduced from 55%, as stated by Akcelik, to 28%. Finally, explanations of the OD flow effects on a micro level are discussed.

1. INTRODUCTION

Roundabouts are normally considered as a series of T-intersections, each one regarded as being independent of the other ones. An effect of this is that it is only the total circulating flow which influence the entry capacity, not its origin. Thus, the OD flows are of no importance. Of about ten investigated roundabout capacity models (Hagring 1996) only the Swedish one (CAPCAL, Vägverket 1995) at that time turned out to consider OD flows. Since then, Akcelik et al. (1996) and Akcelik (1997), have introduced an OD model that will be discussed in Section 6.

The two circulating streams in the roundabout are defined as the near and far major streams, with respect to the entering vehicles or the yield line. For the case of two entry lanes, the inner and outer minor lane are so defined that the outer lane is the one closest to the kerb line, see Figure 1.

2. THE CURRENT SWEDISH CAPACITY MODEL—CAPCAL

The origin and destination of the circulating flow has a considerable effect on capacity. In Figure 2 the minor streams of a four-armed roundabout are defined. For approach D the circulating flow is then defined as $q = q_{Al} + q_{At} + q_{Bl}$. However, the circulating flow is reduced for some of the minor streams entering the intersection, as shown in Table 1. Note that there is a difference between circulating flow and major flow.

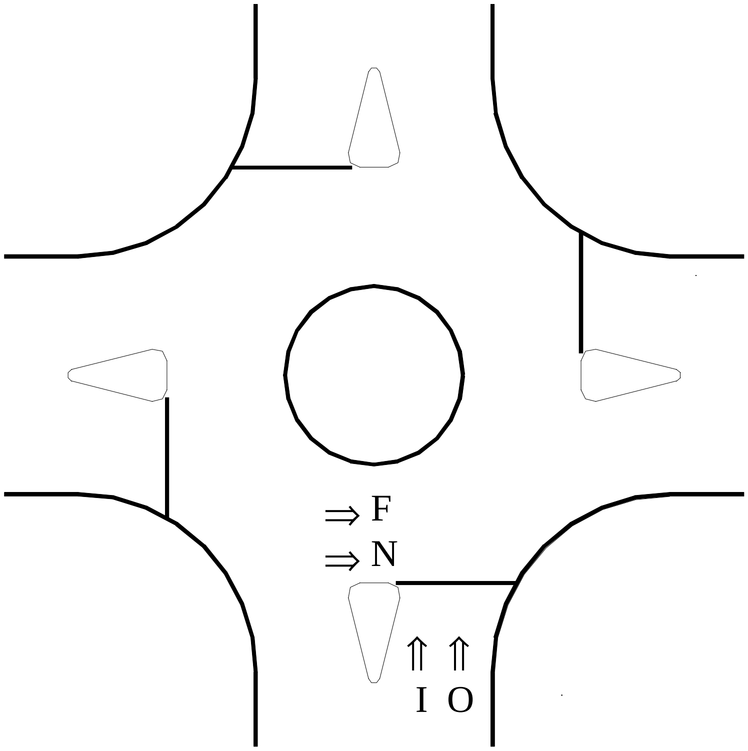

FIGURE 1 Definition of the far and near major lanes/streams and the inner and outer minor lanes/streams; F being the far lane, N being the near lane, I being the inner lane and O being the outer lane.

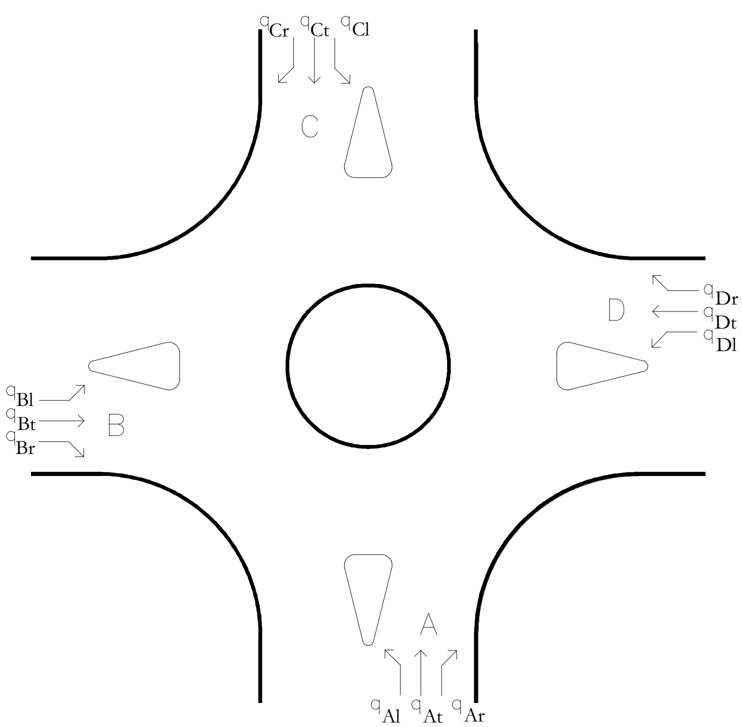

FIGURE 2 Definition of the minor streams of a four-armed roundabout.

TABLE 1 Definition of Circulating and Major Flow

Minor movement	Circulating flow	Major flow
q_{Dl}	$q_{Al} + q_{At} + q_{Bl}$	$q_{Al} + q_{At} + q_{Bl}$
q_{Dt}	$q_{Al} + q_{At} + q_{Bl}$	$x_1 q_{Al} + q_{At} + q_{Bl}$
q_{Dr}	$q_{Al} + q_{At} + q_{Bl}$	$x_2 q_{At} + x_2 q_{Bl}$

The reduction factors x_1 and x_2 are depending on the geometry of the weaving area in quite a complicated manner and the reader is directed to Hagring (1996) and Vägverket (1995) for details. As can be deduced from Table 1 the major flow for a right-turning vehicle can be low or zero even if the circulating flow is large and thus is the origin of the flow important.

The effect of the reduction factors is that the origin of a circulating stream will have a large effect on capacity. However, recent measurements of the critical gaps in Swedish roundabouts (Hagring 1996, 1998a) have shown that the CAPCAL model does not describe the interaction situation properly. A new model for the capacity of roundabouts has therefore been developed.

3. RECENT RESEARCH ON SWEDISH ROUNDABOUTS

The research can be summarized as follows (the reader is directed to Hagring 1996 and 1998a for details):

The critical gaps differ between the near and far lanes. The critical gaps are larger for the near lanes for both the inner and outer lanes. This is a result from an investigation based on an extension of the Miller and Pretty (1968) maximum likelihood model for the estimation of critical gaps to the case of two major lanes with separate critical gaps. In Table 2 the estimated average critical gaps are shown. As can be seen, the difference in critical gaps between the near and far lanes is about 0.2 to 0.3 s.

The critical gaps differ between the outer and inner lanes. In an entry with two minor lanes the critical gaps are differing between the lanes. The critical gap for the inner lane is about 0.4 s larger due to a more difficult interaction, as can be seen from Table 2. However, the figures in this table are based on data sets where it was possible to estimate separate critical gaps for the near and far major lanes. If the difference between the critical gaps for the outer and the inner major lanes were estimated for all data sets and without taking notice of the allocation of the major flow onto the near and far major lane, the difference was found to be about 0.6 s (Hagring 1996). With this simplified model it was possible to relate the critical

TABLE 2 Estimated Average Critical Gaps

Minor lane	Major lane	
	Near lane	Far lane
Outer lane	4.273	3.998
Inner lane	4.615	4.403

gap to the size of the roundabout, the latter measured by the length and the width of the weaving area:

$$T = 3.91 - 0.0278L + 0.121w + 0.592(N_L - 1) \quad (1)$$

where
T = the critical gap
L = the length of the weaving section
w = the width of the weaving section
N_L = lane number (outer lane = 1, inner lane = 2).

The length and the width of the weaving section is explained in Figure 3.

The critical gaps differ between the different movements. In CAPCAL it is assumed that the critical gap values differ between the movements so that the left-turning vehicles have the largest critical gaps and the right-turning vehicles have the smallest critical gaps. In the studies presented here, it was found that right-turning vehicles in the outer lane had significant smaller critical gaps than the other movements (normally only through-driving vehicles) in that lane had. The difference was about 0.3 s.

All circulating vehicles are considered as major. This is a result from the estimation of critical gaps for the case of two major lanes with separate critical gaps. Since both minor lanes have critical gaps of about the same size for the far and near major lanes, respectively, it can be concluded that both major streams impede the minor-stream vehicles, the strength of the impediment being expressed by the size of the critical gap. These results confirm those of Troutbeck (1990), who studied the effect of the circulating stream on entering drivers, finding these drivers to be affected by all the circulating streams. The result holds also when the minor and major vehicles do not physically interact. For instance, minor

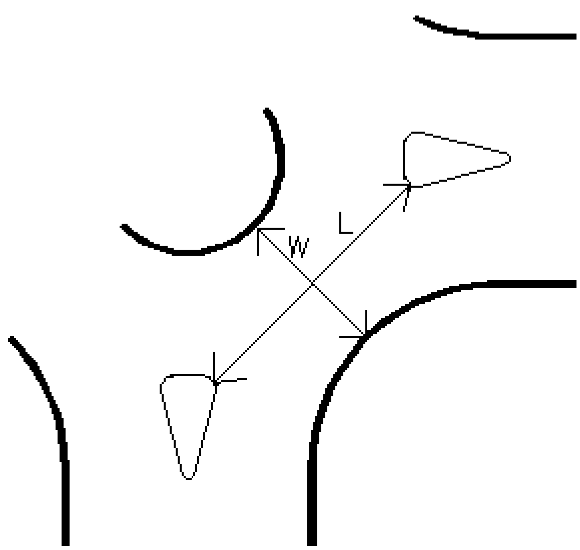

FIGURE 3 The length (*L*) and the width (*w*) of the weaving section.

vehicles in the outer lane, that do not interact with major vehicles in the far lane, have a critical gap for the far lane that is significant greater than zero. The difference between the critical gaps for the near and far lane is about 0.25 s which is about 6% of the critical gap values.

The major flow can be represented by a two-lane M3 distribution. The choice of headway distribution and estimation of the parameters of it has over the years engaged a lot of researchers. An overview of this field is given by Luttinen (1996). Normally, for roads with more than one major lane, the headways has been accounted for as if the road consisted of only one lane. Different authors, for instance Tanner (1967), Troutbeck (1986, 1991), Golias (1986), Fisk (1989) and Hagring (1998b) have treated the problem. The capacity formula resulting from the solution presented by Hagring (1998b) is based on a generalised M3 distribution and includes an unlimited number of major lanes and different critical gaps and follow-up times for the major lanes. The headway distribution is written as

$$H(t) = 1 - \frac{\Lambda}{Q} \prod_i \frac{q_i \alpha_i}{\lambda_i} e^{-\sum_j \lambda_j (t_j - \Delta)}, \ t \geq \Delta \tag{2}$$

where
Δ is the minimum headway between vehicles
α_i is the proportion of free vehicles in lane *i,* i.e., the proportion of headway's > Δ
λ_i is the intensity for longer gaps in lane *i,* i.e., $t > \Delta$
q_i is the flow in lane *i*

$$\Lambda = \sum_i \lambda_i$$

$$Q = \sum_i q_i$$

$\boldsymbol{t} = (t_1, t_2, \ldots, t_n)$, i.e., a vector containing *n* headway's of different size but > Δ.

Thus, Equation (2) expresses the probability of obtaining a combination of headway's greater than $\boldsymbol{t} = (t_1, t_2, \ldots, t_n)$ when the headway's in the separate lanes are M3 distributed. If $n = 1$, Equation (2) will turn into

$$F(t) = 1 - \alpha e^{-(t-\Delta)} \tag{3}$$

The estimation of the parameter values of Δ, α and λ is reported by Sullivan and Troutbeck (1994), Akcelik and Chung (1994) and Hagring (1998). λ is related to *q* by the following equation

$$\lambda = \frac{q\alpha}{1 - q\Delta} \tag{4}$$

Based on field data (Hagring 1998), Δ was set to 1.8 s, and the following relationship for α was found:

$$\alpha = 0.910 - 1.545q \tag{5}$$

The capacity related to Equation (2) is given by

$$C = \Lambda \prod_i \frac{\alpha_i q_i}{\lambda_i} \frac{e^{-\Sigma_k \lambda_k T_k}}{e^{-\Lambda\Delta}(1-e^{-\Sigma_m \lambda_m T_{0m}})} \qquad (6)$$

where T_0 is the follow-up time.

An analysis of Equation (6), see Hagring (1998b), shows that capacity is strongly depending on the allocation on the flow to the various major lanes. The maximum capacity is obtained when the major flow is equally distributed to the major lanes and the minimum capacity when the major flow is allocated to one lane only. The relative difference between the maximum and minimum capacity is increasing with increasing major flow.

4. OUTLINES OF A NEW MODEL

Based on the research results reported in the previous section a new capacity model for two-lane roundabouts, to be used in this paper, was suggested:

Estimation of critical gap. The number of roundabouts, where it was possible to estimate critical gaps for both the near and the far lanes, was not large enough to establish a relation between differing critical gaps in the far and near lane to the geometry of the roundabout. It was therefore assumed that an overall critical gap could be obtained by Equation (1). The critical gaps for the near and far lane was then obtained for the two minor lanes by adding (the near lane) or subtracting (the far lane) an amount of 0.15 s, which is off course not completely correct. The error introduced, however, was judged as very small and of no importance.

Allocation of the major flow on to the two major lanes. Two lane allocation algorithms were suggested. The difference between them is how the left-turning vehicles from the opposite approach are treated. In the first algorithm they are assumed to choose the near or the far lane, at the entry considered, with equal probability. The algorithm can be expressed as

- $q_{NL} = q_{LT} + q_{OL}/2$
- $q_{FL} = q_{LL} + q_{OL}/2$

where
q_{NL} = flow in the near lane
q_{FL} = flow in the far lane
q_{OL} = left-turning flow from the opposite approach
q_{LL} = left-turning flow from the left approach
q_{LT} = through flow from the left approach

In the second algorithm all these vehicles are assumed to choose the near lane, which can be expressed as

- $q_{NL} = q_{LT} + q_{OL}$
- $q_{FL} = q_{LL}$

Estimation of capacity. The capacity was estimated by means of Equation (6), with parameters given by Equations (4) and (5).

Allocation of minor flow on to the two minor lanes. When two minor lanes have one lane in common some algorithm for the allocation of minor flow is needed. There exist at least three different ways to achieve this:

1. Minimization of delay. The drivers choose the lane that gives the lowest delay. Fisk (1991) has suggested a solution for this approach.
2. Equal degree of saturation. Each lane should have the same degree of saturation. This is the procedure adopted by CAPCAL. It can be motivated as it gives an approximate solution for the minimum delay.
3. Allocation by ratios. In Sweden it is commonly observed, although no systematic research has been undertaken, that the outer lane is more utilized than the inner lane, probably due to easier interaction with the major vehicles if the minor vehicle enter from the outer lane.

In this model, equal degree of saturation was used for the allocation of minor vehicles.

Limitation of inflow to the roundabout. Fisk (1991) noted a general problem of estimating the capacity of roundabouts. When the capacity is reached for an entry lane the inflow must be restricted so that it does not exceed the capacity. Fisk proposed an iterative procedure, involving the Gauss-Seidel approach, to solve the problem. This procedure was used in the capacity model.

Estimation of performance measures. Due to the nature of the study it was decided to use only capacity and degree of saturation to describe the function of the roundabout.

5. RESULTS OF VARYING OD FLOWS GIVEN BY THE NEW MODEL

The new model was tested on two synthetic data sets. The first one is represented by a four-armed roundabout where the traffic flow in each arm is 300 vehicles/hour and movement with the following exceptions:

- $q_{AT} = 0$
- $q_{AL} = 900$
- $q_{BL} = 0$

q_{AL} was decreased in steps of 100 vehicles/hour and q_{BL} was increased by the same amount. The result of the estimation of capacity and degree of saturation for approach D is given by Figure 4. The degree of saturation varies between 0.51 and 0.83 and it is obvious that the OD flows have a great influence on the capacity and the degree of saturation. The difference in capacity and degree of saturation is to a part explained by the limited inflow from approach B when q_{BL} is large. This limitation is also an explanation of the local maximum and minimum at the capacity curve in Figure 4. If a one-lane model was used instead, the capacity for the two entry lanes was, as expected, insensitive to changes of the OD flows.

The other data set was obtained from the first one by multiplying the values of the traffic flow for each movement by a factor of 5/6. The result of the estimations is shown in Figure 5. There is a difference in capacity depending on different OD flows, but it is rather

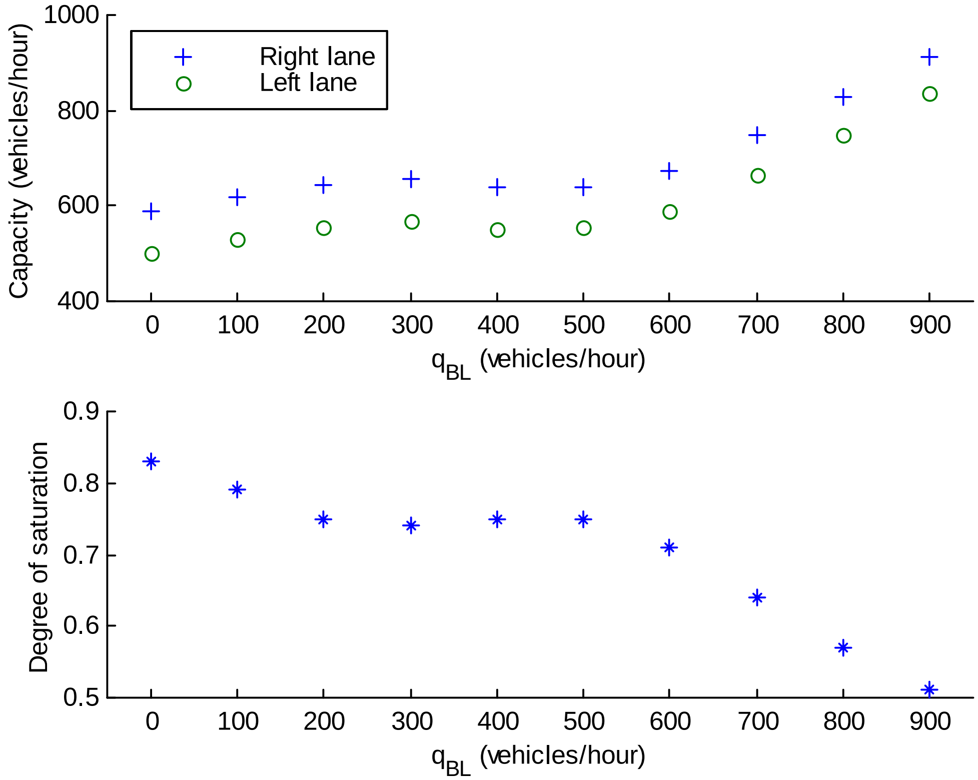

FIGURE 4 The result of the estimation of capacity for approach D, data set 1.

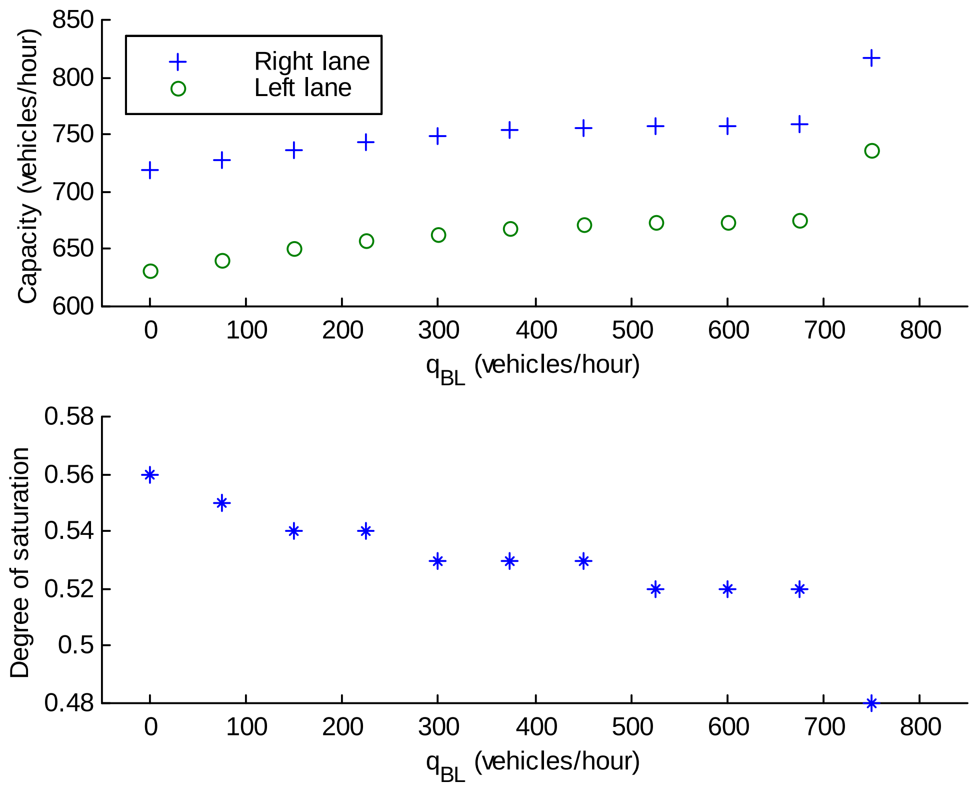

FIGURE 5 The result of the estimation of capacity for approach D, data set 2.

small. The capacity exceeds the inflow and thus there are no limitations on the inflow. It can be concluded that the OD flows can have a great impact on capacity, an impact that increases by increasing traffic flow.

The second lane-allocation algorithm gave approximately the same result as the first one.

6. THE OD FLOW MODEL PROPOSED BY AKCELIK ET AL.

Akcelik et al. (1996) and Akcelik (1997) have analyzed the effects of OD flows on capacity and developed a procedure to treat these effects. For simplicity we call this model the OD model. The basic gap acceptance capacity is reduced by a factor that takes the origin-destination pattern into account. This factor is in turn determined by two measures of the traffic condition in the roundabout, the proportion of the total circulating stream flow that originated from the dominant approach (p_{cd}) and the proportion of queued vehicles for that part of the circulating stream that originated from the dominant approach (p_{qd}). The dominant approach is defined as the approach that has the highest value of the product of these two measures. The implication of this is that the more unbalanced the approach flows are, the more will capacity be reduced. The reduction of the capacity is ranging between 4% and 55%.

There are at least two important differences between this model and the model outlined in the previous sections. First of all, the OD model is applicable also to one-lane roundabouts. Second, the OD model is symmetric, i.e., it makes no difference which of the approaches that are dominant. An analysis of the OD model shows that the effects of the OD flows is mixed with the effects of the proportion of queuing vehicles in the approaches. Assume that we have a roundabout with four arms and that the circulating flow for one of the entries is varied between 100 and 1400 vehicles per hour. The circulating flow consists of one part from the approach that is nearest upstream and one part from the opposite approach. If these parts are equal, then the p_{cd} values for the two approaches considered are equal. The decrease of the capacity, due to changes in the proportion of queued vehicles, will vary between 0% and 28% when the circulating flow varies between 100 and 1400 vehicles/hour. If the approach flows are completely asymmetric, i.e., one approach has zero flow, the decrease in capacity will vary between 0% and 55%. This means that half of the reduction comes from the proportion of queuing vehicles only. In Figure 6 this is illustrated by an example, based on Swedish roundabout measurements. The figure shows that capacity is reduced quite heavily even if there is no OD flow is symmetric. The OD model indicates that the SR45/AUSTROADS method (Troutbeck 1989) overestimates capacity (see for instance Akcelik 1998, p. 98). However, half of the overestimation is not dependent on the OD flow.

The mechanisms behind the reduced capacity is not reported in the papers by Akcelik et al. (1996) and Akcelik (1997). The phenomenon discussed, i.e., the difference between the observed capacity and the capacity predicted by the SR45/AUSTROADS method, can only have two explanations: the gap acceptance behavior is in some way altered or the distribution of headways is altered. It is known (see for instance Troutbeck 1990) that the size of the major flow can effect the size of the critical gaps and the follow-up times but

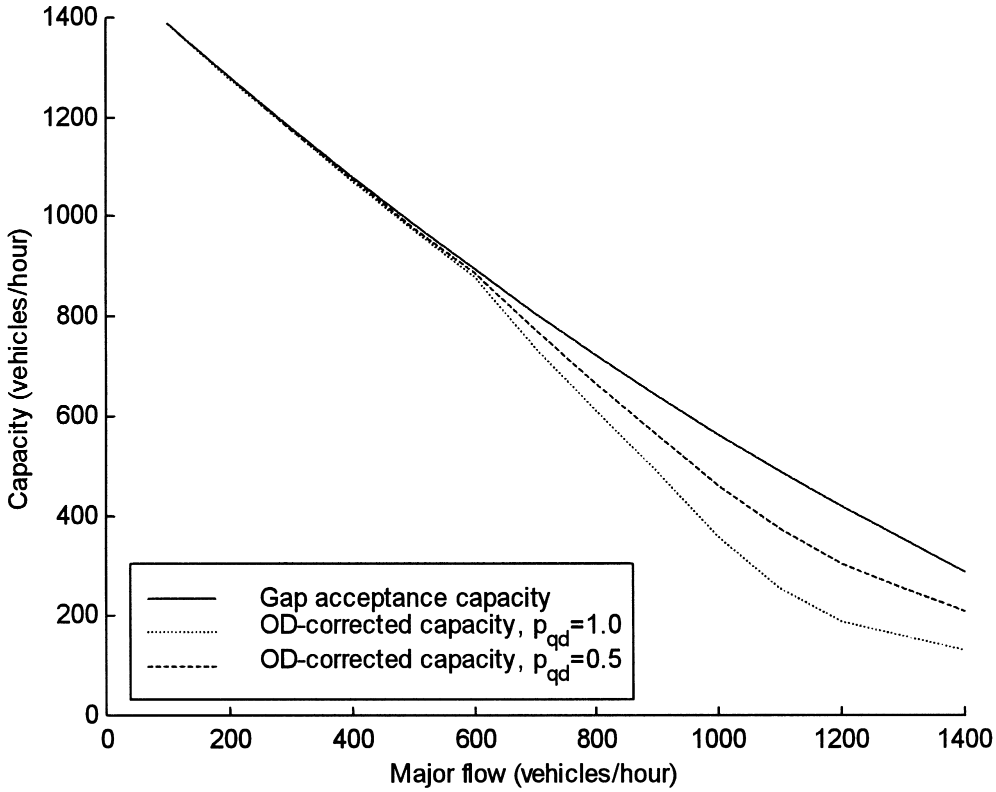

FIGURE 6 Capacity predicted by an ordinary gap acceptance model and by the OD model.

here the size of the major flow remains the same so it is probably only the headway distribution that is altered.

The OD model was calibrated by a simulation program, MODELC, which is not described in the papers by Akcelik et al. (1996) and Akcelik (1997). A description of it is, however, found in Chung et al. (1992). In a comparison of MODELC and INSECT—another roundabout simulation program reported in that paper—fixed critical gap and follow-up headway were used. The result of the simulation showed that MODELC was sensitive for changes in the OD pattern. Estimated values of the delay (see Table 4 in Chung et al. 1992) show that the OD effects are not symmetric—the delay is longer if all circulating vehicles come from the opposite approach, i.e., if all circulating vehicles come from the nearest approach the delay will be shorter. This is in accordance with the results reported in section 5—the greatest capacity was obtained when all circulating vehicles come from the nearest approach. Although not explicitly stated in any of the papers cited above, one can draw the conclusion that the reported OD effect depends on variations in the distribution of headways.

7. CONCLUSIONS

The OD flows can have a considerable effect on capacity. The effects can be estimated by the model developed by the author in this paper (two-lane roundabouts only) or by the model developed by Akcelik (1997).

The effect of the OD flows on capacity is explained by the allocation of the circulating flow on to the two circulating lanes in the model developed by the author. In the model developed by Akcelik (1997) there is no explanation given explicitly, although one can draw the conclusion that the effect is dependent on changes in the headway distribution for the circulating flow.

The effects on capacity given by the OD model presented by Akcelik (1997) is to a large extent dependent on the proportion of queued vehicles and not only on the OD pattern. This means that the overestimation of capacity, predicted by the SR45/AUSTROADS capacity model, is not only dependent on the OD flow.

The result from the study undertaken by Chung et al. (1992) indicate that the OD effect is asymmetric while the effects of the model presented by Akcelik (1997) state that the effect is symmetric.

If the gap acceptance behavior is altered in some way this can only be detected by field measurements. Changes in the distribution of headways can be detected through simulation although the results of the simulation is highly dependent on the calibration of the model. Thus, it seems desirable to carry out field measurements and to compare the observed gap acceptance behavior and the distribution of headways from sites with different OD pattern. Otherwise we will remain ignorant of the mechanisms behind the effects of unbalanced OD patterns, especially in one-lane roundabouts.

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