CAPACITY ENHANCEMENT AND LIMITATION AT ROUNDABOUTS WITH DOUBLE-LANE OR FLARED ENTRIES

Ning Wu, Ph.D.
Privatdozent, Institute for Traffic Engineering, Ruhr University, D-44780 Bochum, Germany
phone: +49 234 3226557, fax: +49 234 3214151
e-mail: ning.wu@rub.de, http://homepage.rub.de/ning.wu

ABSTRACT

This paper presents a method to deal with the enhancements/reductions on capacity at roundabouts with double-lane or flared areas at the entries and capacity restraints at the exits. For taking into account the flared single-lane entries or double-lane entries with short-lane configurations, an enhancement/correction factor is introduced. With this factor, the length of the double-lane or flared area can be taken into account. In order to consider the entry capacity depending on the limited capacities of the exits, a reduction factor is derived according to the OD-relationship. The result of the proposed method is then verified with field measurements in Germany.

1 INTRODUCTION

Using gap-acceptance theory, the potential capacity of an entry at roundabouts can be estimated. The potential capacity is normally a function of the critical gap, the follow-up time, the minimal intra-vehicle time-headway, the number of entry and circulating lanes, as well as the circulating flow rate. For example, a generalized function of the potential capacity was given by the author (Wu, 1997a). This functional expression can be applied to both single-lane and double-lane entries. This capacity formula is also incorporated in the German Highway Capacity Manuel (FGSV, 2001).

In reality, most single-lane entries at roundabouts are flared because of the design geometry. These flared single-lane entries can provide more capacity than the normal single-lane entries. However, the flared entries are not double-lane entries because the flared area is not always available for vehicles approaching the roundabouts. The potential capacity of a double-lane entry can never be totally attained. For the same reason, the capacity of a double-lane entry must be reduced by a factor < 1, if one of the two lanes is of limited length. Here, a simple theoretical approach for determining the capacity of flared single-lane entries or at double-lane entries with short lanes is introduced in section 3.

The potential capacity of an entry can only be achieved if there are no restrains at the exits of the roundabout. If the capacities of the entries are higher than that of the exits, the entry capacities are not achievable. That is, the capacity of an entry is subject to the capacities of the exits. Furthermore, it is also subject to the Origin-Destination (OD) -relationship between the entries and exits. This capacity limitation depending on the capacity restrains at the exits is considered in detail in section 4.

To calculate achievable capacity, both the capacity limitations of the flared single-lane entries (or double-lane entries with short lanes) and the capacity restraints of the exits must be taken into account.

2 POTENTIAL ENTRY CAPACITY AT ROUNDABOUTS

The present author (Wu, 1997a) modified the basic idea of Tanner (1962) for estimating capacity at unsignalized intersections and proposed the following formula for the potential capacity of an entry (both single-lane and double-lane) to a roundabout:

$$q_e = \left(1 - \frac{\Delta \cdot q_c}{3600 \cdot n_c}\right)^{n_c} \cdot \frac{3600 \cdot n_e}{t_f} \cdot \exp\left(-\frac{q_c}{3600} \cdot (t_0 - \Delta)\right) \tag{1}$$

where	q_e	= maximal entry flow (capacity of the entry)	[veh/h]
	q_c	= flow on circulating lanes at the subject entry	[veh/h]
	n_c	= number of circulating lanes	[-]
	n_e	= number of lanes in the subject entry	[-]
	t_0	= $t_c - t_f / 2$	[s]
	t_c	= critical gap	[s]
	t_f	= move-up time	[s]
	Δ	= minimum headway between vehicles in the circulating lanes	[s]

Figure 1 shows the capacity according to Equation (1) with the parameters t_c=4.12s, t_f=2.88s and Δ=2.10s. These parameters have been found to represent driver behavior at roundabouts in Germany (cf. Wu, 1997a). This capacity formula is also incorporated in the German Highway Capacity Manuel (FGSV, 2001).

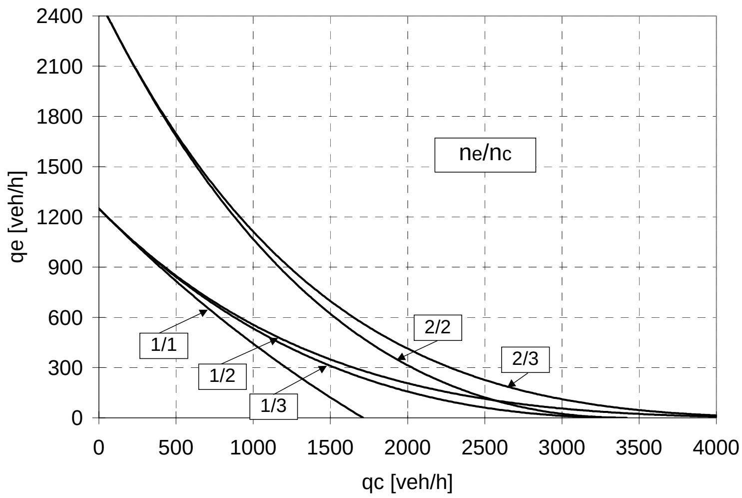

Figure 1 - Capacity at roundabouts (eq. (1))

For double-lane entries, Equation (1) gives the potential entry capacity as a function of the lane capacity. Accordingly, an entry with two lanes has exactly the same potential capacity as that of two lanes. Thus, Equation (1) can be written by

$$q_e = c_{\ln} \cdot n_e \tag{1a}$$

with $c_{\ln}$ = capacity of a single lane with infinite length [veh/h]

The capacity of a single lane is given by

$$c_{\ln} = \left(1 - \frac{\Delta \cdot q_c}{3600 \cdot n_c}\right)^{n_c} \cdot \frac{3600}{t_f} \cdot \exp\left(-\frac{q_c}{3600} \cdot (t_0 - \Delta)\right) \tag{2}$$

The capacity calculated from (1a) can only be utilized if the number of lanes in the roundabout is equal to or higher than the number of lane at the subject entry. This is always the case in Germany because of safety concerns. In this case, two vehicles can simultaneously enter different lanes in the roundabout. The gaps used for merging may not be very different from the case of single-lane entries. In other countries (e.q. United Kingdom and France), this condition is not guaranteed. For that case, Equation (1a) is not suitable for calculating capacities of the double-lane entries.

Certainly, in order to take into account the regionally related traffic conditions, any other lane-based capacity formula can be used for calculating the lane capacity instead of the Equation (2) (e.g. Akcelik, 1997; Hagring, 1996; also Kimber, 1980). For example, the Equation 17-70 in the US Highway Capacity Manual (TRB, 2000) should used for the United States.

In Figure 2 and Figure 3, a comparison of the results from Equation (1) versus measurements (Stuwe, 1992, 1-minute intervals of saturation flows, measured in Germany) is illustrated for some special double-lane entries. Here, the measured roundabouts are very large and they also have multilane exits. Therefore, all vehicles coming in can also come out without queuing at the exits. It turns out that the Equation (1) is a good representation of the average of the 1-minute capacities. Therefore, because the hourly capacity is simply the average of 60 1-minute capacities, it is also a good representation of the hourly capacities.

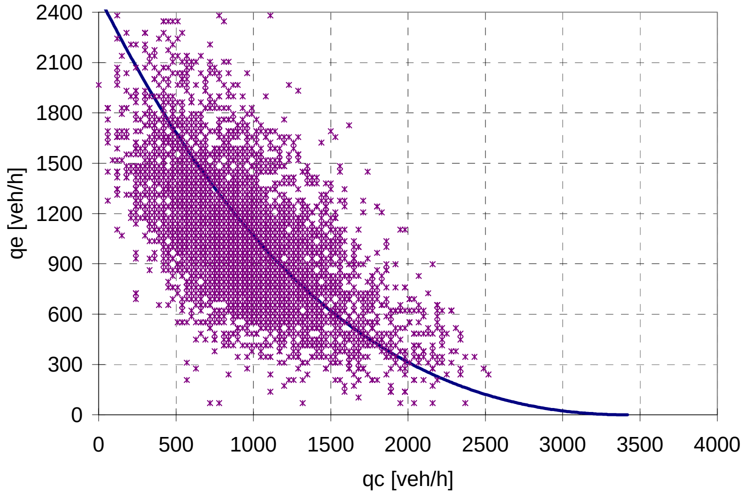

Figure 2 - Comparison of eq. (1) with measurements for 2/2-roundabouts with multilane exits, n = 4574 (Data, Stuwe, 1992)

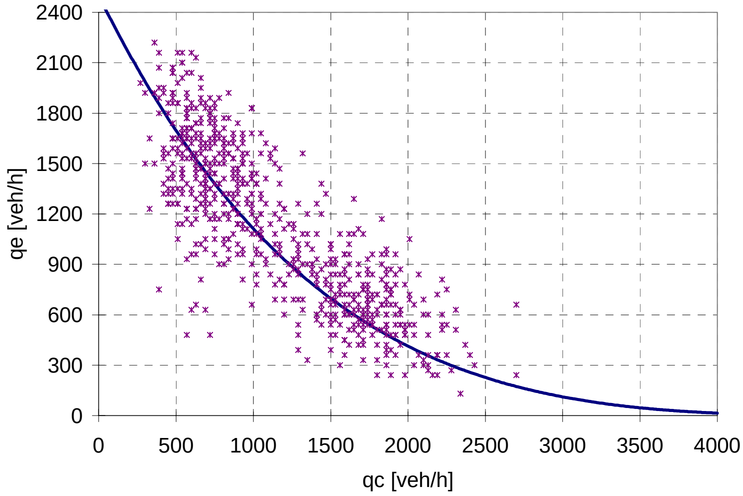

Figure 3 - Comparison of eq. (1) with measurements for 2/3-roundabouts with multilane exits, n= 295 (Data, Stuwe, 1992)

However, if the exits at a roundabout have only one lane, the capacity resulting from Equation (1) cannot be utilized because the exits will build the system bottlenecks, which then determine the entire system capacity. For example, we cannot expect the total capacity of a roundabout be greater than the total exit capacities, regardless of which capacities the entries have.

In Figure 4 some measurements for double-lane entries at midsized roundabouts in Germany with single-lane exits are illustrated together (Brilon and Bäumer, 2004). Here, however, the second lanes in the entries are not infinitely long. They have normally a length of about 50m. It can be seen that the capacity estimated by Equation (1) cannot be completely reached. The reason for this discrepancy can be on the one hand the limited length of the second lanes in the entries and on the other hand the limited exit capacities due to the single-lane configuration. Both limitations must be taken into account in order to calculate the total capacity.

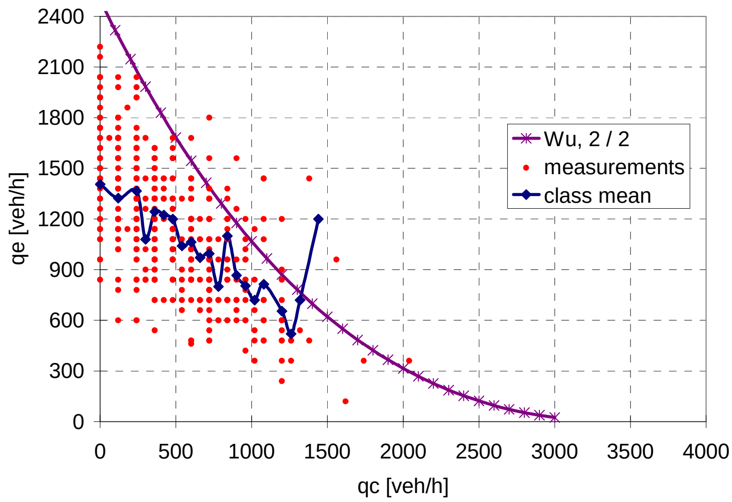

Figure 4 - Comparison of eq. (1) with measurements for midsized 2/2-roundabouts with single-lane exits, n= 541 (Data Brilon and Bäumer, 2004)

3 ENHANCEMENT/CORRECTION FACTOR FOR CAPACITY OF FLARED SINGLE-LANE ENTRIES OR DOUBLE-LANE ENTRIES WITH SHORT LANES

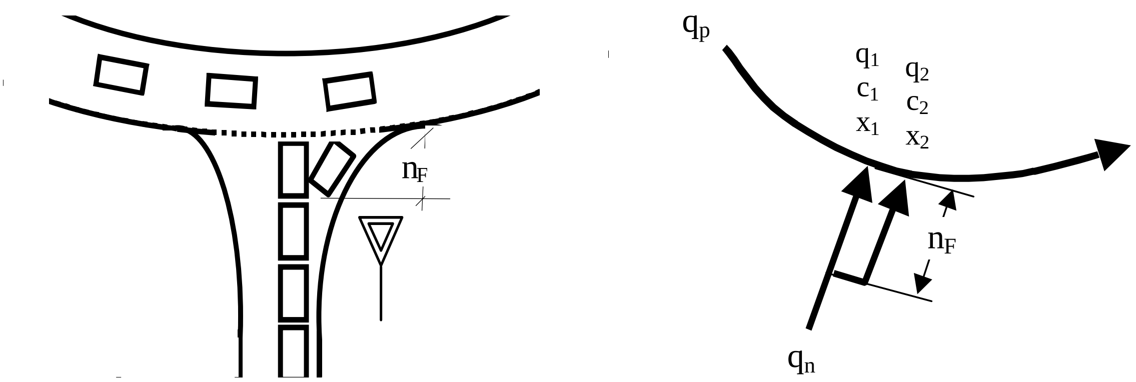

Figure 5 - Flared entries / entries with short lanes at roundabouts

Equation (1) calculates the potential entry capacity in such a way that the particular geometry of the entries is not considered. Only the number of the lanes at the entries is used as a parameter. Accordingly, an entry can only be considered as either a single-lane or a double-lane entry. The lengths of the individual lanes cannot be considered. However, in reality there are rarely entries having exactly the width of one lane at roundabouts. If a single-lane entry is flared due to the large entry radius, it can be used by vehicles as an additional waiting area, which operates like an additional lane (Figure 5). This additional quasi-lane is normally short (ca. 5 to 10m). Here, the potential capacity for double-lane entries cannot be entirely utilized. On the other hand, for a double-lane entry where one of the traffic lanes has only a limited length (short lane), the capacity of double-lane entries also has to be reduced for the same reason.

Based on empirical data, Kimber (1980) introduced an approach for taking into account the effect of flared single-lane entries or double-lane entries with short lanes. This approach takes into account many geometrical parameters at roundabouts, in particular also the length of the flared area or the length of the short lane. This approach is based strongly on data obtained in United Kingdom and it seems to be not directly portable for the conditions in other countries.

This author (Wu, 1997b, 1999) presented a theoretical model with which the capacity of the entries with short lanes at unsignalized intersections can be calculated. This model is in the mathematical sense universal and accordingly, also portable for entries at roundabouts with flared entries or short lanes. From this model, a method for calculating the capacities of entries with flared areas or short lanes at roundabouts can be obtained.

The problem in this paper can be understood as that of two short lanes with a common merge point (cf. Figure 5). Here, the entry capacity is given by (Wu, 1997b, 1999)

$$c_F = \frac{q_1 + q_2}{\sqrt[n_F+1]{x_1^{n_F+1} + x_2^{n_F+1}}} = \frac{q_1 + q_2}{\sqrt[n_F+1]{\left(\frac{q_1}{c_1}\right)^{n_F+1} + \left(\frac{q_2}{c_2}\right)^{n_F+1}}} \qquad (3)$$

with	c_F	=	capacity of the considered entry	[veh/h]
	c_1	=	capacity of lane 1 as a separate lane	[veh/h]
	c_2	=	capacity of lane 2 as a separate lane	[veh/h]
	q_n	=	total traffic flow at the entry	[veh/h]
	q_1	=	traffic flow of lane 1	[veh/h]
	q_2	=	traffic flow of lane 2	[veh/h]
	n_F	=	length of the short lane	[veh]
	q_p	=	circulating traffic flow	[veh/h]
	x	=	saturation degree = q/c	[-]

As a simplification, the capacities of both lanes (for the case that they are considered as separate lanes) are assumed to be identical and the traffic flow on both short lanes to be equally distributed. Thus,

$$c_1 = c_2 = c_{\ln}(q_p)$$

$$q_1 = q_2 = \frac{q_n}{2}$$

and

$$x_1 = x_2 = \frac{q_n}{2c_{\ln}}$$

with $c_{\ln}$ = capacity of a separate lane with infinite length = $f(q_p, n_c)$ (i.e. Equation (2))

The total capacity (eq. (3)) of the entry under these assumptions is

$$c_F = \frac{q_1 + q_2}{\sqrt[n_F+1]{x_1^{n_F+1} + x_2^{n_F+1}}} = \frac{q_1 + q_2}{\sqrt[n_F+1]{2} \cdot x_1} = \frac{q_n}{\sqrt[n_F+1]{2} \cdot \frac{\frac{q_n}{2}}{c_{\ln}}} = \frac{2 \cdot c_{\ln}}{\sqrt[n_F+1]{2}} \qquad (4)$$

Equation (4) can be rewritten as

$$c_F = \frac{2}{\sqrt[n_F+1]{2}} \cdot c_{\ln} = 2^{\frac{n_F}{n_F+1}} \cdot c_{\ln} = f_F \cdot c_{\ln} \tag{5}$$

with

$$f_F = \frac{2}{\sqrt[n_F+1]{2}} = 2^{\frac{n_F}{n_F+1}} \tag{6}$$

The enhancement/correction factor f_F as a function of n_F is presented in Figure 6. The value of $c_{\ln}$ is calculated from (2). Based on the result of (4), the FHWA Roundabout Guide (FHWA, 2000) incorporated the same enhancement/correction factor for double-lane entries at roundabouts.

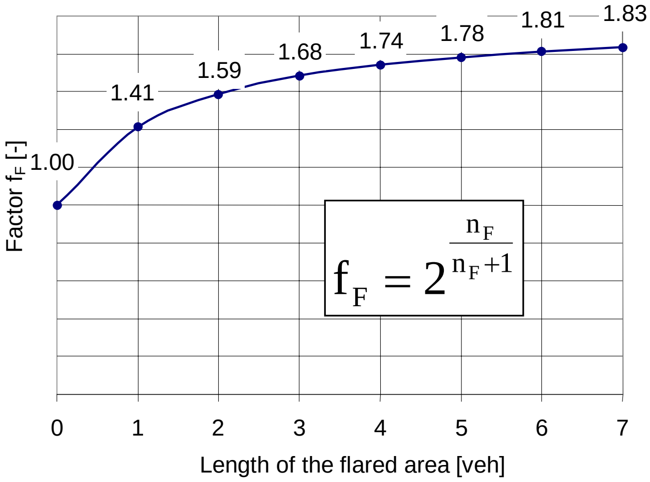

Figure 6 - Enhancement/correction factor f_F for roundabouts with flared entries according to eq.(6)

The enhancement/correction factor f_F shows the effect of flared area on the capacity. The value of f_F is in the case of n_F=0 equal to 1 (i.e., no flared area, only one lane at the entry) and in the case of $n_F=\infty$ equal to 2 (i.e., two separate lanes at the entry). In this way, the boundary conditions at both ends of the possible data range are fulfilled. Moreover, Figure 6shows that even at n_F=1 (the flared area can only accommodate two vehicles side by side) the capacity of the entry can be enhanced by 41%.

4 CAPACITY RESTRAINTS DUE TO SINGLE-LANE EXITS

The potential capacity of an entry can only be utilized if all entering vehicles can depart at the exits without impedance. If the capacities of the entries are higher than the capacities of the exits, the former are limited by the latter. In reality, most of the drivers prefer waiting at the entries to waiting on the circulation lanes before the exits. Thus, the capacity of an entry is reduced dependent on the capacities of the exits. Furthermore, this reduction is also depends on the OD-relationship between the entries and exits because an exit at a roundabout is usually used by traffic flows from all the other entries (cf. also Alsop, 1998).

Given the OD-matrix between the entries and exits of a roundabout and assuming that the capacity of the exit *j* is proportional (if an exit is operating at capacity, the proportion of the flow rate from other entries to the exit should remain constant) to the rate of traffic flow from the entry *i* to the exit *j*, the maximum rate of flow from the entry *i* to the exit *j* which can be accommodated in exit *j* is

$$C_{i,j} = C_j \cdot \frac{OD_{i,j}}{D_j} \tag{7}$$

with $C_{i,j}$ = capacity of entry i given capacity of exit j [veh/h]
C_j = capacity of exit j (i.e. 1200 veh/h) [veh/h]
$OD_{i,j}$= flow rate from entry i to exit j [veh/h]
D_j = destination flow from all entries to exit j [veh/h]

For the case that $C_{i,j}$ is totally utilized, the maximal possible flow rate at the entry i is

$$C_{i,j}^{\ *} = C_{i,j} \cdot \frac{O_i}{OD_{i,j}} = C_j \cdot \frac{OD_{i,j}}{D_j} \cdot \frac{O_i}{OD_{i,j}} = C_j \cdot \frac{O_i}{D_j} \tag{8}$$

with O_i = origin flow from entry i to all exits [veh/h]

$C_{i,j}^{\ *}$ is the maximal flow rate at entry i for the case that at exit j the capacity C_j is reached.

The maximal flow rate of the entry i is the harmonic mean of $C_{i,j}^{\ *}$ over all exits. That is, for a roundabout with N legs

$$C_{i,\max} = \left(\sum_{j=1}^{N} \frac{a_{i,j}}{C_{i,j}^{\ *}} \right)^{-1}$$

with $a_{i,j}$ = proportion of the traffic flow from entry i to exit j to the total flow at the entry i [-]

With $a_{i,j} = OD_{i,j} / O_i$ we have

$$\begin{aligned} C_{i,\max} &= \left(\sum_{j=1}^{N} \frac{1}{C_{i,j}^{\ *}} \cdot \frac{OD_{i,j}}{O_i} \right)^{-1} = \left(\sum_{j=1}^{N} \frac{1}{C_j \cdot \frac{O_i}{D_j}} \cdot \frac{OD_{i,j}}{O_i} \right)^{-1} \\ &= \left(\sum_{j=1}^{N} \frac{D_j}{C_j \cdot O_i} \cdot \frac{OD_{i,j}}{O_i} \right)^{-1} = \left(\sum_{j=1}^{N} \frac{D_j}{C_j} \cdot \frac{OD_{i,j}}{O_i^2} \right)^{-1} \end{aligned} \tag{9}$$

For $C_{i,max}$ and C_j, the following inequality holds

$$\sum_{i=1}^{N} C_{i,\max} \le \sum_{j=1}^{N} C_j \tag{10}$$

For the special case $C_j = C_a$ = const. (all exits have the same capacity) is

$$C_{i,\max} = \left(\sum_{j=1}^{N} \frac{D_j}{C_j} \cdot \frac{OD_{i,j}}{O_i^2} \right)^{-1} = \left(\sum_{j=1}^{N} \frac{D_j}{C_a} \cdot \frac{OD_{i,j}}{O_i^2} \right)^{-1} = \frac{C_a}{\sum_{j=1}^{N} D_j \cdot \frac{OD_{i,j}}{O_i^2}} \tag{11}$$

And for the special case that $D_j = D$ = const and $O_i = O$ = const (equal distribution of traffic flows in all entries an exits) is

$$C_{i,\max} = \frac{C_a}{\sum_{j=1}^{N} D \cdot \frac{OD_{i,j}}{O^2}} = \frac{C_a}{\frac{D}{O^2} \cdot \sum_{j=1}^{N} OD_{i,j}} = \frac{C_a}{\frac{D}{O^2} \cdot D} = C_a \tag{12}$$

Here, $\sum_{i=1}^{N} C_{i,\max} = \sum_{j=1}^{N} C_j = N \cdot C_a$ has its maximal value.

5 ACHIEVABLE CAPACITY OF AN ENTRY

The actual capacity that an entry at roundabouts can utilize is the capacity from the gap-acceptance theory (e.g. eq. (1)) modified by the limitations (eq. (6) and eq. (9)). The achievable capacity of the entry *i* is then the smaller of c_F and $C_{i,max}$. That is

$$C_i = \min(c_{\ln} \cdot f_F,\ C_{i,\max}) \qquad (13)$$

with f_F from eq. (6) (correction factor for short-lanes at the entry)
$c_{\ln}$ from eq. (2) (or any other lane-based capacity formula)
$C_{i,max}$ from eq. (9) (capacity limitation at the exits)

Unfortunately, the measurements in the investigation (Brilon and Bäumer, 2004) for double-lane entries with single-lane exits (Figure 4) were carried out without prior knowledge of the OD-relationship. Thus, a direct comparison to Equation (13) is impossible. Here, in order to test the range of achievable capacities at entries to roundabouts with single-lane exits, and in order to show the sensibility of the capacity restraints to the OD-relationship, the following geometric and traffic conditions are assumed:

- The roundabouts are intersections of two streets (N = 4)
- At all entries, the double-lane section is about 50 m long
- At the roundabouts, the opposing entries of the same street have the same flow rate
- In all entries, both the left-turning and the right-turning traffic are 20% of the total entry flow
- The flow-split between the two streets varies from 50/50 to 70/30
- The capacity at all exits is 1200 veh/h

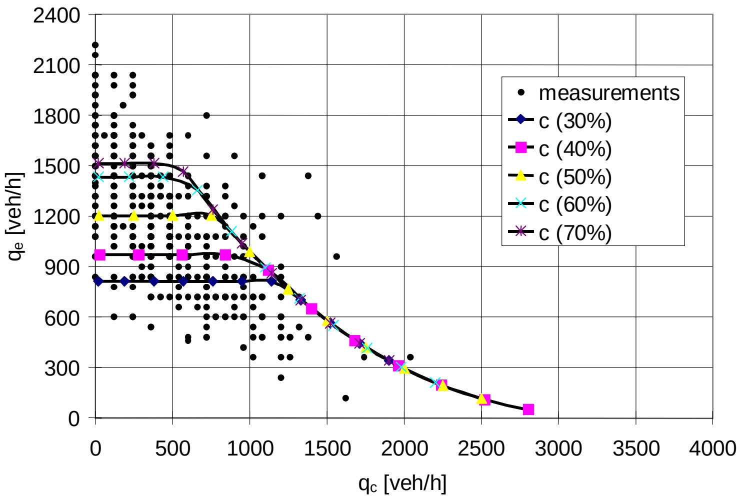

Figure 7 - Comparison of the range of achievable capacities from (eq.(13)) and from measurements for different flow-split (30%-70%)

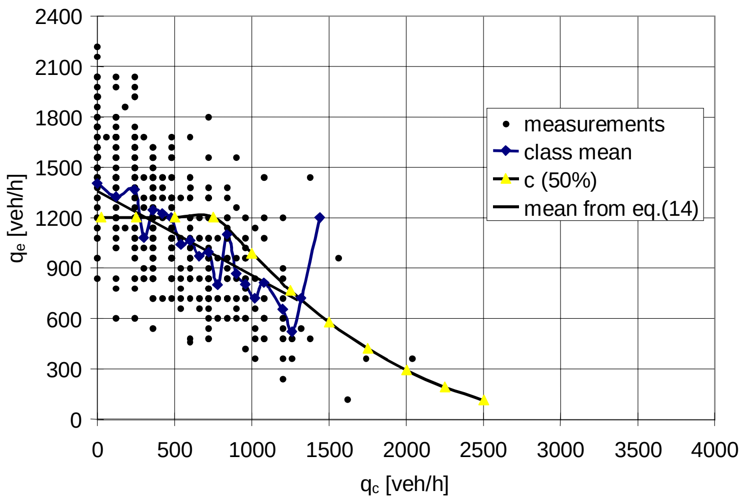

Figure 8 - Mean value of achievable capacities for roundabouts with double-lane entries and single-lane exits

With theses predefined conditions, the achievable capacity is calculated from Equation (13). The results are illustrated together with the measurements in Figure 7. It can be seen that the range of the calculated achievable capacities properly covers the same range as the measurements.

Furthermore, the mean values of the calculated achievable capacities are compared with the class means of the measurements. The agreement is very good (Figure 8). Thus, in case the OD-relationship is not available, this mean value of the achievable capacities can be used as an approximation. The regression function of the achievable capacities in the area of $C_{i,\max} \leq c_F$ is

$$C_{i,\text{max,mean}} = 1355 - 0.5 \cdot q_c \tag{14}$$

Thus, the mean value of the real capacities is

$$C_{i,mean} = \min(c_{\ln} \cdot f_F,\ C_{i,\max,mean}) \tag{15}$$

with f_F from eq. (6)
$c_{\ln}$ from eq. (2) (or any other lane-based capacity formula)
$C_{i,\text{max,mean}}$ from eq. (14)

In Figure 8 also the achievable capacity for the case that the traffic flow is equally distributed (flow-split=50%) is illustrated. The region on the left-hand side of the curve shows clearly the capacity limitation due to the exit capacity (1200 veh/h).

It can also be seen in Figure 7, that the maximum achievable capacity (for q_c=0) of an entry can be below 900 veh/h for asymmetric flow distribution (e.g., for flow-split = 30%). It can be even lower than the capacity of a single-lane entry (cf. Figure 1). However, for single-lane entries, we should also use n_F=0 in eq. (13) (and eq. (6)) for taking into account the capacity limitation at exits.

6 SUMMARY AND CONCLUSIONS

The capacity at roundabouts with single-lane exits is in general limited by the capacity at the exits. These limitations depend on the OD-relationship of the traffic flows. In addition, enhancement of the entry capacity at roundabouts with double-lane entries is limited by the length of the double-lane area. If the OD-relationship is known, the capacity of an entry can be calculated from eq. (13).

For the case that the OD-relationship is unknown, Equation (15) is recommended for calculating the mean capacity at the entry.

7 REFERENCES

AKCELIK, R. (1997). Lane-by-Lane Modeling of Unequal Lane Use and Flares at Roundabouts and Signalized Intersection: the SIDRA Solution. *Traffic Engineering & Control*, Vol. 38, No. 7/8.

ALSOP, R.E (1998). Analysis of traffic conditions at congested roundabouts. In: *Mathematics in Transport Planning and control - Proceedings of the Third IMA International Conference on Mathematics in Transport Planning and Control*, Cardiff, April 1998 (ed. J. D. Griffiths), 1-16. Oxford: Pergamon.

BRILON, W.; BÄUMER, H. (2004). Kompakte zweistreifig befahrbare Kreisverkehre (Compact roundabouts with 2-lane circulating carriageways). *Straßenverkehrstechnik.* 7/2004, pp.333ff. Kirschbaum Verlag GmbH, Bonn.

FGSV (2001). *Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS 2001, Germany Highway Capacity Manuel).* Forschungsgesellschaft für Straßen- und Verkehrswesen (Hrsg.), Nr. 299, FGSV Verlag GmbH, Köln.

FHWA (2000). *Roundabouts: An Informational Guide*. Federal Highway Administration, U.S. Department of Transportation, Publication No. FHWA-RD-00-067. 2000.

HAGRING, O. (1996). The Use of the Cowan M3 Distribution for Modeling Roundabout Flow. *Traffic Engineering & Control,* , No. 5/1996.

KIMBER, R.M. (1980). *The capacity of roundabouts.* TRRL, LR 942.

TANNER, J.C. (1962). A theoretical analysis of delay at an uncontrolled intersection. *Biometrica* 49 (1 and 2), pp.163-70.

STUWE, B. (1992). Untersuchung der Leistungsfähigkeit und Verkehrssicherheit an deutschen Kreisverkehrsplätzen (Investigation of Capacity and Safety at German Roundabouts). Schriftenreihe des Lehrstuhls für Verkehrswesen der Ruhr-Universität Bochum, Heft 10.

TRB (2000)**.** *Highway* Capacity *Manual* (HCM 2000). TRB, National Research Council, Washington, D.C.

WU, N.(1997a). An Universal Formula for Calculating Capacity at Roundabouts. *Arbeitsblaetter*, Institute for Traffic Engineering, Ruhr-University Bochum, No.13.

WU, N. (1997b). Capacity of Shared-Short Lanes at Unsignalised Intersections. In M. Kyte (ed.): *Proceeding of the Third International Symposium on Intersections Without Traffic Signals,* Portland, Oregen, USA, July 1997. University of Idaho, Moscow.

WU, N. (1999). Capacity of Shared/Short Lanes at Unsignalised Intersections. *Transportation Research,* A33, Issue: 3-4. Elsevier Science Ltd., New York, Tokyo, Oxford.