Unsignalized Intersections in Germany - a State of the Art 1997

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ABSTRACT

Research results on the field of unsignalized intersections from Germany were of some importance for practical application in the past also in other countries. Since the first two international workshops in 1988 and 1991 some progress has been made on some aspects of theory for TWSC intersections. This paper tries to provide short descriptions of those new ideas which might be of more general interest. Thus contributions on the following fields are described: two-stage priority, flared minor street entries and short lanes, as well as formulas for impedance factors. For roundabouts the following items are explained: current capacity formulas based on empirical linear regression technique, a more universal gap-acceptance technique for roundabouts, capacity reduction by pedestrians on Zebra crossings in entries and exits of roundabouts. Also experience from practical application of roundabouts is mentioned, like principles of design, safety, and experiments with mini-roundabouts. The paper gives a brief explanation of the topics mentioned and makes reference to some of the publications where these issues are explained more comprehensively.

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1. INTRODUCTION

Country reports on unsignalized intersections have been given from Germany by several contributions at the previous two international symposia (1), (2). Meanwhile some further progress has been achieved on several sectors of the relevant traffic engineering theory. This, to some extend, is also due to the challenges in connection with the close cooperation with American colleagues on the NCHRP-Project 3-46 (3). The most spectacular and obvious development, however, is incorporated by a large number of new roundabouts, which are now installed in Germany - with some delay to other European Countries like France or Switzerland et al. Meanwhile roundabouts have become the most attractive type of intersection design for new medium size intersections and for reconstructions as well.

Also on the field of guidelines some new developments have to be reported. For roundabouts three guidelines should be mentioned, two of which are more focused on urban situations (4)(5), whereas another guideline (6), given by the federal DOT, is only valid for rural roundabouts. Moreover, since 1993 there is a first draft of a German Highway Capacity Manual (7) containing one chapter for TWSC-intersections and another for roundabouts. Currently a committee has been established to work on the first official edition of this manual which should be authorized by the federal DOT and the German organization FGSV (corresponding to the American TRB). This first official edition is planed for the year 2000. Meanwhile the improved chapter for TWSC-intersections and roundabouts has been worked out as a next draft (8). Most of the methodological improvements for this chapter are mentioned in this paper. This paper tries to provide short descriptions of those new ideas which might be of more general interest.

2. NEW DEVELOPMENTS IN THEORY OF TWO-WAY-STOP-CONTROL INTERSECTIONS

2.1 Two-Stage Priority

At many unsignalized intersections there is a space in the center of the major street available where several minor street vehicles can be stored between the traffic flows of the two directions of the major street, especially in the case of multilane major traffic. This storage space within the intersection enables the minor street driver to pass each of the major streams at a time. This behavior can contribute to an increased capacity.

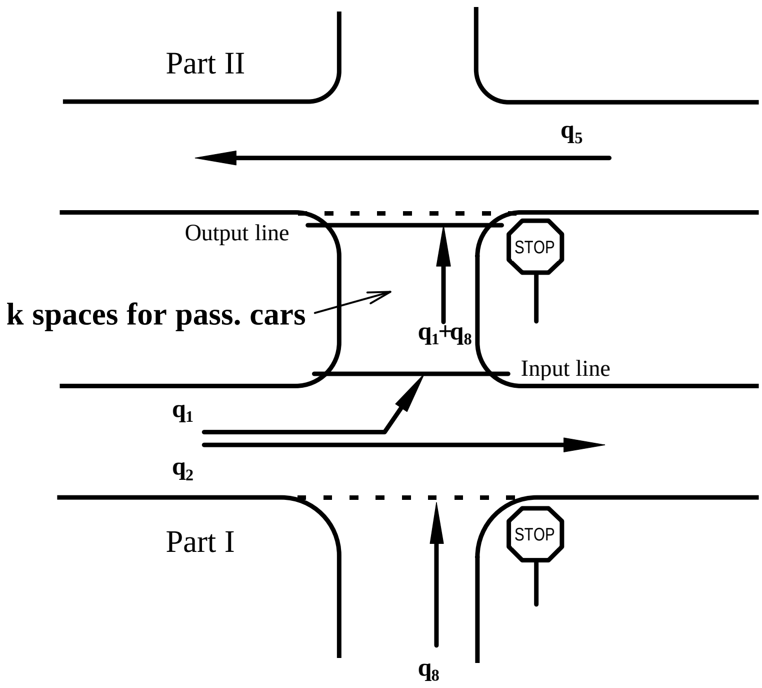

Figure 1: Minor street through traffic (movement 8) crossing the major street in 2 phases. The theory discussed here is also available if the major street provides more or less than 2 lanes per direction.

Brilon et al. (9) developed a model considering this type of intersection based on a concept from Harders (10). However, some major amplifications as well as a correction and an adjustment to reality were made to achieve better correspondance to realistic conditions. This model is used both in the new versions of the US- and the German Highway Capacity Manual.

In the model an intersection consisting of two parts is considered (cf. fig. 1; numbers of movements according to the HCM). Between the partial intersections I and II there is a storage space for k vehicles. This area has to be passed by the left turner from the major street (movement 1) and the minor through traffic (movement 8). Also the minor left turner (movement 7) has to pass through this area. Movement 7 can be treated like movement 8 and is here eliminated for simplification. It is assumed that the usual rules for unsignalized intersections from the highway code are applied by drivers at the intersections. Thus movements 2 and 5 (major through traffic) have priority over each other movement. Movement 1 vehicles have to obey the priority of movement 5 whereas movement 8 has to give the right of way to each of the movements shown in fig. 1 . Movement 5 stands here for all major traffic streams at part II of the intersection. These, depending on the layout of the intersection, could include through traffic (movement 5), left turners (movement 4) and right turners (movement 6).

The steps of computation which are necessary to estimate the capacity under these circumstance are:

$$y = \frac{c(q_1 + q_2) - c(q_1 + q_2 + q_5)}{c(q_5) - q_1 - c(q_1 + q_2 + q_5)} \tag{1}$$

$$c_T = \frac{\alpha}{y^{k+1} - 1}\left\{y \cdot \left(y^k - 1\right) \cdot \left[c(q_5) - q_1\right] + (y-1) \cdot c(q_1 + q_2 + q_5)\right\} \qquad \text{for } y \neq 1 \tag{2}$$

$$c_{T(y=1)} = \frac{a}{k+1}\left[k \cdot \left[c(q_5) - q_1\right] + c(q_i + q_2 + q_5)\right] \qquad \text{for } y = 1 \tag{3}$$

c_T = total capacity of the intersection for minor through traffic

with
$$a = \begin{cases} 1 & for\ k = 0 \\ 1 - 0.32 \cdot \exp(-1.3 \cdot \sqrt{k}) & for\ k > 0 \end{cases} \tag{4}$$

q_1 = volume of priority street left turning traffic at part I

q_2 = volume of major street through traffic coming from the left at part I

q_5 = volume of the sum of all major street flows coming from the right at part II. Of course, here the volumes of all priority movements at part II have to be included. These are: major right (6, except if this movement is guided along a triangular island separated from the through traffic) , major through (5), major left (4); numbers of movements according to HCM 1994, chapter 10.

$c(q_1 + q_2)$ = capacity at part I

$c(q_5)$ = capacity at part II

$c(q_1+q_2+q_5)$ = capacity at a cross intersection for minor through traffic with a major street traffic volume of $q_1+q_2+q_5$

(all capacity terms apply for movement 8 . They are to be calculated by any useful capacity formula, e.g. the Siegloch-formula)

The Equations are only valid for $c(q_5) - q_1 > 0$.

For simplified application of this theory some graphs have been produced. In fig. 2 the calculation for $k = 2$ is illustrated. Here the capacities $c(q_1 + q_2)$ and $c(q_5)$ can be introduced independent of the type of formula from which they have been determined. The parameter c_0 indicates the capacity for the case of zero major flow. It is equal to $1/t_f$. The advantage of these graphs is that they can be applied with each arbitrary value of t_c, t_f, and q_1.

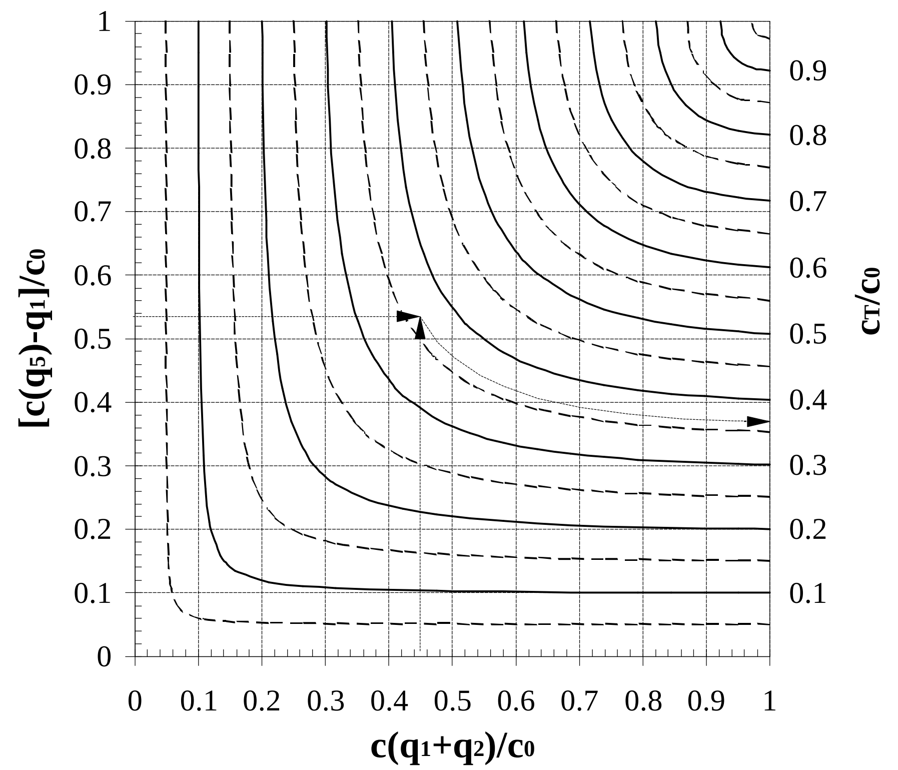

Figure 2: Capacities $\hat{c}_T = c_T / c_0$ for movement 8 in relation to standardized values of capacities and of q_1 (for k=2)

2.2 Shared Lanes and Flared Minor Street Entries

The basic calculation procedures assume in a first step that each of the traffic streams, which have to give way, has its own traffic lane at the intersection. The capacity for the individual movements (left turn, straight ahead and right turn) are calculated separately. If the streams share a common traffic lane, the capacity of the shared lane is then calculated according to the shared lane procedure invented by Harders (10) (cf. eq.10-9 in HCM 1994).

In reality we find, however, constellations which are an intermediate case. These are short additional lanes sometimes with only one single place (cf. e.g. fig.3). Their capacity can neither be estimated by the solution for infinitely long separate lanes nor by the shared lane formula.

To deal with this problem, Wu (11) derived a procedure, which can account for the length of the turning lanes exactly, when calculating the capacity of the shared lane.

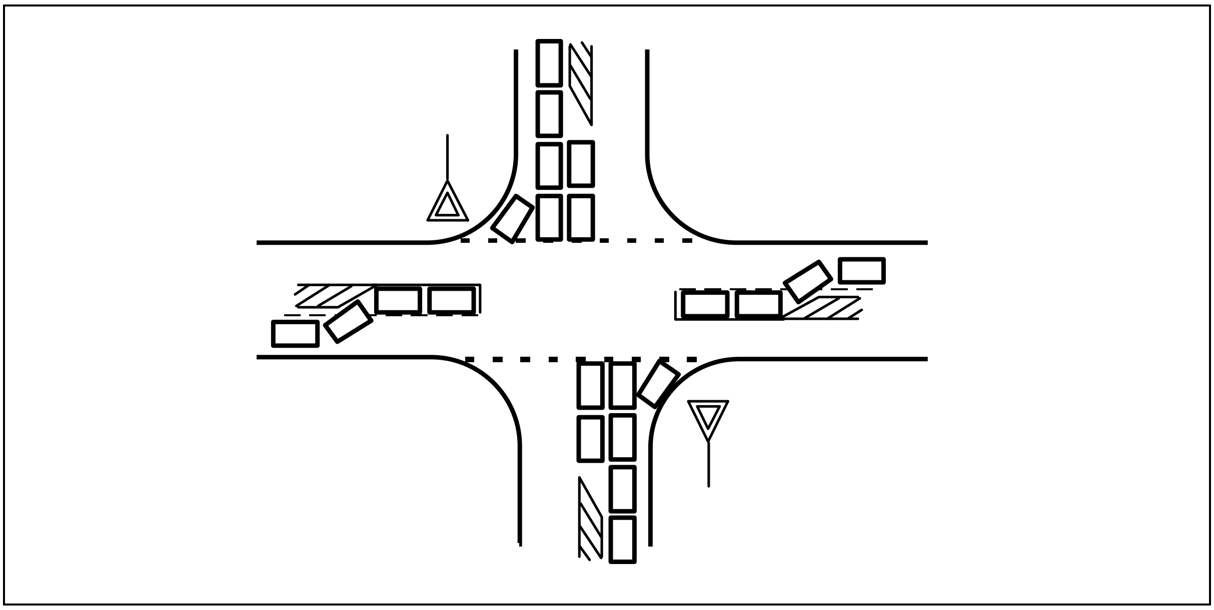

Figure 3: Possible queues at the approaches to an unsignalised intersection

In the coming chapter 10 of the HCM 1997 a pragmatic solution for flared minor street entries will be contained. Thus the effect of one or two additional spaces for right turners from the minor street can be estimated. Meanwhile Wu (11) has developed a theory which leads to a rather universal solution for shared lanes and turning lanes of limited length. It can be applied for different configurations as they are shown in fig.3. For detail the reader is referred to this paper. The outcome of this theory will be part of the Germany Highway capacity Manual.

2.3 Impedance factors at two-way-stop-controlled intersections

Probability of Queue-free State for Streams of Rank 4

In the current calculation guidelines the capacity for streams of higher ranks (higher than 2) is calculated by using a adjustment factor to the basic capacity. This adjustment factor f_k is formed from the probabilities p_0 that no vehicle is queuing in streams of higher priority. For the usual calculation procedures the p_0 for all streams with higher rank of priority have to be multiplied, i.e. for a steam of rank k, this adjustment factor f_k accounts for the impeding effects of higher-ranked streams. It can be expressed as

$$f_k = \prod_{i=2}^{k-1}\left(\prod_j (p_{0,j})_{rank=i}\right) = \prod_{i=2}^{k-1}(p_0)_{rank=i} \tag{5}$$

where $(p_{0,j})_i$ is the probability that conflicting stream j of rank i is in a queue-free state. However, eq.(5) can only be used for the streams of rank 3 carelessly. For streams of rank 4 eq.(5) overestimates the impeding effects, because the probabilities of a queue-free state for streams of rank 2 and 3 are not independent of each other. This has been found by Grossmann (12). To overcome this statistical dependence between queues in streams of rank 2 and 3, he has proposed a correction function based on simulations. This correction function (used in the HCM chapter 10 as eq.10-6 or fig.10-6) is given as:

$$f_4^* = 0.65 f_4 - \frac{f_4}{f_4 + 3} + 0.6\sqrt{f_4} \tag{6}$$

with

$$f_4 = \prod_{i=2}^{3}\left(\prod_j (p_{0,j})_{rank=i}\right) = (p_0)_{rank=2} \cdot (p_0)_{rank=3}$$

Eq.(6) does not fulfill the necessary marginal conditions

$$f_4^*|_{(p_0)_{rank=3}=1} = (p_0)_{rank=2} \quad \text{and} \quad f_4^*|_{(p_0)_{rank=2}=1} = (p_0)_{rank=3} \tag{7}$$

and it overestimates the probability of the queue-free state (13).

A new model to handle this problem was introduced by Wu (13). In this model the queues in higher-ranked streams are considered as **one** big queue (cf. fig. 4). That means: we imagine that the conflict area can be passed by minor street vehicles in the sequence of priority. Queuing vehicles thus form one common queue where rank 2 is in front followed by rank 3 and than by rank 4. Furthermore, the queues in the streams of different ranks and the big queue are considered as M/M/1-queueing systems with sufficient approximation. Thus, we obtain, in the same terminology of HCM (1994),

$$f_4^{\ *} = p' = \frac{1}{1 + \frac{1 - p_{0,j}}{p_{0,j}} + \frac{1 - p_{0,k}}{p_{0,k}}} \tag{8}$$

where p' = adjustment to major street left, minor street through impedance factor;

$p_{0,j}$ = probability of queue-free state for conflicting major street left-turning traffic (product of the p_0 for both directions);

$p_{0,k}$ = probability of queue-free state for conflicting minor street through traffic from the opposite direction.

Eq.(8) is used in the new German Highway Capacity Manual (instead of eq.10-6 of the HCM 1994).

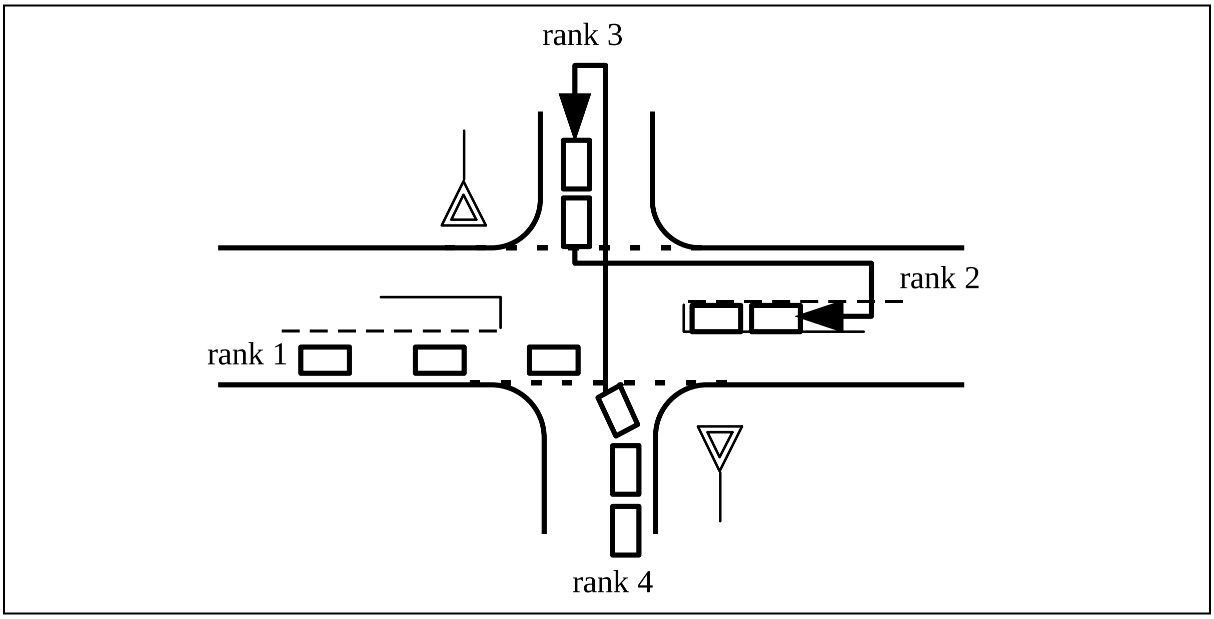

Figure 4: Queues in steams of different ranks and their sequence of operation

2.4 Critical gaps and move-up times

The critical gaps t_c and move-up times t_f in the German guidelines are still based on Harders' research report (14) from 1976. More recent evaluations by several other authors have shown that the strong dependence of these basic parameters on the velocity of major street vehicles does not exist in reality (cf. also (15)). Harder' values for a speed of 60 km/h have, however, proven that they could be applied for all other conditions. Therefore, at the moment it is recommended to use the parameters t_c and t_f which had been obtained for 60 km/h. These are of comparable size as the new parameters for the HCM 1997 (cf. (3)). This year a new research initiative funded by the federal DOT has been started for empirical evaluation of actual t_c and t_f for rural highways. The results are expected to be introduced into the first edition of the official German HCM in the year 2000.

3. DEVELOPMENTS IN THE THEORY OF ROUNDABOUTS

Roundabouts (in German: Kreisverkehr or with a nickname: Kreisel) have meanwhile become the most popular type of intersection in many areas. They provide advantages in costs, optical design, capacities, space consumption, and safety.

3.1 Capacity of Roundabouts

For the calculation of roundabout capacity some attempts had been made in the 80ies with solutions based on gap acceptance theory. The results were not too promising. Measurements of critical gaps at single- lane roundabouts revealed smaller critical gaps compared to TWSC-intersections and larger move-up times. Both parameters were nearly of similar size, which - at those times - was not believed to be possible. Another problem was that valid procedures for critical gap estimation were not clear at hand (cf. (15)). Another important drawback of gap acceptance solutions was also, that problems occurred on multilane circles with multilane entries regarding the definition: Which is the major stream (only traffic on the nearside circular lane or traffic on all lanes ?) which should be used in capacity formulas?

On the other hand experiments have been made with empirical regression theory methods obtained from British experience. These methods investigate the capacity of roundabout entries from observations of saturated entries and subsequent regression. Here some rather promising results have been obtained. In the first stage an exponential regression line was used, which in its mathematical form was identical with Siegloch's well known capacity formula

$$c_e = C \cdot \exp(-D \cdot q_c) \tag{9}$$

where

c_e = entry capacity

q_c = traffic on the circular roadway upstreams the entry (i.e. without traffic leaving into the same intersection arm)

C, D = parameters to be evaluated from empirical data by regression

Such formula have e.g. been reported by (16) .

Based on several research funds by the federal DOT more and more data for capacity (defined as 1-minute entry flow under saturated conditions) in relation to circular flow have been measured. Comparisons (17) showed that linear functions instead of eq.(9) explained the variance within the data slightly better. Thus they were preferred for further practical use.

$$c_e = A + B \cdot q_c \tag{10}$$

where

A, B = parameters to be evaluated from empirical data by regression

Their other advantage is that they have a clear intersection with the q_c - axis which is not the case with eq.(9). The most recent improvements have been obtained in 1996 with new measurements at single-lane roundabouts. Thus the following parameters A and B are recommended for practical application in eq.(10):

no. of lanes entry / circle	*A*	*B*	N (sample size)
1 / 1	1218	0.74	1504
1 / 2 or 3	1250	0.53	879
2 / 2	1380	0.50	4574
2 / 3	1409	0.42	295
			(no. of observed 1-minute intervals)

Table 1: Parameters for linear regressions (eq.(10))

The capacity estimated by these equations are also illustrated in fig. 5.

Here we see that only the number of lanes should be used as geometric parameters. Stuwe (17) studied also the influence of other parameters like diameter or distance between exit and entry at one intersection arm. Some geometric relations turned out to be of influence. However, their impact on the capacity results was not too strong and some uncertainties came up, whether the resulting equations are really valid for all parameter combinations. Therefore, these more complicated equations are not recommended for practical use. Each of the capacity calculation approaches is available as a computer program called KREISEL (18) which is used in practice and which also is able to apply capacity calculation methods from other countries as well as gap-acceptance based solutions.

One point which still is not sufficiently investigated, is the question of exit capacities at roundabouts. Due to the lack of reliable research results only preliminarily observed figures are in use; i.e. that the maximum outflow from a single-lane roundabout with rather narrow exits is in the range of 1200 veh/h.

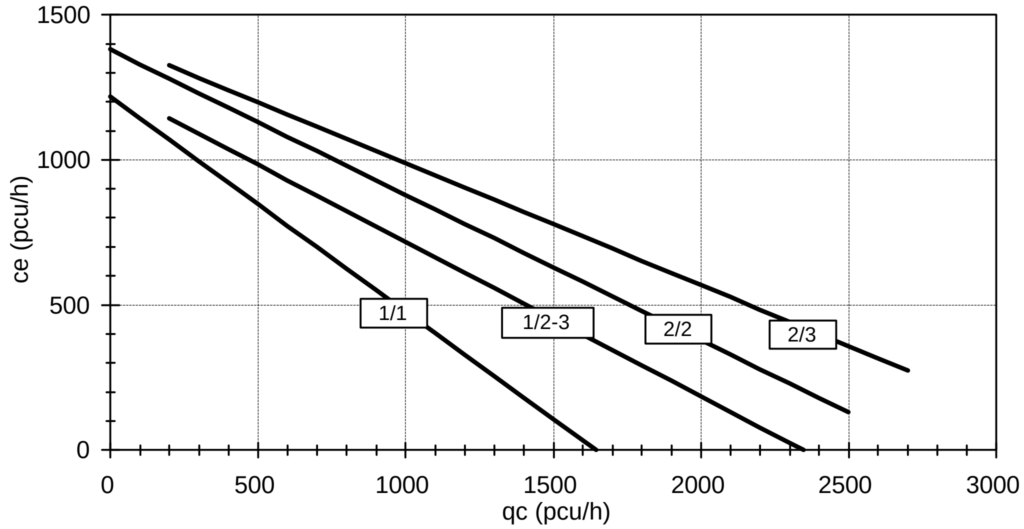

Figure 5: Capacity at roundabouts (eq.(10))

3.2 A universal gap-acceptance theory approach for capacity of roundabout entries

The linear empirical regression approach for estimating the capacity at roundabouts is rather pragmatic. On one side it does not make use of theories for unsignalized intersections. On the other side one can not be sure that these linear functions do also apply in areas of the c_e-q_c-diagram where only few measurement points have been observed. Therefore, Wu (19) modified the basic idea from Tanner (20) and proposed the following formula for the capacity of an entry to a roundabout:

$$c_e = \left(1 - \frac{\Delta \cdot q_c}{n_c}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot \exp\left(-q_c \cdot (t_0 - \Delta)\right) \tag{11}$$

where c_e = maximal entry flow (capacity of the entry)

q_c = flow on circular lanes at the subject entry

n_c = number of circular lanes

n_e = number of lanes in the subject entry

t_0 = $t_c - \frac{t_f}{2}$

t_c = critical gap

t_f = move-up time

Δ = minimum headway between vehicles in the circular lanes

Fig. 6 shows the capacity according to eq.(11) with the parameters t_c = 4.12s, t_f = 2.88s and Δ = 2.10s. This parameters have been found to represent driver behavior at roundabouts in Germany (cf. (17)), if eq.(11) is used as capacity model. .

In figs.7 through 11 some comparisons for results from eq.(11) versus measurements (1-minute intervals of saturation flows) are illustrated. It shows a good representation of the average capacities with eq.(11). Moreover, it could be shown that the average of 1-minute capacities is a valid representation of hourly capacities, which is a basis for the whole empirical regression theory.

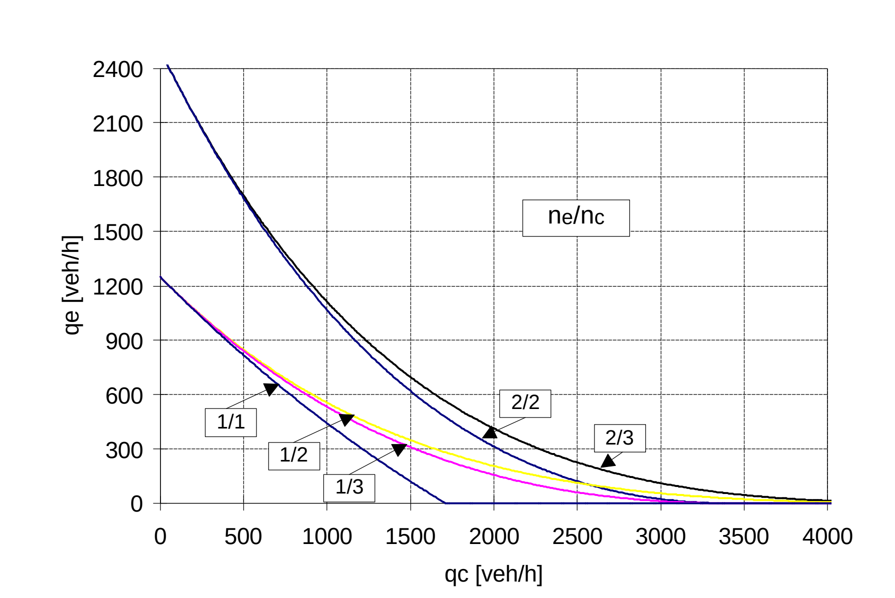

Figure 6:

Capacity at roundabouts (eq.(11))

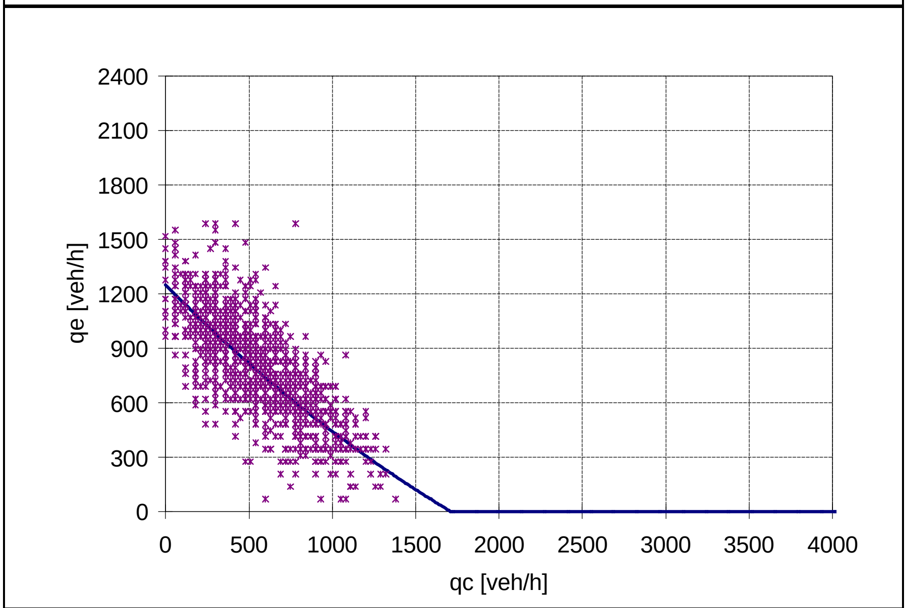

Figure 7:

Comparison of capacity for 1/1-roundabouts

— eq.(11)

** measurements

no. of 1-minute intervals = 1504

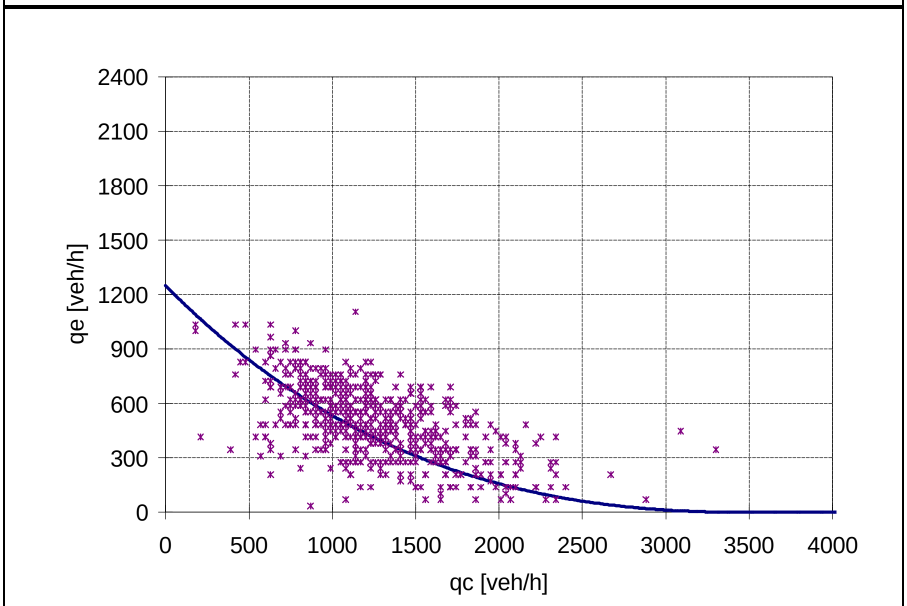

Figure 8:

Comparison of capacity for 1/2-roundabouts

— eq.(11)

** measurements

no. of 1-minute intervals = 636

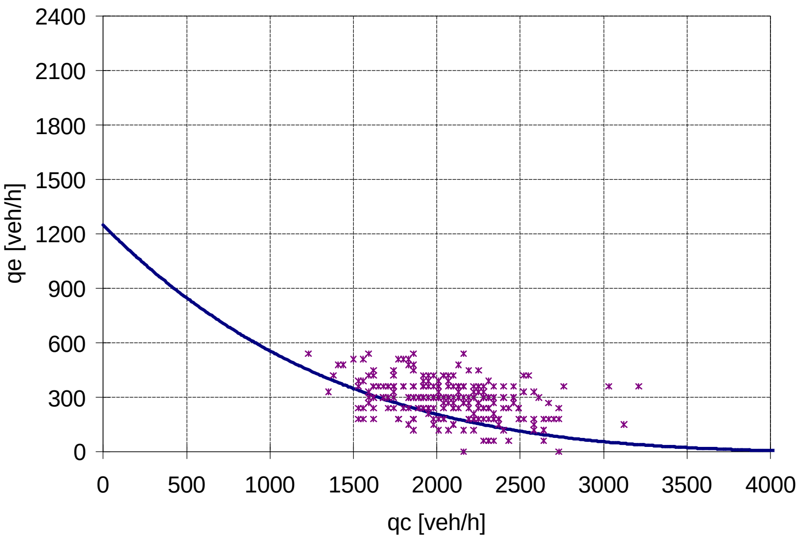

Figure 9:
Comparison of capacity for 1/3-roundabouts

— eq.(11)

** measurements

no. of 1-minute intervals = 243

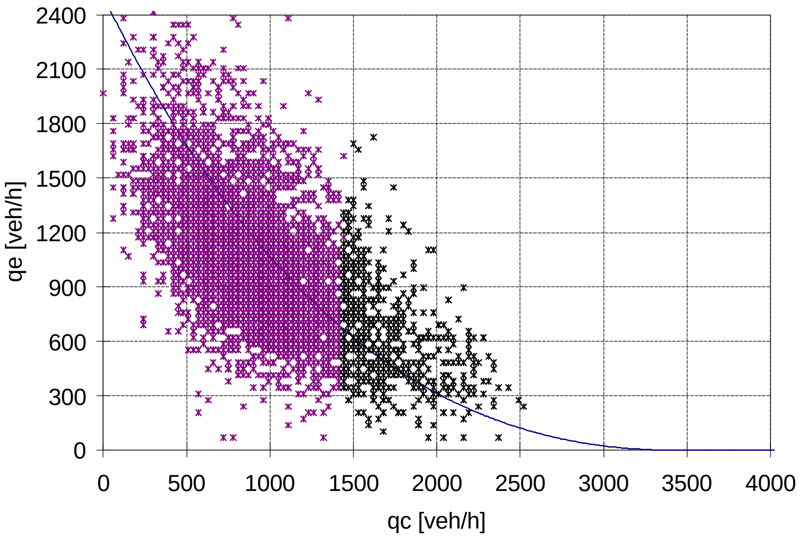

Figure 10:
Comparison of capacity for 2/2-roundabouts

— eq.(11)

** measurements

no. of 1-minute intervals = 4574

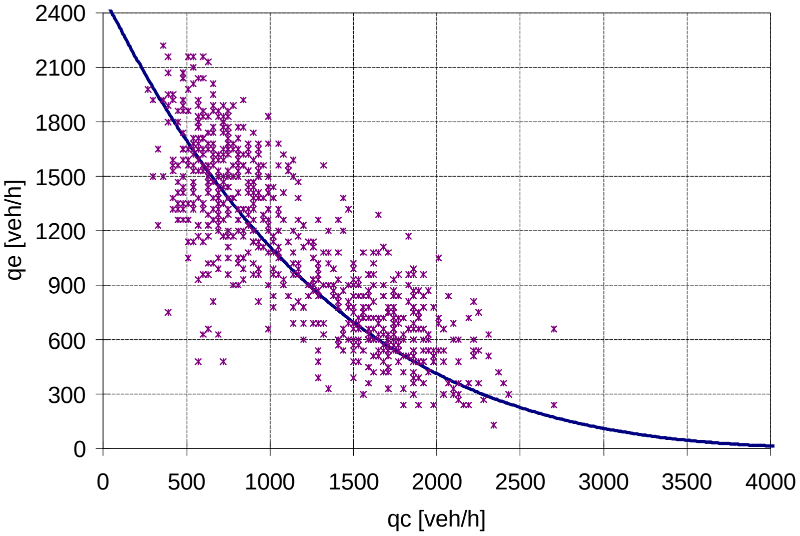

Figure 11:
Comparison of capacity for 2/3-roundabouts

— eq.(11)

** measurements

no. of 1-minute intervals = 295

3.3 Capacity reduction by pedestrians

At roundabouts, pedestrians crossing the entry may impede the capacity of the approach. This applies especially if pedestrians have priority over motor vehicles due to Zebra crossings. The international literature provides one theoretical method to account for these effects (Marlow, Maycock, (21)). Empirical research, however, showed that this theory is overestimating the impedance by pedestrians. (cf. (16), (17)). It is self-evident, that the capacity decreases with increasing pedestrian volumes. Moreover, measurements indicate that the pedestrian impedance decreases with increasing circulating flow, which also becomes evident when we are looking at pedestrians which are crossing without problems between queuing vehicles. To represent these effects two graphs are proposed for practical applications (figs.12 and 13). They result from regressions based on measurements in Germany. According to these results there are no more impeding effects for entry capacity above 900 pcu/h of circulating flows. The factors obtained from fig.12 or 13 have to be multiplied with the capacities according to paragraphs 3.1. and 3.2 to obtain the maximum volumes which can be handled by the entry.

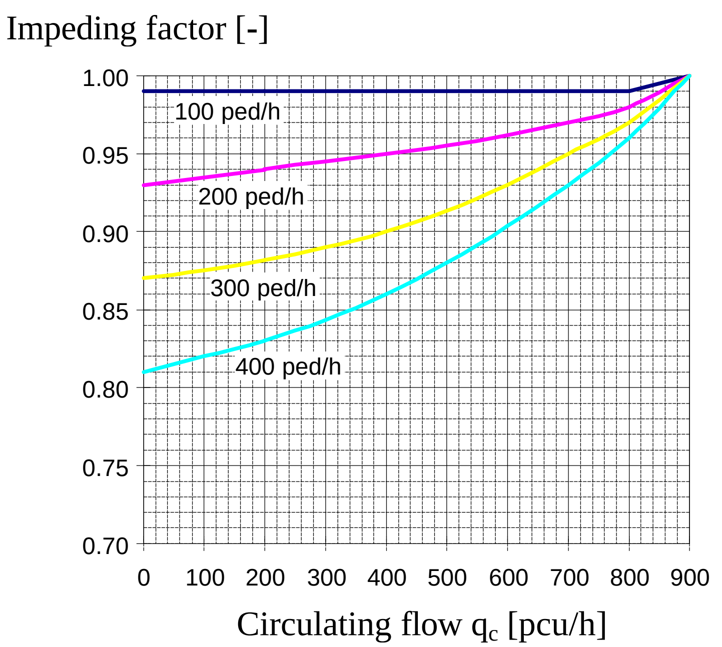

Figure 12: Impeding factors due to pedestrians at roundabouts with one circular lane

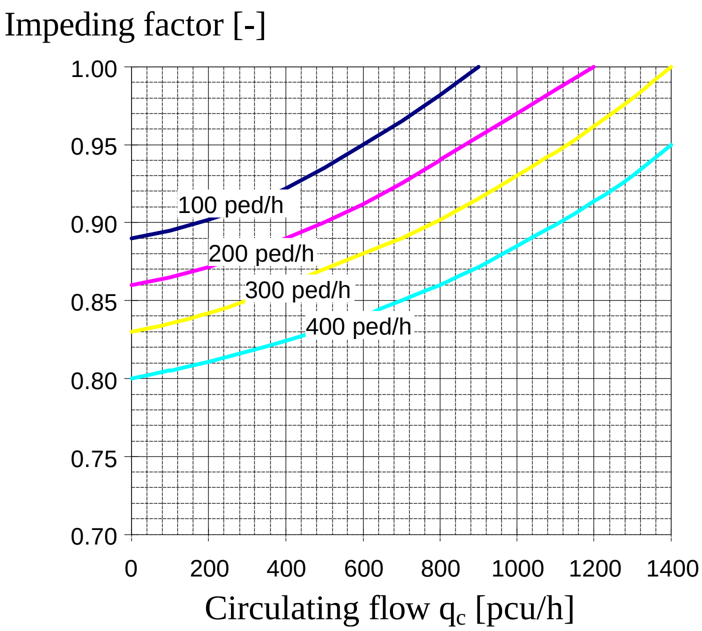

Figure 13: Impeding factors due to pedestrians at roundabouts with two circular lanes

3.4 Delays and queue length

Delay at roundabout entries in Germany is mostly calculated with Kimber, Hollis' (22) universal delay formula which is also taking into account the effects of time dependencies - also instationarities during the peak itself - and oversaturations. The formula accounts for average delay during a time period. The more recently published delay formula from Brilon (23) is not yet used in practice. Also the delay formulas from the HCM are not in use.

For queue length not the average is of interest. Here the maximum values are important for intersection design. Several - also rather approximative - solutions are in use. As a rather well sophisticated theoretical solution Wu's (24) recommendations should be mentioned, which are also contained in the HCM 1994 (fig. 10-8).

For simplifying the calculation of percentiles of queue lengths at unsignalized intersections, Wu (25) proposed the following formula as another approximation:

$$N_a \approx \frac{QT}{4}\left\{x-1+\sqrt{(1-x)^2+\frac{8x}{QT}\cdot\left[-\ln(a)\right]}\right\} \tag{12}$$

where N_a = (1-α)%-percentile of queue lengths

x = saturation degree during the dimensioning period T

Q = capacity during the dimensioning period T

n_e = number of lanes in the subject entry

For instance, to estimate the 95-percentile of the queue length, one has to apply α=0.05 to obtain

$$\begin{aligned} N_{95} &\approx \frac{QT}{4}\left\{x-1+\sqrt{(1-x)^2+\frac{8x}{QT}\cdot[-\ln(0.05)]}\right\} \\ &\approx \frac{QT}{4}\left\{x-1+\sqrt{(1-x)^2+3.0\cdot\frac{8x}{QT}}\right\} \end{aligned} \tag{13}$$

Setting α=0.01 we obtain the 99-percentile of th queue lengths:

$$\begin{aligned} N_{99} &\approx \frac{QT}{4}\left\{x-1+\sqrt{(1-x)^2+\frac{8x}{QT}\cdot[-\ln(0.01)]}\right\} \\ &\approx \frac{QT}{4}\left\{x-1+\sqrt{(1-x)^2+4.6\cdot\frac{8x}{QT}}\right\} \end{aligned} \tag{14}$$

4. APPLICATION OF TWSC-INTERSECTIONS AND ROUNDABOUTS IN PRACTICE

4.1 Design guidelines for TWSC-intersections

TWSC-intersection design is standardized in the guidelines RAS-K1 (26) from 1988. No new developments can be foreseen for conventional intersection design in Germany at this time, since these rules provide a reliable standard for safe design.

4.2 Design guidelines for roundabouts

There are three guidelines for the design of single-lane roundabouts in Germany (4)(5)(6). The first one was published in 1993 and was developed on behalf of the State DOT of Northrhine-Westfalia. A similar guideline was edited in 1994 by the State DOT of Saxonian. Both guidelines focus on urban situations. Another guideline which deals with single-lane roundabouts at federal highways in rural areas was edited by the Federal Ministry of Transport in 1995.

The main geometric elements of a roundabout according to German guidelines are shown in fig.14.

Geometric Element	**Urban Area**	**Rural Area**
Inscribed Circle Diameter	26 m **30 m** 35 m	35 m **40 m** 45 m
Width of Circulating Roadway	8.00 m **7.00 m** 6.50 m	6.50 m **6.00 m** 5.75 m
Entry Width	3.25 m - 3.50 m	3.50 m - 3.75 m
Exit Width	3.25 m - 3.75 m	3.50 m - 3.75 m
Entry Radius (near side curb)	10 m - 12 m	12 m - 14 m
Exit Radius (near side curb)	12 m - 14 m	14 m - 16 m
Cross slope of Circulating Roadway ("-": slope to the other side)	- 2.5 %	- 2.5 %
Width of Splitter Island		
without pedestrians crossing	-	1.60 m
with pedestrians crossing	2.00 m	2.00 m
with cycles crossing	2.50 m	2.50 m

Figure 14: Basic geometric elements of a roundabout

4.3. Safety of Roundabouts

Several German studies show that roundabouts provide lower accidents rates and lower accident severity than other intersections types. Brilon, Stuwe, Drews (17) as well as Pohl (27) performed before-after studies on traffic safety of roundabouts. The results are shown in fig.15. This figure shows the reduction of accidents costs due the construction of a roundabout in comparison to the former intersection. The accidents costs - on average - were reduced by 57%. The more significant improvements were obtained on rural intersections, where the accidents costs were only 16% of the situation before. Thus, especially on rural crossroads the traffic safety was extremely improved by building new roundabouts. Severe black spots could thus be altered into in conspicuous nodes of the highway network. If we look on different groups of road users we see that all groups benefit from roundabout safety, especially vehicle occupants and pedestrians.

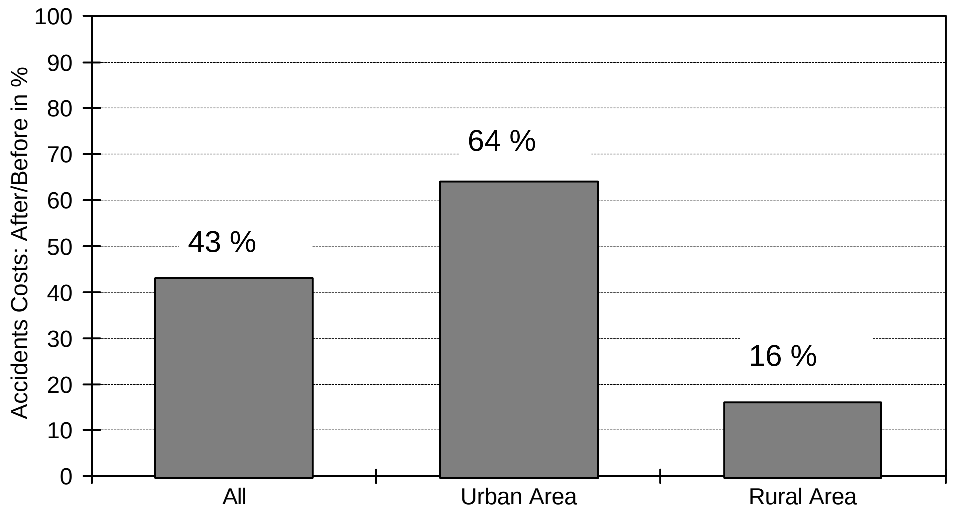

Figure 14: Change of accidents costs after building a roundabout

4.4. Mini Roundabouts

In several European countries a smaller type of roundabout, called mini roundabout, is used. Mini roundabouts for Germany are characterized by a diameter less than 26m and a central island which is designed to be used to some extend by larger vehicles. In 1996 the State DOT of Northrhine-Westfalia decided to experiment with this type of intersection also in Germany. As a consequence the first German mini roundabout was constructed in the town of Harsewinkel. The first three month's experience is rather positive. Although the central island would allowed to be crossed, car drivers try to avoid this. They use the circular roadway very carefully. Only trucks and busses with their rear wheels penetrate the central area. No problems regarding safety have occurred up to now. This solution enables the operation for 15 000 veh/h on a very limited space without remarkable delays, which - before the reconstruction - covered the whole town caused by this central junction. Of course, the mini circle is also a very cheap type of traffic control. In 1997 it is planned to reconstructed 11 further intersections into mini roundabouts. The first results of this research project are expected for 1998.

5. CONCLUSION

Unsignalized intersections are still an area of research in Germany. New theoretical results have been obtained for the analysis of specific geometrical design, e.g. wide medians on the major street or short lanes of the minor approach. But also for the treatment of conventional intersections additional results have been obtained, e.g. for the impedance factors for rank-4 movements. Other areas are still unsolved, like the inclusion of pedestrian flows into capacity estimations or the effects of upstream signals. Here the new HCM 1997, chapter 10 could provide solutions which can also be transferred to Germany.

For roundabouts capacity calculations in Germany are currently mainly based on simple empirical methods, both for vehicle traffic capacity and the influence of pedestrians. One idea for new gap-acceptance solution has been proposed. For the design of compact roundabouts design standards have been established which lead to rather safe traffic operations with little delay for vehicles and pedestrians. Rather large roundabouts (with more than one circulating lane) and very small mini-roundabouts are still treated with care in Germany practice. But it could be expected that also these types will become standard solutions very soon.

REFERENCES

1) Brilon, W. (ed.) *Intersection without Traffic Signals*. Springer-Verlag, 1988.

2) Brilon, W. (ed.) *Intersection without Traffic Signals II*. Springer-Verlag, 1991.

3) Kyte, M., W. Kittelson, W. Brilon, R. Troutbeck, el al. *Capacity and level of service at unsignalised intersections*. Final report, volume 2 - Two-way stop-controlled intersections. NCHRP, Project 3-46. Dec. 1995.

4) NRW. *Kleine Kreisverkehrsplaetze - Empfehlungen zum Einsatz und zur Gestaltung*. Bausteine Nr. 16, edited by: Ministerium für Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen, 1993.

5) Freistaat Sachsen. *Empfehlungen zum Einsatz und zur Gestaltung kleiner Kreisverkehrsplätze.* Staatsministerium für Wirtschaft und Arbeit des Freistaates Sachsen. Roundabouts Guideline 3, 1994.

6) BMV. *Einsatz und Gestaltung von Kreisverkehrsplätzen an Bundesstraßen außerhalb bebauter Gebiete*. Bonn-Bad Godesberg, 1995.

7) D-HCM. *Verfahren für die Berechnung der Leistungsfaehigkeit und Qualitaet des Verkehrsablaufes auf Straßen (Draft of a German Highway Capacity Manual)*. Schriftenreihe "Forschung Straßenbau und Straßenverkehrstechnik", Heft 669, 1994.

8) D-HCM (German Highway Capacity Manual, Version 1997). *Chapter 8: Unsignalized Intersections.* Research report, Institute for Traffic Engineering, Ruhr-University Bochum, 1997.

9) Brilon, W., N. Wu, K. Lemke. *Capacity at Unsignalized Two-Stage Priority Intersections*. Annual Meeting of TRB, Washington. 1996. TRB preprints no. 961280.

10) Harders, J. *Die Leistungsfaehigkeit nicht signalgeregelter staedtischer Verkehrsknoten (The capacity of unsignalized urban intersections)*. Schriftenreihe "Strassenbau und Strassenverkehrstechnik", Vol. 76, 1968.

11) Wu, N. *Capacity of Shared-Short Lanes at Unsignalised Intersections*. Paper presented in this book, 1997.

12) Grossmann, M. *Methoden zur Berechnung und Beurteilung von Leistungsfaehigkeit und Verkehrsqualitaet an Knotenpunkten ohne Lichtsignalanlagen*. Dissertation, Ruhr-Universitaet Bochum, Institute for Traffic Engineering, No. 9, 1991.

13) Wu, N. *Capacity and Probability of Queue-free State at Unsignalized Intersections*. Arbeitsblaetter, Institute for Traffic Engineering, Ruhr-University Bochum, No.12, March 1997.

14) Harders, J. *Messung von Grenz- und Folgezeitlueken als Grundlage für die Brechnung der Leistungsfaehigkeit von Lanfstraßenknoten (Measurement of critical time gap and move-up time as foundation for the calculation of capacity on rural highways)*. Schriftenreihe "Strassenbau und Strassenverkehrstechnik", Vol. 216, 1976..

15) Brilon, W., R.J. Troutbeck, R. Koenig. Useful Estimation Procedures for Critical Gaps. Paper presented in this book, 1997.

16) Stuwe, B. *Untersuchung der Leistungsfaehigkeit und Verkehrssicherheit an deutschen Kreisverkehrsplaetzen (Capacity and Safety of Roundabouts in Germany)*. Dissertation, Ruhr-Universitaet Bochum, Institute for Traffic Engineering, No. 10, 1992.

17) Brilon, W., B. Stuwe, and O. Drews. *Sicherheit und Leistungsfaehigkeit von Kreisverkehrsplaetzen (Safty and capacity of roundabouts)*. Research report, Institute for Traffic Engineering, Ruhr-University Bochum, 1993.

18) Brilon, W., N. Wu. User Manual of KREISEL, 1996.

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

20) Tanner , J.C. *A theoretical analysis of delay At An Uncontrolled Intersections*. Biometrica 49 (1 and 2), pp.163-70, 1962.

21) Marlow, M. and G. Maycock. *The effect of Zebra crossings on junction entry capacities*. TRRL SR 724, 1982.

22) Kimber, R.M., E.M. Hollis. *Peak period traffic delays at road junctions and other bottlenecks.* Traffic Engineering and Control, No.10, 1978, pp.442-446.

23) Brilon, W. *Delay at oversaturated unsignalized intersections based on reserve capacities.* TRBannual meeting 1995, preprint 950013.

24) Wu, N. *An Approximation for the Distribution of Queue Lengths at Unsignalised Intersections*. In Akcelik, R. (ed.), Proceeding of the second International Symposium on Highway Capacity, Sydney, 1994, Volume 2, pp. 717-736.

25) Wu, N.: *Verteilung der Rueckstaulaengen an Knotenpunkten ohne Lichtsignalanlagen (Distribution of queue lengths at unsignalized intersections)*. To be published in "Strassenverkehrstechnik", March 1997.

26) RAS-K1. *Richtlinien für die Anlage von Strassen.* FGSV, 1988.

27) Pohl, H. *Sicherheit von Kreisverkehrsplaetzen außerorts (Safety of rural roundabouts).* Studienarbeit, Institute for Traffic Engineering, Ruhr-University Bochum, 1995.