Toward a New German Guideline for Capacity of Unsignalized Intersections

WERNER BRILON, MICHAEL GROSSMANN, AND BIRGIT STUWE

The upcoming German guideline for calculating the capacity of unsignalized intersections is described. Information is included on fundamental aspects of the theory as well as on the proposed procedure that results from several research projects carried out on behalf of the West German Federal Minister of Transport. The new guideline will be a revision of the German procedure introduced in 1972, which has been transferred as Chapter 10 of the 1985 *Highway Capacity Manual* (HCM). Furthermore, a selection of formulas for roundabout capacity is given. Capacity and delays of unsignalized intersections have been investigated in Germany in a long series of research projects during the 1960s and 1970s. These results led to the German guideline of 1972, which was mainly based on Harders' pioneering work. The problems with the 1972 procedure and Chapter 10 of the HCM can be summarized as follows: (a) differences to the simple Poisson case, (b) concept and size of critical gaps, (c) determination of impedance factors, (d) double introduction of Rank 2 and Rank 3 traffic streams, and (e) delays and level of service. After the publication of the 1985 HCM, the problem of capacity at unsignalized intersections received new attention in Germany. A series of research projects was started, the aim of which was to develop a new guideline for practical application. The results of these investigations will be introduced into the German committee's discussions within a short time.

The upcoming German guideline for calculating the capacity of unsignalized intersections is described. Information is included on fundamental aspects of the theory as well as on the proposed procedure that results from several research projects carried out on behalf of the West German Federal Minister of Transport. The new guideline will be a revision of the German procedure introduced in 1972 (*1*), which has been transferred as Chapter 10 of the 1985 *Highway Capacity Manual* (HCM) (*2*). Furthermore, a selection of formulas for roundabout capacity is given. Capacity and delays of unsignalized intersections have been investigated in Germany in a long series of research projects during the 1960s and 1970s, a survey of which was given by Brilon (*3,4*). These results led to the German guideline of 1972, which was mainly based on Harders' pioneering work (*5*). The problems with the 1972 procedure and Chapter 10 of the HCM can be summarized as follows: (a) differences to the simple Poisson case, (b) concept and size of critical gaps, (c) determination of impedance factors, (d) double introduction of Rank 2 and Rank 3 traffic streams, and (e) delays and level of service. After the publication of the 1985 HCM, the problem of capacity at unsignalized intersections received new attention in Germany. A series of research projects was started, the aim of which was to develop a new guideline for practical application. The results of these investigations will be introduced into the German committee's discussions within a short time.

Lehrstuhl für Verkehrswesen, Ruhr Universität Bochum, Universitätsstrasse 150, 4630 Bochum 1, Germany.

HANDLING THE DIFFERENCES BETWEEN ACTUAL TRAFFIC STREAMS AND THE SIMPLE POISSON MODEL

The former versions of guidelines (*1,2*) are based on a simple Poisson model for each of the traffic streams at an intersection. Moreover, these procedures are only valid for streams with non-time-dependent traffic volumes. Siegloch (*6*) has studied the influence of non-Poisson properties of traffic streams on the main road. He found that more realistic headway distributions could change the capacity of the intersection considerably. On the one hand, slight disturbances of the headway distribution decrease the capacity. However, normal or heavy disturbances (i.e., platooned traffic) can increase capacity considerably, for example, up to 1.2 times the Poisson case [see Figure 4 in Brilon (*3*)]. These effects have been confirmed by several authors [see Zhang (*7*) and Chodur et al. (*8*)], but Siegloch's (*6*) figures and tables still seem to be the most extensive documentation of this phenomenon. Nevertheless, under average conditions and realistic distributions of headways in the priority stream, the capacity is similar to the one calculated with the help of a simple Poisson model.

Therefore, the simple Poisson case will still be the basis of the future German guideline. The intention is to use Siegloch's capacity formula to describe the maximum number of minor-stream vehicles that can pass through a priority traffic stream of a given volume:

$$G = \frac{3{,}600}{t_f} \cdot e^{-pt_0} \tag{1}$$

where

- G = capacity of the minor stream [passenger car units per hour (pcu/hr)];
- p = $q_p/3{,}600$;
- q_p = volume of the priority stream [vehicles per hour (veh/hr)];
- t_0 = $t_g - t_f/2$;
- t_g = critical gap (minimum headway between vehicles in the main street traffic streams that enables at least one vehicle in a minor traffic stream to pass through the intersection); and
- t_f = move-up time (minimum headway between vehicles in a minor traffic stream entering into the same main stream gap).

The results of the formula are similar to Harders' (5) original formula

$$G = q_p \frac{e^{-p(t_g - t_f)}}{e^{pt_f} - 1} \tag{2}$$

which was the basis of the Chapter 10 procedure. The differences between Equations 1 and 2 are within a margin of 10 pcu/hr. Results of Equation 1 are shown by Figure 1. In the final version of the new guideline, a series of four similar figures will be included for left-turning traffic from the priority road, right-turning traffic from the minor road, through movements, and left-turning traffic from the minor road.

The German guideline only applies to single lanes for each movement. According to other German guidelines, unsignalized intersections in multilane streets are to be avoided because of traffic safety.

CONCEPT AND SIZE OF CRITICAL GAPS AND MOVE-UP TIMES

In a recent publication, Kimber (9) reiterates his former argument that the concept of mathematical models with gap acceptance theory leads to unrealistic estimations of capacity. He has developed an empirical approach by using regression techniques. These ideas, of course, should be considered and evaluated carefully and comparisons should be begun as soon as possible.

However, further study over a number of years is required to develop this empirically supported concept as an alternative to the gap acceptance theory. Moreover, there is the problem of transferring the results to the situation in another country and the tremendous expenditure for comprehensive empirical evaluations. Therefore, the next German guideline for unsignalized intersections will still be based on gap acceptance theory.

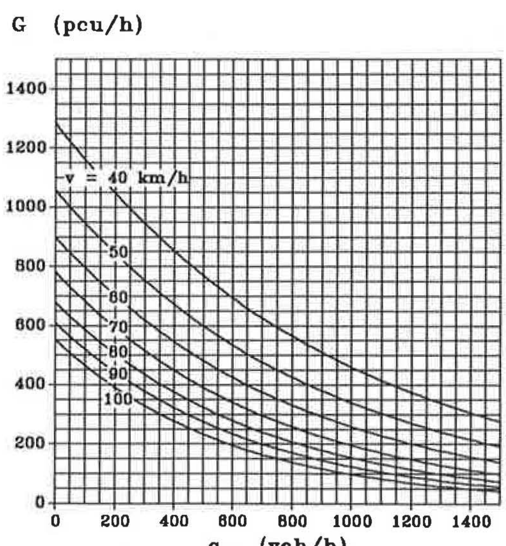

FIGURE 1 Capacity calculated from Equation 1 in relation to priority volume q_p and average main-road velocity v_m for through traffic on the minor road.

The only empirical results for representative critical gaps and move-up times under German conditions are those of Harders (10) (see Table 1), described in English by Brilon (3). This data base might have become obsolete and driver behavior could have changed in the meantime. Another objection is that the influence of the velocities on the major street might be overestimated in these values. Nevertheless, Harders' results are still the most recent and above all the most comprehensive values for critical gaps and move-up times. During the study, 33 intersections were observed for more than 109 hr, resulting in 30,000 measured values. Moreover, some sample comparisons conducted with priority street velocities of 50 km/hr confirmed Harders' results. These values characterize driver behavior in West Germany in 1976. Before applying the formulas in other countries, these parameters must certainly be evaluated again.

Another influence on capacity is caused by the variations in critical gaps and move-up times among drivers and even for one driver over time. This effect has been studied, for example, by Ashworth (11). Theoretically, he found a relationship between reduction in minor-road capacity and variance of critical gap distribution for different levels of major-road volume. The reduction in capacity can vary up to 40 percent depending on the other parameters. On the other hand, a recent research project (12) has found that this effect is compensated if at the same time a more realistic headway distribution is used.

DETERMINATION OF IMPEDANCE FACTORS

At an intersection, different ranks of priority can be assigned on the basis of highway code regulations. Rank 1 is defined for movements with priority over all other conflicting movements. Each traffic stream (movement) that has to give priority to another movement of Rank r is at least of Rank $r + 1$ (see Figure 2).

Impedance factors in the former guidelines included this hierarchy for the different movements at an intersection [for more details, see Chapter 10 in the HCM (2)]. Originally, in the basic queuing model, the impedance factor is the probability that no vehicle is queuing in the minor traffic stream. It is a fundamental property of queuing systems with one service channel that

$$p_0 = 1 - a \tag{3}$$

TABLE 1 CRITICAL GAPS t_g AND MOVE-UP TIMES t_f FOR PASSENGER CARS IN WEST GERMANY (10)

		Average velocity v_m on the major road						
Type of minor stream		40	50	60	70	80	90	km/h
Left turns from the major road	t_g	4.5	5.2	5.8	6.5	7.1	7.8	s
	t_f	1.7	2.1	2.5	2.8	3.2	3.6	s
Right turns from the minor road	t_g	5.0	5.8	6.5	7.2	7.9	8.7	s
	t_f	2.1	2.6	3.1	3.6	4.1	4.5	s
Through traffic on the minor road	t_g	5.1	5.8	6.5	7.3	8.0	8.7	s
	t_f	2.8	3.4	4.0	4.6	5.3	5.9	s
Left turns from the minor road	t_g	5.6	6.4	7.2	8.0	8.8	9.6	s
	t_f	2.7	3.3	3.9	4.5	5.1	5.7	s

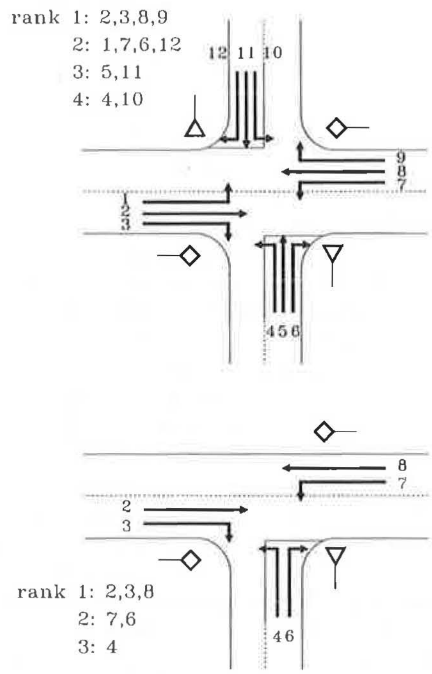

FIGURE 2 Traffic streams and their rank of priority.

where

p_0 = probability of the empty system,
a = utilization factor ($= q_n/G$),
G = capacity of the minor stream (pcu/hr), and
q_n = volume of the minor stream (pcu/hr).

This regularity has already been pointed out by Siegloch (*6*). The original curve for p_0 in the 1972 German procedure (*1*) and the HCM (*2*)—which is wrong—was based on approximations from Harders (*5*). Equation 3 can be applied for the probability of no queuing in movements of Rank 2. Impedance factors in different streams of Rank 2 can be multiplied as proposed by Figure 10–4 in Chapter 10 of the HCM (*2*) or Table 5 in Brilon (*3*), because queuing in these streams is independent of each other, which has also been proven by extensive computer simulations (*12*).

INTRODUCTION OF RANK 3 AND RANK 4 TRAFFIC STREAMS

In former publications, several authors objected that traffic streams of Ranks 2 and 3 are introduced twice into the calculations according to the German (*1*) and American (*2*) procedures. These streams are on the one hand added to the main-street volumes [see Figure 10–2 in the HCM (*2*)]. On the other hand, they are introduced into the impedance factors by which the basic capacities G of streams of Ranks 3 and 4 are diminished to calculate the actual capacities L by

$$L = p_0 G \qquad (4)$$

Brilon (*3*) has discussed arguments that support this double introduction (see his Figures 7 and 8).

The reasons for this are as follows:

- During times of queuing in Rank 2 streams (e.g., left turners from the priority street) the Rank 3 vehicles (e.g., left turners from the minor street at a T-junction) cannot enter the intersection because of traffic regulations by highway code. Because the portion of time provided for Rank 3 vehicles is p_0, the basic capacity calculated from Equation 1 for Rank 3 streams has to be diminished by the factor p_0 for the corresponding Rank 2 streams (Equations 3 and 4).
- Even if no Rank 2 vehicle is queuing, these vehicles influence Rank 3 operations, because a Rank 2 vehicle approaching the intersection within a time of less than t_g prevents a Rank 3 vehicle from entering the intersection.

A recent research project (*12*) has proven that among the possibilities considered, the existing approach (Equation 4) for Rank 3 operations is the best one to account for these relations. For Rank 4, however, a minor change of the procedure proved to be necessary, because the probabilities $p_{0,r3}$ (= no vehicle is queuing in Rank 3 streams) depend on $p_{0,r2}$ for Rank 2 movements. This relationship is shown in Figure 3. The diagonal would represent the case of statistical independence between the impedance factors of Rank 2 and Rank 3 movements. This assumption of independence, as the basis of the procedures in the HCM (*2*), underestimated the actual capacity L. To enable an easy consideration of statistical interrelations between $p_{0,r2}$ and $p_{0,r3}$, the solid line in Figure 3 has been developed. It is a representation of simulation results with more than 300 different combinations of traffic flow volumes. The value $p_{0,x}$ represents the impedance factor $p_{0,x}$, which has to be applied instead of the product $p_{0,r2} \cdot p_{0,r3}$. Again, this new factor is only necessary for the computation of Rank 4 capacities.

DELAYS AND LEVEL OF SERVICE

The existing procedures do not clearly distinguish between different level-of-service (LOS) values. For the German

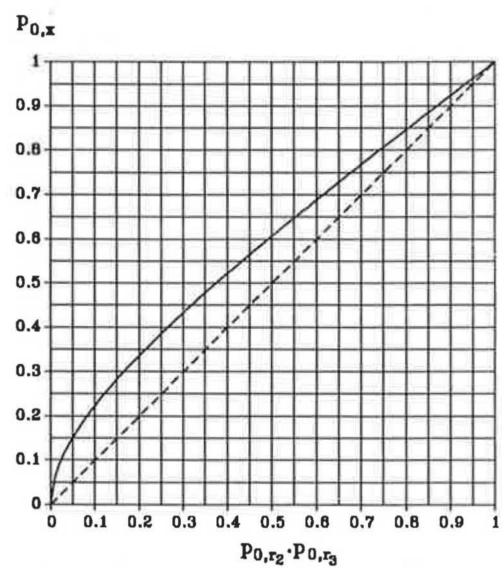

FIGURE 3 Corrected impedance factor $p_{0,x}$ for evaluating actual capacity of a Rank 4 stream.

guideline, this argument is of minor importance, because the German concept is more aimed at capacities and the direct evaluation of LOS parameters like delays.

To estimate delays, a series of formulas for the simple case of one priority stream and one minor stream has been developed. From the theoretical point of view, Kremser's formulas—as presented by Brilon (*3*)—can be used for steady state conditions. Assuming that t_g and t_f are constant values and that the headways are exponentially distributed both in the major and minor stream, Kremser (*13,14*) derived equations that can be simplified as

$$D = \frac{E(W_1)}{x} + \frac{n}{2} \cdot \frac{y \cdot E(W_1^2) + z \cdot E(W_2^2)}{xy} \tag{5}$$

$$E(W_1) = \frac{1}{p} \cdot (e^{pt_g} - 1 - pt_g) + d$$

$$E(W_1^2) = \frac{2}{p} \cdot (e^{pt_g} - 1 - pt_g) \cdot \left(\frac{e^{pt_g}}{p} + d - t_g\right) + d^2 + t_g^2 \tag{6}$$

$$E(W_2) = \frac{e^{pt_g}}{p} \cdot (1 - e^{pt_f})$$

$$E(W_2^2) = \frac{2e^{pt_g}}{p^2} \cdot [(e^{pt_g} - pt_g) \cdot (1 - e^{-pt_f}) - pt_f e^{pt_f}] \tag{7}$$

where

D = average delay (s) for minor street vehicles,
$x = y + z$,
$y = 1 - nE(W_2)$,
$z = nE(W_1)$,
W_1 = delay for a minor vehicle arriving at the intersection when no other vehicle is queuing,
W_2 = waiting time in the first queuing position for those vehicles that have arrived in a higher position of the queue,
$E(W_i)$ = first moment of W_i,
$E(W_i^2)$ = second moment of W_i,
d = time needed for orientation after arriving at the first position of the queue $\approx t_f$,
$n = q_n/3{,}600$, and
q_n = volume of the minor stream.

With constant values for t_g and t_f, D is a function of the volumes q_p and q_n. Even this formula (Equation 5), which gives the impression of being rather complicated, is only an approximation. It is valid only for the unrealistic case of $t_g = t_f$. Poeschl (*15*) provides more exact but also more complicated formulas for $E(W_1)$ and $E(W_1^2)$. (His formulas are much too complicated for practical application.)

Therefore, the delay formula of Harders (*5*) can be recommended as a good approximation:

$$D = \frac{1 - \gamma}{L - q_n} \cdot 3{,}600 \tag{8}$$

where

$$\gamma = e^{-(pt_g + nt_f)}$$

These formulas only apply for the simple queuing system with one major stream (priority stream) and one minor stream (e.g., Streams 1, 6, 7, and 12). A correct formula for other movements of Ranks 3 and 4 or for more realistic traffic flow assumptions is not available. For these cases, computer simulation techniques seem to be the only practicable tool.

Irrespective of the delay formula used, the so-called "Harders' trick" is true. This means that with constant reserve capacity R,

$$R = L - q_n \tag{9}$$

[see Equation 10–2 in the HCM (*2*)], average delay D tends to remain on a nearly constant level (see Figure 4). Hence, with R greater than 100 pcu/hr the average delay of minor vehicles D is less than 35 sec. Therefore, the future German guideline will use this limit of $R \geq 100$ pcu/hr as the limit of practical capacity for minor traffic streams at unsignalized intersections. Recently, Brilon and Grossmann (*12*) also proved that Harders' trick—in principle—is also valid for traffic streams of Rank 3 and 4. In these cases, however, the average delay becomes insignificantly higher but remains below 45 sec (for R = 100 pcu/hr). In the final version of the new German guideline, figures similar to Figure 4 will be included for Rank 2, Rank 3, and Rank 4 streams.

On the basis of this fundamental idea, the LOS also in a future HCM could be determined from reserve capacities (Equation 9) similar to those in Table 10–3 in the HCM (*2*). The values of this table could be adjusted to the delays to be applied for different LOS values. However, the queue lengths,

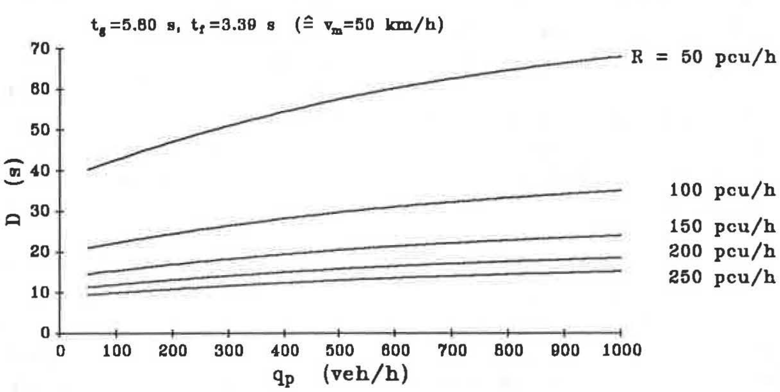

FIGURE 4 Average delay for a Rank 2 stream of the volume $q_n = L - R$ for different values of q_p.

aspects of fuel consumption, emission of pollutants, and difference between a specific traffic situation and total saturation should also be considered. Because each of these aspects differs for unsignalized and signalized intersections, it is not necessary that delays at each LOS correspond at both types of intersections.

TIME-DEPENDENT TRAFFIC VOLUMES

During recent years, traffic performance at intersections with time-dependent traffic volumes (peak-hour effect) has been studied by several authors. Results from Stamm (*16*) and Tonke (*17*) are also discussed in Brilon (*3*). Zhang (*7*) and Chodur et al. (*8*) also obtained more recent results. In qualitative terms, these results can be summarized as follows:

- The total capacity would increase considering time-dependent priority streams;
- If, however, the peaks of traffic volumes in priority streams and minor streets coincide, capacity decreases and delays increase (*3*).

Therefore, traffic performance depends on the offset between traffic peaks on the priority street and the minor street to a high degree. It is acknowledged that details of these relations cannot be expressed by a simple paper-and-pencil procedure.

PROPOSED PROCEDURE

The new procedure, which is going to be proposed to the German guideline committees in early 1991, can be characterized by the following features:

- Each of the movements at an intersection has to be evaluated by its traffic volume. There are 12 movements at a four-way intersection and 6 at a three-way intersection (see Figure 2). Heavy vehicles in the minor streams have to be converted to pcu with the help of special conversion factors [see Table 10–1 in the HCM (*2*)].
- The hierarchy of the traffic streams regarding priority brings about the order of evaluating the capacity for each minor stream *i*. First, the basic capacity G_i will be taken from a diagram like Figure 1. Parameters are the velocity on the main street and the volume of the priority stream q_p. This priority stream is composed of different streams that are placed hierarchically over the actual minor stream [see Figure 10–2 in the HCM (*2*)].
- The actual capacity L_i for Rank 2 movements (left turners from the major road and right turners from the minor road) is equivalent to the basic capacity. For the actual capacity of streams of Rank 3 or Rank 4 traffic, the queuing of privileged streams has to be considered by reducing the basic capacity with the impedance factor p_0 of the corresponding privileged streams (for Rank 3 streams, using Equations 3 and 4; for Rank 4 streams, using Equations 3 and 4 and Figure 3).
- If there is a shared lane for more than one movement, the common capacity is calculated from the individual capacities according to the individual volumes using Equation 10–1 in the HCM (*2*).
- Because the actual capacity describes the situation of very long queues and delays, the practical capacity is estimated by the actual capacity L_i minus a reserve capacity R_i (e.g., R_i = 100 pcu/hr). Depending on this reserve, a specific LOS characterized by average delay D can be guaranteed (see Figure 4).
- An unsignalized intersection can be called efficient for a chosen LOS value, if the traffic volumes of all minor streams are less than the corresponding practical capacities: $q_i < L_i - R_i$.
- In order to get more detailed information about traffic quality regarding queues and delays, simulation technique proves to be a useful tool. Therefore, the computer program KNOSIMO (*18*), which is already in practical use, has been developed. KNOSIMO estimates expectations, standard deviations, and total distributions of delays and queue lengths for each single traffic stream at an intersection also for time-dependent traffic volumes. KNOSIMO can be operated on a normal personal computer.

ROUNDABOUTS

Roundabouts are of increasing interest to traffic planners in Germany. Reasons for this are good experiences reported from other countries, chances of a well-designed adaptation of an intersection into an urban environment, and positive expectations regarding traffic capacity.

Therefore, a series of investigations of roundabout capacity has been conducted by the Ruhr University on behalf of the Federal Minister of Transport (*19*). Several methods of investigation have been studied and experimented with. Finally, an empirical method comparable to Kimber's approach (*20*) was used.

A group of 10 roundabouts was selected for the measurements out of more than 100 unsignalized circular intersections in West Germany. Each of the roundabouts provided situations with high traffic volumes of up to more than 3,000 veh/hr. In the course of the measurements, the streets entering into the roundabout were observed with video equipment that had a digital clock inserted into each frame. Measurements were carried out during times of continuous traffic jams on the entrance roads.

From the video recordings, the number of entering vehicles and the number of circulating vehicles was counted in 1-min intervals. It was presumed that the capacity of the entrance during this interval can be derived from these observations of continuous queuing on the approaching road during a 1-min interval.

On the basis of this assumption, the observed values of capacity (q_e = maximum volume of entering traffic in pcu/hr) were compared with those of circulating traffic (q_c in pcu/hr) observed on the circular road just upstream from the entrance. The measurement points for q_c and q_e were analyzed by regression techniques. Instead of a linear approximation used by, e.g., Kimber (*20*) and Louah (*21*), an exponential regression line was used because of a better agreement with capacity formulas for unsignalized intersections, e.g., Siegloch's formula (see Equation 1). Complementary simulations proved that with some minor bias—from a theoretical point of view—this technique represents the $q_e - q_c$ relation also for 1-hr intervals.

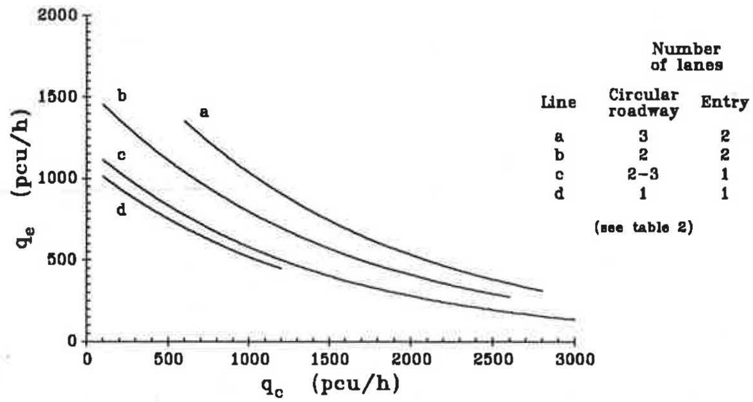

FIGURE 5 Regression curves for calculating the capacity of roundabouts.

Several types of roundabouts were investigated. The greatest samples could be observed at two-lane entrances into two-lane roundabouts. The total diameters of the circular roadways were between 40 and 142 m. Here the results seem to be a reliable representation of German conditions. At roundabouts with other combinations of entering and circulating lanes, the sample is not sufficient for final results. The reasons are that only a few of the one-lane roundabouts provided high traffic volumes and that only one roundabout with more than two circular lanes could be found.

Comprehensive results of the analysis are given in Table 2. The equations are illustrated by Figure 5. This figure indicates the range of q_c values for which empirical data could be obtained. These preliminary formulas are used in practice for capacity calculations of roundabouts in West Germany. They are implemented into the computer program KREISEL (*22*), which is also able to calculate capacities according to the English (*20*) and French (*21*) formulas and according to gap acceptance techniques.

On the whole, capacities of roundabouts in Germany seem to be considerably lower than the values predicted by the English formulas. The range of the German results is between 0.7 and 0.8 of the English values. However, there is good agreement between French and German results.

Reasons for differences may be explained by different driver behavior in the two countries; e.g., German drivers orientate by lanes, and the left lane of multilane approaches is hardly used. This is also a reason why variations in road widths—like in the English and French formula—do not seem to be good indicators for increased capacities under German conditions. Intersections with extremely high traffic volumes provided increased capacities compared with intersections with average traffic volumes. Because of different driver behavior, capacity formulas for roundabouts should not be transferred between different countries. Instead, each country has to find a solution of its own.

Of course, research on roundabout capacity should be continued in Germany as well. First, a greater data sample is needed for one-lane roundabouts. Furthermore, the influence of traffic volumes leaving the roundabout at the upstream and downstream exits (like in the French formula) should be determined. Finally, the impact of geometric features like the total diameter or the size of the center island on roundabout capacity is of considerable interest.

TABLE 2 FORMULA FOR CALCULATING ROUNDABOUT CAPACITY q_e IN RELATION TO CIRCULATING TRAFFIC VOLUME q_c

Capacity-formula		$q_e = A \cdot e^{-B \cdot \frac{q_c}{10{,}000}}$			
Number of lanes		Parameters		Sample size	Line
Circular roadway	Entry	A	B	(# 1-min.-intervals)	(in fig. 5)
1	1	1,089	7.42	275	d
2-3	1	1,200	7.30	455	c
2	2	1,553	6.69	3,873	b
3	2	2,018	6.68	295	a

REFERENCES

1. Berechnung der Leistungsfähigkeit von Knotenpunkten ohne Lichtsignalanlagen. *Anhang zum Merkblatt für Lichtsignalanlagen an Landstrassen*, Forschungsgesellschaft für das Strassenwesen, Köln, West Germany, 1972.
2. *Special Report 209: Highway Capacity Manual*, TRB, National Research Council, Washington, D.C., 1985.
3. W. Brilon. Recent Developments in Calculation Methods for Unsignalized Intersections in West Germany. In *Intersections Without Traffic Signals*, W. Brilon (ed.), Springer-Verlag, New York, 1988, pp. 111–153.
4. W. Brilon (ed.). *Intersections Without Traffic Signals*. Springer-Verlag, New York, 1988.
5. J. Harders. Die Leistungsfähigkeit nicht Signalgeregelter Städtischer Verkehrsknoten. *Schriftenreihe Strassenbau und Strassenverkehrstechnik*, Heft 76, Bonn, West Germany, 1968.
6. W. Siegloch. Die Leistungsermittlung an Knotenpunkten ohne Lichtsignalsteuerung. *Schriftenreihe Strassenbau und Strassenverkehrstechnik*, Heft 154, Bonn, West Germany, 1973.
7. X. Zhang. Einfluss des Grades der Teilgebundenheit auf die Wartezeit an Knotenpunkten ohne Lichtsignalanlagen. *Forschungsbericht*, Technische Hochschule, Darmstadt, 1986.
8. J. Chodur, S. Gaca, and M. Tracz. Störungen des Verkehrsablaufes an Höhengleichen Knotenpunkten ohne LSA-Steuerung bei Instationärem Zufluss. *Die Strasse*, Heft 7, 1989.
9. R. M. Kimber. Gap-Acceptance and Empiricism in Capacity Prediction. *Transportation Science*, Vol. 23, No. 2, May 1989.
10. J. Harders. Grenz- und Folgezeitlücken als Grundlage für die Leistungsfähigkeit von Landstrassen. *Schriftenreihe Strassenbau und Strassenverkehrstechnik*, Heft 216, Bonn, 1976.

11. R. Ashworth. The Capacity of Priority-Type Intersections with a Non-Uniform Distribution of Critical Acceptance Gaps. *Transportation Research*, Vol. 3, 1969.
12. W. Brilon and M. Grossmann. Aktualisiertes Berechnungsverfahren für Knotenpunkte ohne Lichtsignalanlagen. *Forschungsbericht*, Ruhr Universität, Bochum, Germany, 1990.
13. H. Kremser. Ein Einfaches Wartezeitproblem bei Einem Poisson'schen Verkehrsfluss. *Österreichisches Ingenieur-Archiv*, Band 16, Heft 1, 1961.
14. H. Kremser. Ein Zusammengesetztes Wartezeitproblem bei Poisson'schen Verkehrsströmen. *Österreichisches Ingenieur-Archiv*, Band 17, Heft 3, 1962.
15. F. J. Poeschl. Die Nicht Signalgesteuerte Nebenstrassenzufahrt als Verallgemeinertes M/G/1-Warteschlangensystem. *Zeitschrift für Operations Research*, Vol. 27B, 1983.
16. J. M. Stamm. Der Instationäre Verkehrsablauf an Knotenpunkten ohne Lichtsignalanlagen. Dissertation, Technische Hochschule, Darmstadt, 1974.
17. F. Tonke. Wartezeiten bei Instationärem Verkehr an Knotenpunkten ohne Lichtsignalanlagen. *Schriftenreihe Strassenbau und Strassenverkehrstechnik*, Heft 401, Bonn, West Germany, 1983.
18. M. Grossmann. KNOSIMO—A Practicable Simulation Model for Unsignalized Intersections. In *Intersections Without Traffic Signals*, W. Brilon (ed.). Springer-Verlag, Berlin, 1988, pp. 263–273.
19. W. Brilon and B. Stuwe. Einsatzmöglichkeiten von Kreisverkehrsplätzen und Aufgeweiteten Knotenpunkten unter Besonderer Berücksichtigung Ausländischer Erfahrungen. *Forschungsbericht*, Ruhr Universität, Bochum, West Germany, 1990.
20. R. M. Kimber. *The Traffic Capacity of Roundabouts*. Report LR 942. Transportation and Road Research Laboratory, Crowthorne, England, 1980.
21. G. Louah. Recent French Studies on Capacity and Waiting Times at Rural Unsignalized Intersections. In *Intersections Without Traffic Signals*, W. Brilon (ed.). Springer-Verlag, Berlin, 1988, pp. 248–262.
22. KREISEL. Computer Program for Calculating the Capacity of Roundabouts. *Lehrstuhl für Verkehrswesen*, Ruhr Universität, Bochum, West Germany, undated.

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.