Capacity and Design of Traffic Circles in Germany

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Capacity and traffic safety of traffic circles in Germany have been investigated in comprehensive research projects carried out at the Ruhr University Bochum. On the basis of observations of real traffic conditions, formulas for predicting traffic circle capacity under conditions in Germany have been developed. These formulas have been specified in terms of the number of lanes in the circle and in the entry. The capacities of traffic circles measured in Germany appear to be considerably less than the values predicted by English formulas. For German traffic circles, capacity has been measured at between 0.7 and 0.8 of English values. However, there is good agreement between calculations for French and German capacity. The influence of geometric parameters was also investigated. In addition to the number of lanes in the circle and in the entry, geometric parameters turned out to be significant for estimating the capacity of traffic circles. These parameters are inscribed circle diameter, number of traffic circle arms, and distance between exit and entry of the observed arm. Traffic circles in Germany also provide a considerable increase in traffic safety when compared with normal signalized or unsignalized junctions. Before and after investigations at small, single-lane traffic circles showed that traffic circles have a lower severity of accidents, whereas the number of accidents stayed almost the same. Experience with existing traffic circles resulted in some significant recommendations for the design of traffic circles. Using the suggested design criteria, good experience has been shown in several cases and has led to a rapid increase in the number of new single-lane traffic circles. Public opinion also favors traffic circles.

Traffic circles in Germany have a tradition from the beginning of this century. Therefore, a number of traffic circles from the 1950s and early 1960s are still in operation. During the 1970s this type of intersection was completely abandoned. Traffic engineers believed that the benefits of traffic circles were not too good. In recent years, because of international experience and overwhelmingly good results of new experiments, traffic circles with a modern design are again the center of interest to traffic engineers. Therefore, new traffic circles in Germany are rapidly increasing. Many new constructions or conversions of cross junctions into traffic circles have already been carried out. The experience with both new and older types of construction during several years of practice and research are discussed in this paper.

CAPACITY

Experts around the world agree that traffic circles without traffic signals can be operated usefully only if the circulating lane has the right of way and the arriving traffic must yield. Thus, a traffic circle can be regarded as a series of T-shaped entries into a one-way circular road. This makes it possible to apply the classical priority theory (*1*). For traffic circles, however, the British regression theory appears to be more useful (*2,3*). This method ascertains capacity formulas by observing entries to traffic circles during times of continual congestion. The entering traffic and the traffic within the traffic circle are counted in short time intervals (e.g., 1 min). The measuring points are compared and represented by a regression line. Because there is continual congestion in the entry during the entire measured time, every suitable gap in the main stream is used. Therefore, the observed values are also the capacity in the observed situation.

An objection to this method is that a wide scatter of points cannot be represented precisely enough by a single line. This is incorrect. Half of the mean variation of the points results from the statistical characteristics of the 1-min interval measurements. As a result of the regression technique, the actual capacity in longer time intervals (e.g., 1 hr) is very reliably determined. This was confirmed by simulation (*4*). The other half of the mean variation results from individual driver behavior and local peculiarities of the investigated traffic circles.

In a recent study (*5*), such measurements and evaluations were carried out for 11 traffic circles in Germany. Compared with a straight line as a regression equation for the representation of measurements, a regression function according to Siegloch's equation has proven to be slightly better:

$$q_{e,\max} = A \cdot e^{-B/10{,}000 \cdot q_c} \quad (1)$$

where $q_{e,\max}$ is maximum possible traffic volume of the entry in passenger car units (pcu) per hour, and q_c is traffic volume in the traffic circle at the entry in pcu per hour.

The constants A and B in this equation have been determined separately from the measurements by regression calculation for different types of entries. The results are given in Table 1 and shown in Figure 1, which indicate that the results depend on the number of lanes in the circle and the entries. For conversion into pcu, single-unit trucks were rated as 1.5 pcu, trucks and trailers as 2 pcu, and motorbikes as 0.5 pcu (*6*).

The reliability of these values varies for different configurations. For two-lane traffic circles with two-lane entries, a sample of several thousand measuring points with large variations of q_c was developed. These equations are very reliable. Among the single-lane traffic circles, only three could be found to fulfill the conditions (considerable congestion for a long time). Only one three-lane traffic circle was available. There

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TABLE 1 Calculating Traffic Circle Capacity—Parameters *A* and *B*

Number of lanes: Circular roadway	Entry	A	B	Number of measure-ments
3	2	2018	6.68	295
2	2	1577	6.61	4574
2-3	1	1300	8.60	867
1	1	1226	10.77	1060

are no traffic circles with more than three circulating lanes in Germany. Further investigation is necessary, particularly for single-lane traffic circles. A corresponding research project has meanwhile been initiated by the Federal Minister of Transport in Germany.

Comparing the corresponding formulas of the most frequent case of single-lane traffic circles from other countries shows that the postulated capacities are rather close to the lower limit, and therefore on the safe side. A similar comparison for two-lane traffic circles is given by Brilon (*3*). It is remarkable that a doubling of lanes (from single-lane to two-lane) does by no means lead to a doubling capacity. The capacity increase is at best about 30 to 40 percent, because the left lane of the entry is only rarely used in Germany [see Figure 12 in the work by Brilon (*3*)]. This behavior is caused by the drivers' fear of being unable to reach the desired exit from the left circulating lane. This was also found by Troutbeck (*7*). Therefore, an extension of traffic circle measurements to more than two lanes is not expected to cause a considerable capacity increase in Germany. Troutbeck also found that capacity increased by 70 to 80 percent when the number of lanes was doubled.

In foreign countries, many investigations have shown that besides the number of lanes, other characteristics of geometric design influence capacity as well (*2,7,8*). In the data of Brilon and Stuwe (*9*), influences other than the number of lanes in the circle and the entry could not be determined. But in recent investigations, during which the volume of data was increased considerably, some geometric parameters turned out to be of significant influence (*5*). These were, in addition to the number of lanes in the entry and the circle, the inscribed circle diameter (*D*), the number of traffic circle arms (*A*), and the distance between exit and entry of the observed arm (*EM*). The differences resulting from these when compared with the earlier single variable equation are important. Nevertheless, these results are preliminary.

A further point for discussion is whether the traffic leaving the traffic circle at an exit has an influence on the next entry (*2*). An influence of this kind could not be ascertained using German data. Simon (*10*) found the same results from data for Switzerland. Both questions, however, will be investigated further on the basis of a larger sample.

The formulas given in Equation 1 should not be overinterpreted. If the resulting capacity is 600 pcu/hr, this can mean that in fact values of 630 or 570 pcu/hr can occur as well. Therefore, the results of the equation should be regarded as a realistic estimate of the magnitude of capacity. For single-lane traffic circles, the following problem can arise from the equations: even with larger q_c values, L is greater than 0. Alternatively, it is obvious that downstream of the entry on a single-lane traffic circle, no more than about 1,800 pcu/hr can pass the traffic circle. Therefore, the curve has to be broken off pragmatically, as shown in Figure 1. Theoretically, this should also be considered for traffic circles with more than one lane per direction. This question, however, is less relevant for these cases than for a single-lane traffic circle, because situations with such traffic loads hardly ever occur.

The calculated capacity should not be directly used in practice as limit of traffic load, because it is associated with considerable congestion. Therefore, to achieve an acceptable traffic quality, the limits for practical use have to be lower than the values obtained from Equation 1. The following values result from the theory of unsignalized intersections (*6*): the mean delay is less than 40 sec/vehicle if a capacity reserve of 100 pcu/hr is subtracted according to Equation 1 [i.e., the practical usable limit of capacity, L, is 100 (*11*)]. This is a considerable simplification. For a closer look, the mean delays can be calculated according to the universal delay formula by Kimber and Hollis (*12*). Their formula takes into account the effect resulting from actual temporal changes in traffic volume. All

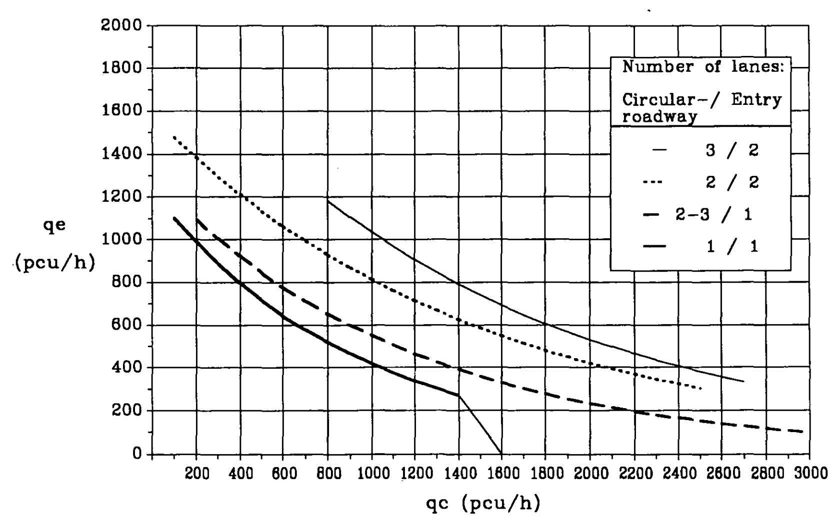

FIGURE 1 Regression curves for determination of traffic circle capacity.

calculations can be made with a multilingual computer program provided by Brilon and Wu (*13*).

The results of these calculations for a large number of cases make it possible to reach the general conclusion regarding capacity that is given in Table 2. In Table 2, ADT means the average total traffic passing the traffic circle per day. If the left-turning streams are very strong, capacity can be less than the minimum, *M*. The upper limit of capacity, *U*, may be exceeded only if the share of right-turning streams is very large or if extreme congestion is accepted. If the ADT values are between *M* and *U*, the capacity should be calculated using the previously introduced technique. These statements are valid for traffic circles with four or more legs. For three-legged traffic circles, the limits for the overall load can also be lower.

Of course, a comparison of capacity of traffic circles with other intersection types is quite interesting. First of all, it can be stated that traffic circle capacity will always surpass that of a four-way intersection or T-junction without traffic signals. Therefore, the real competitors are traffic circles and signalized intersections. If the signals are two-phase-controlled, they can be more favorable than the traffic circle. A four-phase-controlled signal, however, which is very popular in Germany because of improved safety, is in general associated with longer delays than the traffic circle. The investigations show that traffic circles are an alternative solution especially for smaller multiphase-controlled intersections. Capacity for multiphase-controlled intersections can surpass a traffic circle only if the intersection is widened by multilane operation of the traffic streams.

TRAFFIC SAFETY

Traffic circles are very popular in many countries, particularly because of their high traffic safety. In the United Kingdom, they are regarded to be by far the safest type of intersection (*14*). In France conversions of intersections into traffic circles have led to a considerable increase in traffic safety inside (*15*) and outside (*16*) of towns. The traffic safety advantages of traffic circles mainly result from the decrease in accident severity. In Germany, there are some older traffic circles. Harder and Kinzel (*17*) reported very high accident rates on the order of six accidents per 10^6 vehicles on older traffic circles, but also found relatively low costs per accident. Because of this type of experience, there is still a lot of skepticism among German practicians concerning traffic circles.

To collect more recent data, Brilon and Stuwe (*5,9*) investigated 14 traffic circles and 14 junctions near the traffic circles. The results are summarized in Table 3. These results are explained in detail elsewhere. Special attention was paid to the individual analysis of every intersection in order to rule out the influence of individual peculiarities on the overall results.

TABLE 2 Minimum and Upper Limits of Capacity

		Roundabout 1-lane ADT	Roundabout 2-lane ADT
no problems regarding capacity	M	< 15000	< 18000
upper limit of capacity	U	25000 - 28000	35000 - 40000

TABLE 3 Accident Rate, Accident Cost, and Mean Accident Cost

ROUNDABOUTS	AR	ACR	MC	JUNCTIONS	AR	ACR	MC
medium and large roundabouts	6.58	24.90	3.78	junctions with traffic signals	3.35	21.73	6.49
smaller roundabouts	1.24	4.67	3.77	junctions without traffic signals	1.00	11.96	11.96

Note: AR = accident rate (10^6/veh), ACR = accident cost rate (DM/10^3 veh), MC = mean accident cost (1,000 DM/accident), and DM = deutsche mark (1.7 DM = $1.00, 1993 U.S. dollars)

The investigations show that traffic circles can be categorized by accident clearly into two groups as follows:

- Multilane traffic circles with an inscribed circle diameter of 40 to 142 m that always had an old design, and
- Small single-lane traffic circles with inscribed circle diameters of 28 to 40 m and modern design.

All accident parameters indicated that traffic safety in both groups differed considerably in scale. The older, larger traffic circles have accident rates similar to those reported by Harder and Kinzel. In this sample, however, the modern, small traffic circles have proved to be the safest intersection, especially if the accident cost rate is regarded as the central criterion.

It is also interesting to make a before and after comparison. This could be done for seven traffic circles (Table 4). More traffic circles with the necessary data could not be found. Because of the lack of suitable data, some very short after periods and different seasons had to be included. The sample size is too small, however, to draw strong conclusions. Nevertheless, if these data are considered together, the overall changes are significant and speak well for the traffic circle. Although the number of accidents (expressed by the accident rate) stayed the same, the accident severity (expressed by the accident cost rate) was clearly reduced after transformation into a new traffic circle.

These examples give only a preliminary impression. The investigations of traffic safety must therefore be continued. A general conclusion can be made, however. In Germany the installation of properly designed traffic circles appears to increase traffic safety, especially small, single-lane traffic circles. These can be regarded as a type of intersection with a high degree of traffic safety.

PRINCIPLES OF PROPER TRAFFIC CIRCLE DESIGN

If it were intended to derive design elements for traffic circles with a perfect scientific meticulousness, it would be necessary to experiment on a range of different intersection forms. Hardly anyone would fund such a project, and no town will agree to have experimental intersections constructed. Nevertheless, indications can be derived from foreign experiences, particularly on the basis of experiences with other types of intersection. These indications are derived from the four standard demands for a safe design of an intersection: clarity of the

TABLE 4 Before and After Comparisons

	JUNCTION							ROUNDABOUT						
	from	to	AR	Sl	Se	F	ACR	from	to	AR	Sl	Se	F	ACR
Bochum	'82 -	'85	1.63	13	1	-	16.96	6.87 -	8.90	0.73	3	-	-	1.50
Brühl	6.87 -	7.89	1.26	7	3	-	21.47	12 mon. prov.		2.24	4	1	-	20.9
	(signalized)							8.90	-16.5.91	1.73	4	-	-	6.17
Ispringen	'87 -	'88	1.74	2	7	2	168.9	7.90	-17.3.91	1.47	-	-	-	2.53
Kamen	1985		0.75	1	-	-	13.71	'86 -	'89	0.81	1	-	-	2.44
Königsfeld	'88 -	8.89	2.16	2	-	-	13.16	9.89 -	'90	2.52	-	-	-	4.33
Leimen	'87 -	'89	0.62	3	1	-	7.32	'90 -	4.91	0.96	1	-	-	6.14
Sinnersd.	'85 -	11.89	0.06	-	-	-	0.25	12.89	-16.5.91	0.64	1	-	-	4.30
sum	225 months			31	16	2		169.5 months			14	1	-	
weighted average			1.00				23.52			1.22				5.78

AR = accident rate [accidents/ 10^6 veh]
ACR = accident cost rate [DM / 10^3 veh]

Sl = slightly injured persons
Se = seriously injured persons
F = Fatal accidents

situation for the approaching driver, visibility between road users at the inner intersection areas, comprehensibility of traffic operations, and passability for the largest permitted vehicles (such as trucks or articulated buses). Furthermore, a safe intersection is designed on the basis of the principle of harmony between design, construction, and operations. In other words, traffic regulation must be adjusted to the structural design and vice versa. Every violation of this principle creates the risk of an accident. This principle—applied to traffic circles—results in the requirement that entries must lead to the circulating lane in a vertical (i.e., radial) way. An acute-angled or tangential entry causes rear-end collisions in the approach and priority conflicts. This has been proved by Leutzbach and Ernst (*18*).

Particularly for the smaller single-lane traffic circles, further basic questions of design are associated with passability. In general, it can be assumed that traffic circles are intended to be used without restrictions by all vehicles that are licensed for road traffic. According to German regulations, every vehicle must be able to pass a circle with an outer radius of 12.5 m and a width of 7.2 m. Until October 1988 these standards were 12 and 6.7 m. Vehicles using these new standards are still the exception. Because these standards can be reached only at a very low velocity by heavy-duty vehicles or by articulated buses, an additional space of 0.40 to 0.50 m on each side is recommended for practical use in road traffic. Therefore 26 m can be regarded as the lowest value for the outer diameter of a traffic circle. This leads to a very broad circulating lane with a very small central island. Because an increase in outer radius is associated with a decrease in the width of the circulating lane, as shown in Figure 2, a larger radius is recommended.

Traffic circles that have been designed by the authors show that a minimum outer diameter of 30 m can lead to satisfactory results for both traffic engineering aspects and design. As shown in Figure 2, a circulatory highway width of 6.2 m must be assumed for the largest licensed vehicle. Considering a sufficient clearance, the resulting width of the circulating lane is 7 m. This combination of diameter and lane width leads to the effect that the central island of the traffic circle makes it impossible to look through the intersection (non-transparent traffic circle). A circulating lane with such an extreme width can cause problems with the appearance of the road space. Moreover, it could be passed at a relatively high velocity, if a free use of the whole width was possible. Therefore, the inner circle has been paved in several cases. For reasons of durability, this pavement should be laid very tight, bordered by a curb, and raised further up to the central island, which can be 2 to 3 cm higher than the asphalt surface of the circulating lane.

Experience has shown that this construction makes all passenger car drivers and motorcyclists use the outer area of the circulating lane. The paved zone is only sometimes used by the inner rear wheel of trucks and trailers. Some doubts about this construction have been raised—motorcyclists may have problems when touching the raised edge and snowplows may have difficulties. Previous experience, however, has not confirmed these doubts. Thus, the outer diameter of 30 m is the minimum value recommended when space is limited. If suf-

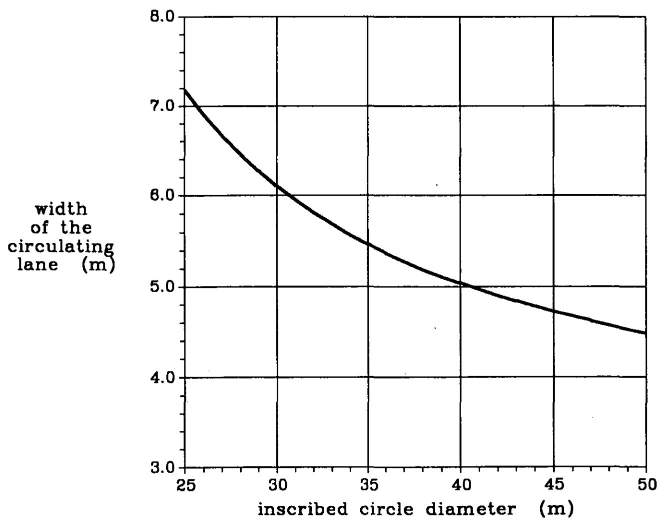

FIGURE 2 Width of circulating lane (without room to move) as function of outer radius.

ficient space is available and the traffic circle can be fitted into the environment, a larger outer diameter of about 40 m with a lane width of 6 m is recommended. A further increase in diameter facilitates higher velocities and, therefore, does not contribute to increased traffic safety.

Passability must be guaranteed in the entries and exits as well. Mistakes in design are often made in the exits. In most cases, it is sufficient to round off the corners according to the swept paths in the German guideline for intersection design (*19*). For an even more detailed examination of passability, Schult (*20*) developed a computer procedure. Except for the necessary flare at the corners, the entries and exits have the same widths as the neighboring road sections. Widening in the vicinity of the traffic circle is not recommended because it would lead to an unwelcome acceleration. If an entry is wider than 3.5 m, it should be reduced to this measure in a sufficient distance from the circulating lane. If necessary, separate lanes for buses can be added to the normal lane and carried to the outer border of the circulating lane. Thus, the traffic circle facilitates a simple way of giving priority to public transport. This design has been used in Switzerland (*21*).

Another construction detail worth mentioning is the cross slope. It should never be directed inward because this would lead to an unwelcome traffic acceleration in the traffic circle. Moreover, an inward curve would cause a negative cross slope for entering vehicles at the kinematically most problematic point of the traffic circle: the road section leading from the entry onto the circulating lane. Therefore, the cross slope should be directed outward. This also improves the visibility and clarity for drivers approaching the traffic circle. The cross slope should be 1.5 to 2.5%, which is necessary for drainage. If the whole area of the traffic circle slopes, an extreme negative cross slope can result in some sections of the circulating lane. Definitive results are not available yet. According to recent insights, however, negative cross slopes of more than 5 percent in traffic circles should not be tolerated. If this is not possible, a different type of intersection should be chosen. Of course, the drainage system should be adjusted exactly to the slope of the lane surfaces. In most cases, a level surface plane is recommended.

High-quality standards must be demanded for the asphalt surface of the circulating lane and the entries. Braking friction in the entries and lateral friction, especially caused by articulated trucks with several axles, means that the surface construction is heavily used. All curbs in the traffic circle and in the entries—especially at the pedestrian islands—should be made of a permanent white material. Reflectors can be attached to the edges of the dividing islands. These actions would improve visibility for drivers approaching the traffic circle. The same effect could be achieved by one or more signposts on the approaches to the intersection (at least outside of towns where there is no lighting) showing the traffic circle symbol. To improve visibility, the central island should be planted or equipped in a nontransparent way, that is, free sight from the entry through the traffic circle to the opposite exit is obstructed. It must, however, be guaranteed that the sight distance while driving on the circulating lane is sufficient. This is achieved primarily by the paved inner circle. It is particularly important that the central island be free of any objects that could be dangerous obstacles if hit by a vehicle, especially trees and poles, but also low bordering walls. For safety reasons, sloping curbs are the recommended construction for all curbs. These considerations have to be taken very seriously, because the central island can be hit because of inattentiveness (e.g., caused by drunkenness). With the proscribed measures, such an accident is likely to be harmless. Otherwise, it will cause serious personal injuries. A wave-like transition from the pavement to the border of the island has proven to be a suitable solution. Traffic circles within towns should be lighted. Placing light poles in the four corners outside the traffic circle is the most favorable construction. In this position, the poles are less hazardous to errant vehicles. Moreover, all islands and curbs are lighted favorably. For the reasons mentioned, an arrangement of light poles on the central island is less favorable.

Pedestrians

For safety reasons, pedestrians should be kept off the circulating lane and the central island, except if the traffic volume of the traffic circle is very low. This can be achieved, for example, by planting the area between the circulating lane and footways. Pedestrians, however, cross the entries and exits of the traffic circle. These pedestrian crossings should have a distance of one passenger car length (6 m) to the circulating lane. This distance enables the drivers to treat the conflicts with pedestrians and priority vehicles in the traffic circle separately. Experience has shown that this more relaxed situation is mainly used to let pedestrians cross the lane without problem. Moreover, in the exits this space is used for queueing in front of the pedestrian crossing.

An island should be installed between entry and exit that can be used by pedestrians as a refuge (splitter island). Without such a deflection island, pedestrians can barely see the traffic situation on the opposite side of the road, particularly for the clockwise walking direction around the traffic circle. With a deflection island, pedestrians only have a very short (3- to 5-m) conflict zone with the vehicular traffic that, moreover, comes from only one direction at a time. This makes it easier for pedestrians to make decisions, and the situation is controllable for children and senior citizens as well. Thus, behavior is more considerate to drivers. Wherever there is pedestrian traffic, the deflection islands should not be left out. The crossing itself can be either constructed as zebra crossing, which gives the absolute right of way to pedestrians in Germany, or constructed without any marking. To make the crossing visible, it is possible to pave it with formed concrete elements. This solution, however, leads to higher noise levels. Moreover, problems with the construction and maintenance of the road surface must be considered. The German guidelines for zebra crossings (*22*) can be used for decisions about the installation of zebra crossings. These guidelines require a minimum 100 pedestrians per hour crossing the road in the peak hour to justify a zebra crossing.

Taking the aforementioned design principles into account, one should, however, think of appropriate solutions that give passengers priority without constructing zebra crossings. If high volumes of pedestrian traffic occur at the crossings, a capacity reduction for motorized vehicles can result. This effect can be computed with a procedure by Griffith (*23*). Marlow and Maycock (*24*) also ascertain congestion lengths. In the calculation procedure presented previously (*13*), this step is included as well. However, given a German traffic circle with a high volume of pedestrians, cyclists, and motorized vehicles (e.g., Münster Ludgeriplatz), the reduction of capacity by pedestrians was considerably smaller than predicted by Marlow and Maycock [see work by Brilon et al. for example (*9*)]. In any case, the procedure by Marlow and Maycock is on the safe side. Further investigations are being prepared.

The capacity reduction resulting from pedestrian traffic becomes particularly obvious in the exits. Here, the pedestrian crossings can cause congestion of vehicles on the circulating lane. If this congestion lasts long, the whole traffic circle can be blocked. Therefore, at least 90 percent of the time, congestion from pedestrian crossings at the exit into the traffic circle should be avoided. In critical cases, this can be achieved by increasing the distance between pedestrian crossing and traffic circle to more than 6 m. In most cases, pedestrians can cross the lanes without noticeable delays. This has been proved by many analyses.

These extensive remarks on pedestrian traffic are by no means intended to give the impression that this is a particularly critical subject regarding traffic circles. Normally, capacity aspects become important only in cases of extremely high volumes of pedestrian traffic, which rarely occur in practice. If the aspects mentioned are considered, traffic safety is generally very high for pedestrians at traffic circles because there are only very narrow conflict zones with the motorized traffic, which, moreover, passes these zones at very low speeds. The detour that pedestrians have to make as a result of this design is small, especially compared with a signal-controlled intersection. Of course, the footway design in the area of the traffic circle must have the effect that pedestrians do not regard it as a detour. In general, however, this aspect turns out to be unproblematic as well.

Cyclists

Bicycle traffic at traffic circles requires special attention in Germany. In general, there are four solutions for guidance on this issue:

1. Grade-separated guidance outside the traffic circle. This solution should be preferred unless general objections to undercrossings or overbridges prevail.
2. Guidance on the circulating roadway without separate lanes for cyclists. This solution is quite advantageous, especially for small traffic circles. Cyclists indicate their desired direction by cycling either on the right side or in the middle of the circulating lane. In the small traffic circles (diameter up to 40 m), they get along well in the motorized traffic without safety risks because cars and bicycles drive at almost the same speed. There are no overtakings in the traffic circle. Of course, cyclists decrease the traffic circle capacity. This can be considered in calculations by counting a cyclist as 0.5 pcu in the earlier equations.
3. Guidance of cyclists on separate bicycle paths. If the roads leading to the traffic circle are equipped with separate cycle paths, these can be continued around the traffic circle. Cyclists then cross the entries and exits on paths on the inner side of the pedestrian crossings. This solution has been implemented successfully at some of the locations mentioned. At small traffic circles, cyclists normally do not have problems when crossing the lanes, with regard to neither safety nor delays. However, one must reckon with cyclists using the cycle paths in both directions. Moreover, bicycle traffic often splits into cyclists needing protection (e.g., children, who use the separate cycle paths) and fast, sporty cyclists who stay on the circulating lane. Considering the aspects mentioned in Guidance 2, there are no objections to this behavior.
4. "Fixed tracks" for cyclists. In the past in Germany cycle paths were often marked, sometimes with a colored surface, at the outer side of the circulating lane. This solution seems to be unfavorable. According to a Swiss investigation (*25*), this solution is even regarded as dangerous. Because of the forced cycling on the right side, cyclists are unable to indicate their desired driving direction. The authors have observed that cyclists often stretch out their left arm while using the fixed track in order to prevent motorized vehicles from cutting in front of them. Moreover, the fixed track systematically leads the cyclists to the conflict zones at the entries. This problem became obvious during the accident investigations: 13 of the 26 seriously injured persons in the sample (see Table 3) were cyclists, 8 of whom were using fixed tracks. Therefore, this solution of a cycle track on the circulating lane must be rejected. If the approaching lanes are equipped with cycle tracks, the tracks should end 20 to 30 m in front of the traffic circle, which is then used by the cyclists according to Guidance 2.

These remarks cannot be regarded as conclusive rules. Rather, the problems of cyclists in traffic circles demand a more extensive investigation.

DESIGN OF ENTIRE TRAFFIC CIRCLE

The entire design of a traffic circle should be adjusted to the urban environment as much as possible. This design can be supported by including circular elements and radial alignments in the planting and building activities around the traffic circle (*26*). The circular central island offers such possibilities for individual design as plantings, memorials, or other objects of local importance. By this, traffic circles become an experience for road users and especially for residents. They can become unique points of orientation in the townscape. Aspects of architectural design, however, should not predominate over traffic engineering requirements. Traffic circles that mainly represent works of modern art are unfavorable, especially from the point of traffic safety.

Even if architectural design is not considered foremost, the traffic engineering elements of design by no means result in sterile technological constructions. Instead, the traffic circles are pleasant in appearance. After new construction of or conversion into traffic circles, road users and residents begin appreciating this type of intersection very quickly. Opinion polls show agreement of more than 95 percent. Wherever there are older traffic circles, citizens and politicians are interested in their preservation and improvement.

Small traffic circles that are designed according to the principles presented in this paper can harmonize different objectives that often cause such conflicts in traffic engineering as capacity, economy, environmental benefits, safety, and design.

REFERENCES

1. W. Brilon. Der Kreisverkehr—eine vergessene Knotenpunktform? (Roundabouts—A Forgotten Type of Intersection?) *Strassenverkehrstechnik*, No. 6, Germany, 1984.
2. G. Louah. *Recent French Studies on Capacity and Waiting Times at Rural Unsignalised Intersections* (W. Brilon, ed.). Springer-Verlag, Germany, 1988.
3. W. Brilon. Leistungsfähigkeit von Kreisverkehrsplätzen. (Capacity of Roundabouts.) *Strassenverkehrstechnik*, No. 5, Germany, 1988.
4. W. Brilon and H. Ohadi. Empirische Überprüfung der Leistungsfähigkeit von Kreisverkehrsplätzen. (Empirical Investigation of Roundabout Capacity.) *Arbeitsblätter AVV Nr. 4*, Arbeitsgruppe für Verkehrstechnik und Verkehrssteuerung der Ruhr-Universität Bochum, Germany, 1988.
5. B. Stuwe. *Untersuchung der Leistungsfähigkeit und Verkehrssicherheit an deutschen Kreisverkehrsplätzen.* (*Investigation of Capacity and Safety at German Roundabouts.*) Dissertation. Lehrstuhl für Verkehrswesen, Ruhr-Universität Bochum, Germany, 1992.
6. W. Brilon and M. Grossmann. The New German Guideline for Capacity of Unsignalized Intersections. In *Intersections without Traffic Signals II*. Springer-Verlag, Germany, 1991.
7. R. J. Troutbeck. *Evaluating the Performance of a Roundabout*. Australian Road Research Board, 1989.
8. R. M. Kimber. *The Traffic Capacity of Roundabouts*. Laboratory Report 942. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1980.
9. W. Brilon, B. Stuwe, et al. *Einsatzmöglichkeiten von Kreisverkehrsplätzen und aufgeweiteten Knotenpunkten unter besonderer Berücksichtigung ausländischer Erfahrungen. Teil A: Kreisverkehrsplätze.* (*Possibilities to Use Roundabouts and Widened Intersections with Special Consideration of Foreign Experiences.*) Forschungsbericht FE 77198, 87 BMV, No. 7, Germany, 1990.
10. M. Simon. *Roundabouts in Switzerland—Recent Experiences, Capacity, Swiss Roundabout Guide*. Emch & Berger Zürich AG, Switzerland, 1990.
11. W. Brilon. *Intersections without Traffic Signals*. Springer-Verlag, Germany, 1988.
12. R. M. Kimber and E. M. Hollis. *Traffic Queues and Delay at Road Junctions*. Laboratory Report 909. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1979.
13. W. Brilon and N. Wu. *Handbuch zum Programm KREISEL. (Manual for the Software Package KREISEL.)* Lehrstuhl für Verkehrswesen, Ruhr-Universität Bochum, Germany, 1990.
14. R. D. Hall and R. A. J. Surl. Accidents at Four-Arm Roundabouts and Dual-Carriageway Junctions—Some Preliminary Findings. *TEC* No. 6, 1982.
15. J. Le Coz. Quimper: Carrefour giratoire à anneau prioritaire. *TEC*, No. 50, 1982.
16. J. M. Gambard. Safety and Design of Unsignalised Intersections in France. In *Intersections Without Traffic Signals*. Springer-Verlag, Germany, 1988.
17. G. Harder and O. Kinzel. Möglichkeiten der Einbeziehung von Unfallkosten im städtischen Bereich in die RAS-W. (Possibilities to Integrate Accident Costs in Urban Areas into the RAS-W.) *Strassenbau und Strassenverkehrstechnik*, No. 471, Germany, 1986.
18. W. Leutzbach and R. Ernst. Verkehr an Kreisplätzen. (Traffic at Roundabouts.) *Strassenverkehrstechnik*, No. 2, Germany, 1969.
19. *German Guideline for Intersection Design* (in German). Forschungsgesellschaft für Strassen-und Verkehrswesen, Cologne, Germany, 1988.
20. R. Schult and J. Holzwarth. Der Flächenbedarf repräsentativer Lastzug- und Sattelzugkombinationen im Strassenverkehr. (Space Required by Representative Truck and Trailer Combinations in Street Traffic.) *Strassenverkehrstechnik*, No. 1, Germany, 1988.
21. H. Bovy. Les giratoires: développements en Suisse romande et élaboration d'un guide suisse. *Strasse und Verkehr*, No. 9, Switzerland, 1990.
22. *German Guideline for Zebra Crossings* (in German). Forschungsgesellschaft für Strassen- und Verkehrswesen, Cologne, Germany, 1984.
23. J. D. Griffiths. A Mathematical Model of a Nonsignalized Pedestrian Crossing. *Transportation Science*, Vol. 15, No. 3, 1981, pp. 223–232.
24. M. Marlow and G. Maycock. *The Effect of Zebra Crossing on Junction Entry Capacities*. Special Report 724. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1982.
25. *Veloverhalten im Kreisel.* (*Bicycle Behaviors in Roundabouts.*) Arbeitsbericht Nr. 1. Emch & Berger AG, Aarau, Switzerland, 1987.
26. Schnüll. *Einsatzmöglichkeiten von Kreisverkehrsplätzen und aufgeweiteten Knotenpunkten unter besonderer Berücksichtigung ausländischer Erfahrungen. Teil B: Fahrverhalten an kleinen Kreisverkehrsplätzen und städtebauliche Integration (cf. 11, Part B: Driving Behavior at Small Roundabouts and Integration into Urban Planning.)* Forschungsbericht FE 77198/87 an den BMV, No. 7, Germany, 1990.

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