# Roundabouts : A State of the Art in Germany

**Werner Brilon**

Professor

Ruhr-University

D - 44780 Bochum
Germany
verkehrswesen@rub.de

Werner Brilon is Professor for Transportation and Traffic Engineering in the Department of Civil Engineering at the Ruhr-University in Bochum, Germany

## Summary

Today, Germany has 15-years of experience with different kinds of modern roundabouts. In addition to that, large conventional roundabouts have been used for 70 years. Modern roundabouts include

- compact single-lane roundabouts with diameters between 26 and 40 m
- mini-roundabouts with a traversable island and diameters between 13 and 25 m
- larger roundabouts (40 –60 m) with 2-lane access for cars and single-lane operation for trucks.

All these types turned out to be very successful regarding both traffic safety and capacity. On the other side the traditional larger 2-lane roundabouts have significant safety problems. The paper describes the German experience from a long series of research projects regarding traffic safety, capacity, and traffic performance estimation as well as geometric design.

**Keywords**: roundabout, capacity, safety, geometric design

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# 1. Introduction

Germany like other European countries, has a long tradition of many decades regarding roundabouts. The roundabouts built between the 1930ies and the 1960ies were, however, limited in number and were mainly of a larger type (fig. 1) with several lanes, both on the approaches and exits as well as on the circle. Especially the city of Hannover, 50 years ago, was rather famous because of her many large roundabouts. Over the years, these conventional roundabouts received a bad reputation regarding their safety. Thus, they were no longer built after the 60s and many of them were replaced by signalized intersections [1].

It was in the early 1980ies that experiments were made with new modern roundabouts inspired by the great success of roundabouts in the UK. At that time, single-lane compact roundabouts were of primary interest. The design standards from the UK, however, were not copied. Instead the basic principles of intersection design were applied quite consequently. These compact single-lane roundabouts became a story of great success. They are now a state-of-the-art solution as it is documented in the corresponding guideline [2]. As a consequence, in recent years also other types of roundabouts receive more and more interest.

For further discussion some consensus about terminology seems to be useful. Therefore, fig. 2 shows which types of roundabouts are usually defined in Germany including also some information about their application both regarding size and traffic volumes. In the following parts of this paper these types are discussed concerning design principles, safety, capacity, and performance of operation.

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*Fig. 1 :* *Large traditional roundabout: Ludgeriplatz in Muenster*

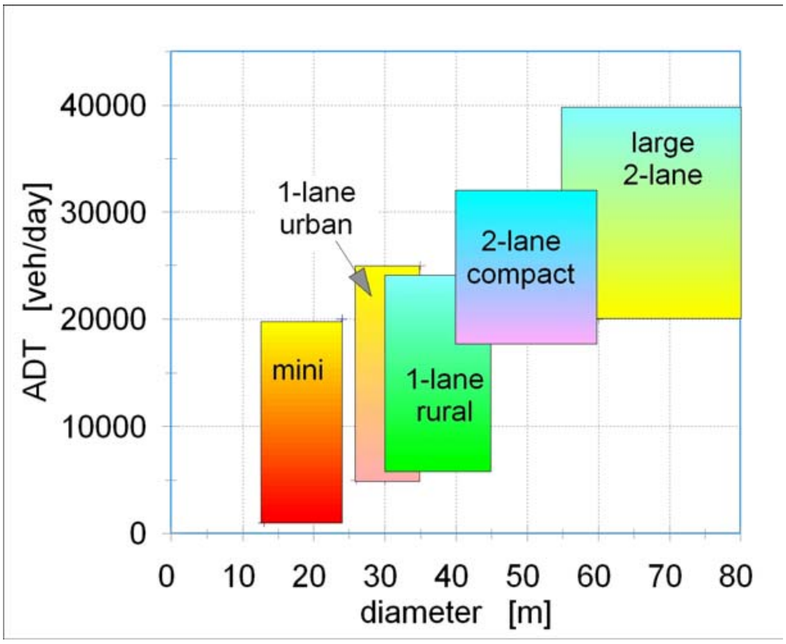


*Fig. 2 :* *Definition of types of roundabouts by their size and maximum capacity in terms of average daily traffic (ADT)*

## 2. Mini-Roundabouts

Mini-roundabouts have a diameter between 13 m and 24 m (measured between the curbs). Their central island can be traversed by larger vehicles if the swept path makes it necessary.

Experiments began in 1995 with 13 intersections that were converted from unsignalized intersections into minis. The success was overwhelming. They could carry up to 17.000 veh/day without mayor delays to vehicles. They could easily be built - sometimes without significant investment costs - and they turned out to be very safe. For the intersections under investigation, the overall safety results were:

| | before | after (Mini) | |
|---|---|---|---|
| accident rate AR | 0,79 | 0,56 | acc. / Mio veh |
| accident cost rate ACR | 9,47 | 3,91 | € / 1000 veh |

Here it should be noted that in Germany, as a tradition and according to official rules, both personal injury accidents as well as damage-only accidents are included in the police files and, thus, also in the described accident rates.

*Fig. 3:* *Mini-Roundabout in Kall built with nearly zero costs (only some asphalt to construct the central island and road markings)*

*Fig. 4:* *Mini roundabout in Bochum built by a reconstruction of the intersection*

As a result of the investigations the following rules are recommended for application [*3*]:

- application only in urban areas (maximum allowed speed = 50 km/h)
- outer diameter between 13 and 24 m
- circular roadway between 4,5 and 5 m

- lateral slope 2,5 % inclined to the outside
- central island with a maximum height of 12 cm (in the center) above the circle, minimum curb height 3 cm
- capacity up to a maximum of 20.000 veh/day
- no flaring of the entries
- only single-lane entries and exits.

Meanwhile, many mini-roundabouts have been built according to these rules, which operate quite successfully (Fig. 3 and Fig. 4).

## 3. Compact Single-Lane Roundabouts

The standard type of a roundabout according to the German philosophy has a diameter between 26 m (as a minimum - better: 30 m) and 45 m. It has only one single lane on each of the entries and exits as well as on the circle. It has a central island which can not be traversed. Due to the needs of larger vehicles (swept path for turning) the circular roadway must be wider than a usual lane. With 26 m diameter, thus, the circle must be widened out up to 8 m. In such cases a paved apron can be recommended for urban installations (Fig. 5). From this type approximately between 1.000 and 2.000 intersections have been installed during the last 15 years both in urban and rural environments (Fig. 6).

Many investigations have been made regarding safety. Some of these result are summarized in the following table.

| | **before** | | **after** | |
|---|---|---|---|---|
| | AR | ACR | AR | ACR |
| Brilon, Stuwe [*4*] | 0.97 | 14.77 | 1,62 | 7,36 |
| Baumert [*5*] | | | | |
| urban | | | 0.53 | 6.02 |
| rural | | | 0,74 | 10.06 |
| Meewes [*6*] | | | 0.92 | 8.0 |
| | acc/$10^6$ veh | €/$10^3$ veh | acc/$10^6$ veh | €/$10^3$ veh |

We see rather low figures for accident rates (AR) and - especially - for accident cost rates (ACR). These numbers are around half of the corresponding rates for both normal unsignalized and even signalized intersections. Especially for rural crossroads the accident risk is only in the range of 10 % compared to an unsignalized intersection. The excellent accident records of compact roundabouts are believed to be mainly due the low speed level of all drivers within the intersection. Thus, a speed reducing design is favored by the guidelines [2]. That means:

- Intersection arms should be directed to the center of the roundabout in a manner rather rectangular to the circle. No tangential entries are allowed. This improves the visibility of the intersection for the approaching driver and causes reduced speeds.
- The transition between the entry lane curbs and the circle should follow circles with a small radius (e.g. 12 -16 m for entries and 14 - 18 m for exits). Of course, these rules are adjusted to the swept path curves of the largest allowed heavy vehicles.
- Moreover, the circle lane should be inclined to the outside (2,5 %). This enables drainage as well as a better visibility for the approaching driver. It reduces driven speeds on the circle.

*Fig. 5:* *Compact single-lane roundabout in the town of Bruehl (near Cologne) with a paved apron at the inner side of the circle (Photo: Nikolaus, Euskirchen)*

*Fig. 6:* *Urban single lane roundabout built on bridges over a creek (Photo: Lustinez, Freiburg)*

For pedestrians and cars the compact roundabout seems to be the safest type among all intersections [*6*]. For pedestrians the paths to cross the entries and exits should be built in a distance of 4 to 5 m away from the external margin of the circle. Zebra crossings (which impose an absolute right of way for pedestrians in Germany) can be installed, but in most cases they are not necessary.

For cyclists the design has to be made with special care. Cycle lanes at the peripheral margin of the circle are not allowed since they are very dangerous to cyclists. Up to a traffic volume of about 15.000 veh/day, cyclists can be safely accommodated on the circular lane without any additional installations. Above this traffic volume separate cycle paths seem to be useful. These, however, should also have a distance of around 4 to 5 m from the circle. A lot of more details should be taken into account for a safe traffic operation at a compact roundabout [*2*]. Mistakes in design usually cause more accidents than necessary, where the cyclists suffer at most from these risks.

## 4. Compact two-lane roundabouts

After all, there was always a rather restrictive view in Germany on new large roundabouts in the style of Fig. 1. They are, however, demanded by the public. The restrictions are based on bad accident experience. As a first approach towards larger roundabouts, a new intersection type has been created: The compact semi-two-lane circle. Ideas for this type were described in a preliminary guideline document and consequently this new type was built by several communities and highway authorities. In succession an investigation on this new type has been performed on behalf of the federal DOT [*11*].

The design of compact semi-two-lane roundabouts is similar to the one of compact single-lane roundabouts. The main difference is the width of the circle lane. It is wide enough for passenger cars to drive side by side, if required. However, the circle lane has no lane marking. Large trucks and busses are forced to use the whole width of the circulatory roadway making their way through the intersection. The fundamental characteristics of these compact semi-two-lane roundabouts are:

- outer diameter: 40 to 60 m
- circle lane width: 8 to 10 m ; without lane marking (to prevent drivers from overtaking)
- single- or two-lane entries
- single-lane exits only
- No bicyclists are allowed on the circle lane.

The design rule is:

- If capacity allows, only single-lane roundabouts should be built.
- If such a type does not match the required capacity, an enlargement should be tested in the sequence:
  1. Bypass lanes (separate direct right-turn lanes)
  2. Compact two-lane circle with single-lane entries
  3. Two-lane entries where necessary

Each unnecessary enlargement should be avoided.

The recently finished research project investigated driver behavior by speeds, conflicts, and test drives with a sample of different drivers. Moreover, accidents (before / after), capacity, and public opinion have been studied at a couple of these compact two-lane circles.

The essential results are that compact two-lane roundabouts are also very safe intersections. In fact, the accident rate is only a little bit higher than the rate at compact roundabouts with one lane in the circle. Also, most accidents at these sites remain without personal injuries. The safety is particularly high if all entries of the roundabout have only one lane and if the volumes of pedestrians and cyclists are low.

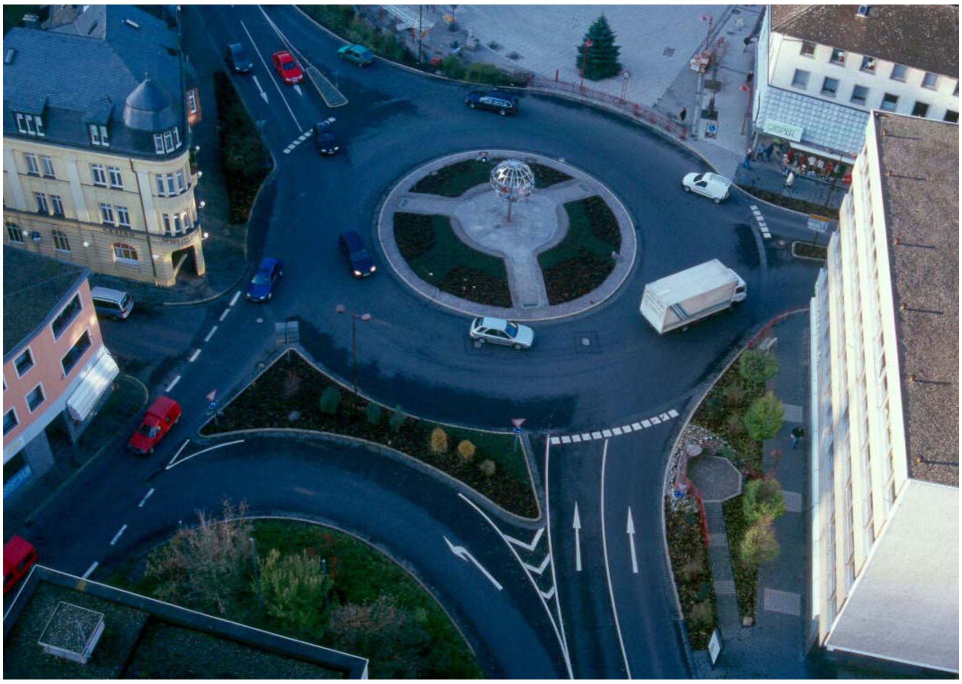

*Fig. 7***:** *Urban compact two-lane roundabout in Idar-Oberstein*

*Fig. 8:* *Rural compact two-lane roundabout in Bad Aibling*

The new compact semi-dual-roundabouts are now accepted by the responsible committees as a state-of-the-art type of intersection. They have been included into a special guideline [*12*] and they will also be described by the new edition of [*2*].


*Fig. 9:* *Typical driver behavior at a compact two-lane roundabout: unused left lane on a two-lane entry*

## 5. Larger Roundabouts

Above this new semi-two-lane type – which by the way is very similar to what other countries like France have built for years as normal single-lane “giratoires” – there are still the larger conventional two-lane roundabouts like the one in Fig. 1. The capacity of these larger roundabouts are rather well investigated (Fig. 11). The high capacities reported in Fig. 11 can only be applied for cases, where the exits provide two lanes. This type of a roundabout is, however, not recommended, neither by guidelines nor by expert’s advise in Germany, due to the experience that they systematically cause a very large number of non-severe accidents. But severe personal injuries do rarely occur. However, two-lane exits are a safety problem at these larger types of roundabouts. Due to interactions of circulating flows with fast vehicles leaving the circle from the inner lane, these two-lane exits often are a reason for injury accidents. Therefore, multilane roundabouts are not recommended for application in Germany. Especially 2-lane exits are completely banned.

It can be expected that new experiments will come up in Germany in the future also with larger roundabouts, e.g. with spiral markings. One recently developed idea for such a larger roundabout is the one in fig. 10 [13]. Here across from the mayor entries a second lane is added on the inner side of the ring, whereas at exits with a significant exiting flow the vehicles on the outside lane are forced to continue their way into the exit. This type could be of special benefit at locations where the through traffic has larger volumes. The example of fig. 10 is under construction in the outer part of the city of Baden-Baden in 2005. However, with new types of intersection there is a tendency in Germany to conduct such experiments very carefully.

What can, however, be reported is that signalized multilane roundabouts have proven to be a good solution in specific situations. Experiments at sites with volumes up to 50000 veh/day were successful both from the view of high capacities (cf. table below) as well as traffic safety [*14*].

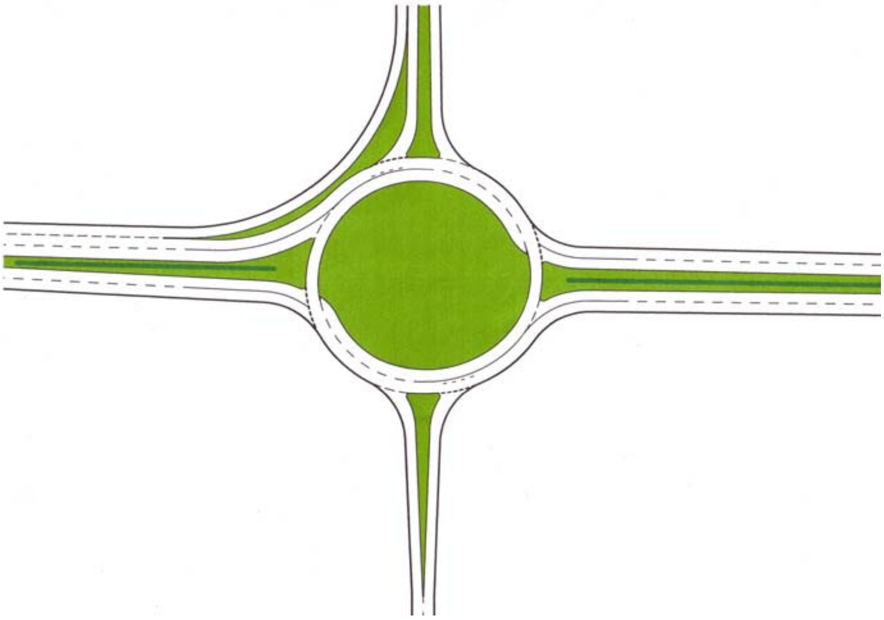

*fig. 10:* *Large **R**oundabout with **A**ddition of **I**nner **L**anes (RAIL) at the entries and one bypass within a 4-lane arterial.*

## 6. Capacity of roundabouts

In Germany the capacity of roundabouts has been studied over many years by a series of investigations. Both gap acceptance theory and the empirical regression method have been in the scope of these activities. Initially there was a preference on empirical linear regression approaches for capacity depending on circulation flow with a distinction by the number of lanes (entry and circulating) [*4*]. Here also a multivariate regression approach using geometric features of the intersection according to the British example has been developed [*16*], a solution which was later adopted by a Polish guideline [*17*]. Nevertheless, this solution was not too successful, since it was too much focused on the specific combination of parameters, which were the basis of calibration. The full range of possible parameter values could, however, not been covered by observations. As a consequence, the multivariate regression equations had a tendency towards a significant misjudgment under combinations of parameter values as they had to be used in practice.

The currently established official procedure is more related to gap acceptance. It uses Tanner's [*18*] equation in a form which was adjusted to the necessities of roundabout analysis by Wu [*19*] :

$$G = 3600 \cdot \left(1 - \frac{t_{min} \cdot q_k}{n_k \cdot 3600}\right)^{n_k} \cdot \frac{n_z}{t_f} \cdot e^{-\frac{q_k}{3600} \cdot \left(t_g - \frac{t_f}{2} - t_{min}\right)} \qquad (1)$$

| | | | | |
|---|---|---|---|---|
| where | $G$ | = | basic capacity of one entry | [pcu/h] |
| | $q_k$ | = | traffic volume on the circle | [pcu/h] |
| | $n_k$ | = | number of circulating lanes | [-] |
| | $n_z$ | = | number of entry lanes | [-] |
| | $t_g$ | = | critical gap | [s] |
| | $t_f$ | = | follow-up time | [s] |
| | $t_{min}$ | = | minimum gap between succeeding vehicles on the circle | [s] |

For the use of these equations the volumes are measured in passenger car units (pcu) with: 1 truck = 1.5 pcu; 1 articulated truck = 2 pcu , and 1 bicycle = 0.5 pcu. For the three parameter $t_g$, $t_f$, and $t_{min}$ the values have been taken from observations by Stuwe [*4*], [*16*]:

$t_g$ = 4,1 s $t_f$ = 2,9 s $t_{min}$ = 2,1 s .

As it can be obtained from the equation, the capacity of each entry depends – of course - on the circulating traffic flow ($q_k$) and on the number of lanes within the circle as well as at the entries. Other geometrical details did not show an important impact on capacities. This is also true for the width of the splitter island, which is used in formulas from Switzerland and France. The application of eq. 1 is illustrated in fig. 11. These curves have been integrated into the current guideline HBS 2001 ([20], German equivalent to the US Highway Capacity Manual). To ease capacity calculations, computer programs which can also apply capacity calculation procedures as they are reported from other countries, are in frequent use [21].

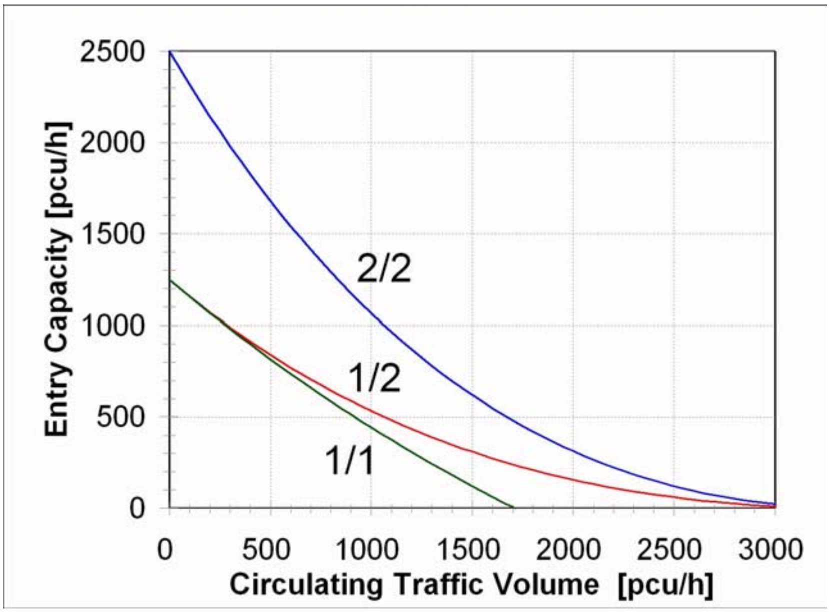


*Fig. 11* *Entry capacity of roundabouts according to the German Highway Capacity Manual (HBS [*20*] ) developed in [*19*] . The numbers indicate the number of lanes : entry/circle.*

With these detailed calculation methods one usually can determine maximum allowable daily volumes for the total intersection according to the following table. Between the ADT-values in line a) and b) more detailed capacity calculations are necessary according to fig. 11.

| | Lanes entry / circle : | 1/1 | compact 2/2 | large 2/2 | signalized 2/2 |
|---|---|---|---|---|---|
| a | can be applied without additional capacity calculations below → | 15 000 | 16 000 | 20 000 | |
| b | has a maximum capacity of → | 25 000 | 32 000 | 35 000 - 40 000 | 50 000 - 60 000 |
| | | veh/d | | | |

Recently also a capacity analysis has been performed for the compact 2-lane roundabouts as they are described in section 4 of this paper [*11*]. Here the methodology was concentrated on the empirical approach, were capacity is based on observations during times of uninterrupted queuing on the entry. On the two-lane entries there were no observations with both entry lanes being completely occupied, even if there were long queues on the right lane (cf. Fig. 9). Therefore, capacity was defined as the throughput of one entry during intervals, during which there was at least a continuous queue on the right entry lane.

Of course, the capacity of the compact two-lane roundabouts should be larger than the capacity of single-lane roundabouts. But the difference is smaller than supposed. Obviously the drivers want to avoid the necessity for lane changes within the circle, which causes them to avoid the left entry lanes. This was also a result of the field surveys. In fact, also the conflict analysis, the accident investigation, and the test drives with a sample of different drivers revealed that lane changing conflicts – especially near exits – turn out to be the most critical maneuvers. As a consequence, the capacity is much lower than the capacity of large roundabouts with two-lane entries, fully two-lane circle, and two-lane exits. The second entry lane has only a rather limited effect on capacity. This effect is also depending on the proportion of left turning traffic (i.e. vehicles to the 3rd – or higher – exit). As a result of the study, the capacity of these compact semi-two-lane roundabouts can be estimated by an analytical method (cf fig. 13). The corresponding curves in the figure are based on eq. 1 with $t_g = 4{,}3$ s, $t_f = 2{,}5$ s, and $t_{min} = 0$. $n_e$ is 1 for single-lane entries and 1,14 for 2-lane entries. It should again be emphasized that this solution applies only on roundabouts as they are characterized in section 4 of this paper.

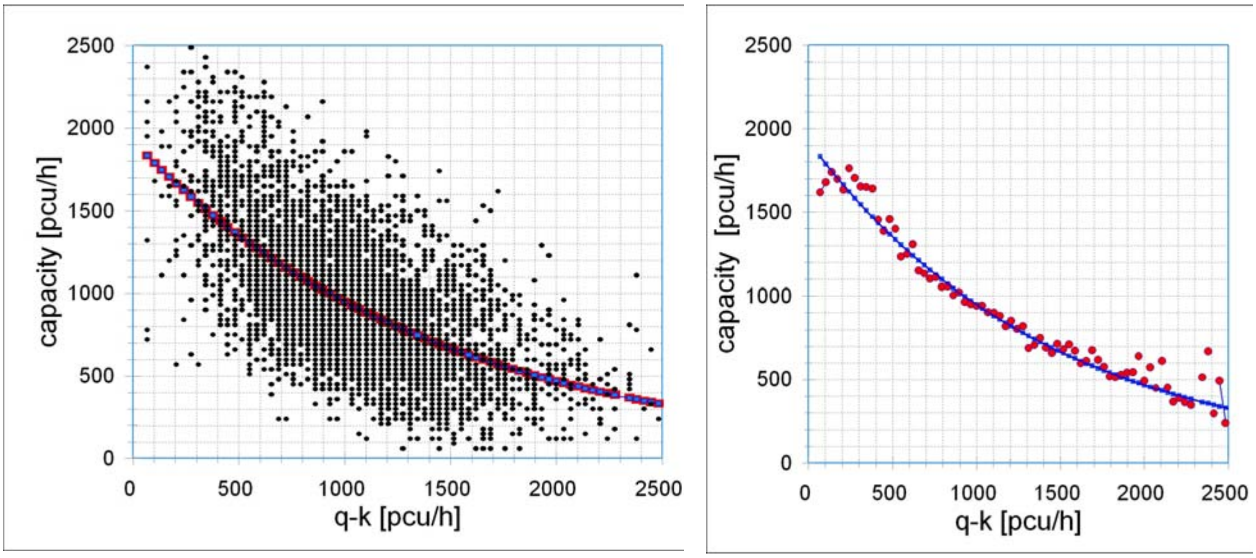


*fig. 12:* *Regression analysis for single points of observed capacity (left side) and averages of the observed points (right side).*

These are capacity calculation methods as they are currently included in the German guidelines. More recently additional studies focusing on the empirical regression approach have been performed by the author. These are based on several thousand 1-minute observation points for each combination of lane configurations. Several regression solutions have been tested. The usual one tries to calculate a regression line out of the full number of observation points (cf. fig 12, left side, with 4500 data points). The second solution first calculates the average entry capacity for each observed value of 1-minute circulating flow with a subsequent regression of these averages (fig. 12 right side).

The data indicate very clearly that a linear line was not at all sufficient to represent the data observed. Instead a regression of the form of eq. 1 proofed to be a much closer approximation, especially for multilane roundabouts. Here it is useful to let $t_{min} = 0$, since otherwise a large number of solutions with nearly equal performance could be found. Then eq. 1 can be simplified into:

$$G = 3600 \cdot \frac{n_z}{t_f} \cdot e^{-\frac{q_k}{3600}\cdot\left(t_g - \frac{t_f}{2}\right)} \qquad (2)$$

which is Siegloch's capacity equation [*22*]. Depending on the lane configuration of the roundabout (RA), the parameters obtained from the statistical analysis including some pragmatic rounding of values are given as:

| | no. of circulating lanes | no. of entry lanes | $n_z$ | $t_g$ | $t_f$ | $t_{min}$ | valid below $q_k$ |
|---|---|---|---|---|---|---|---|
| 1-lane | 1 | 1 | 1 | 4.1 | 2.9 | 2.1 | 1600 |
| 2-lane compact RA (no lane marking on the circle) | 2 | 1 | 1 | 4.3 | 2.5 | 0 | 1600 |
| | | 2 | 1.14 | 4.3 | 2.5 | 0 | 1600 |
| 2-lane large RA (with marked lanes) | 2 | 1 | 1 | 4.3 | 2.5 | 0 | 2000 |
| | | 2 | 1.6 | 4.1 | 3.0 | 0 | 2500 |

Again it should be emphasized that eq. 1 and 2 which are originally obtained from gap acceptance theory, in this context, are only used as regression lines where the parameters are estimated from data points (like fig. 12 shows) using minimization for the sum of quadratic deviations.

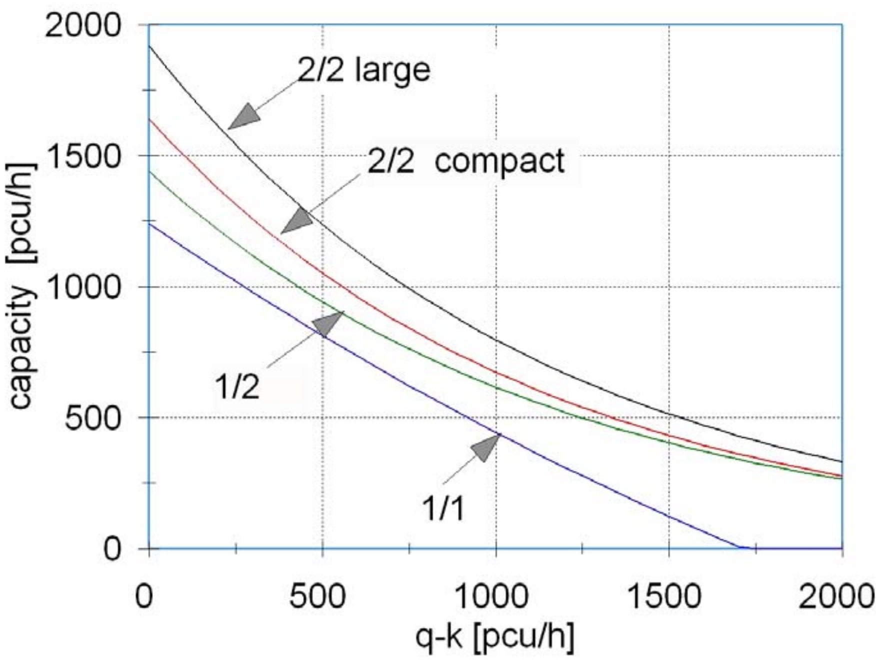


*fig. 13:* *Capacity of roundabouts with different lane configurations according to eq. 1 or 2 with new parameters (cf. table above) . The numbers indicate the number of lanes: entry/circle.*

It should also be mentioned that a method is available from the German guidelines [*20*], which estimates the effect of pedestrians (crossing the entries) on capacity based on research by Stuwe[*16*].

Quite recently, a completely different concept for the understanding of capacity at intersections is under development. From fig. 12 (left side), which shows a wide variety of 1-minute capacity estimations at 2 lane entries to a large 2-lane roundabout, it becomes obvious that the capacity for each specific $q_k$-value in such short intervals is a more like a random variable instead of a constant value, as it is usually treated. Analysis of data leads to the conclusion that a close approximation of the data variability is achieved by a cumulative distribution function $F(q_e)$ which is derived from a Weibull-distribution [*23*]:

$$F(q_e) = 1 - e^{-\left(\frac{x}{A \cdot e^{-B \cdot q_k}}\right)^{\alpha}} \qquad (3)$$

where

$q_e$ = traffic volume on the entry to the roundabout [pcu/h]

The parameters A, B, and $\alpha$ are to be calibrated from observed capacity values $q_e$. Based on a maximum likelihood estimation [*23*] the result for a sample of data from a 1-lane entry to a 1-lane roundabout was: $\alpha = 3$, $A = 21$, $B = 0.04$ . The distribution (according to eq. 3) is illustrated by 3-dimensional plots in fig. 14. We see a rather wide variance for smaller $q_k$ and a rather concentrated form of the distribution for larger $q_k$.*)*.

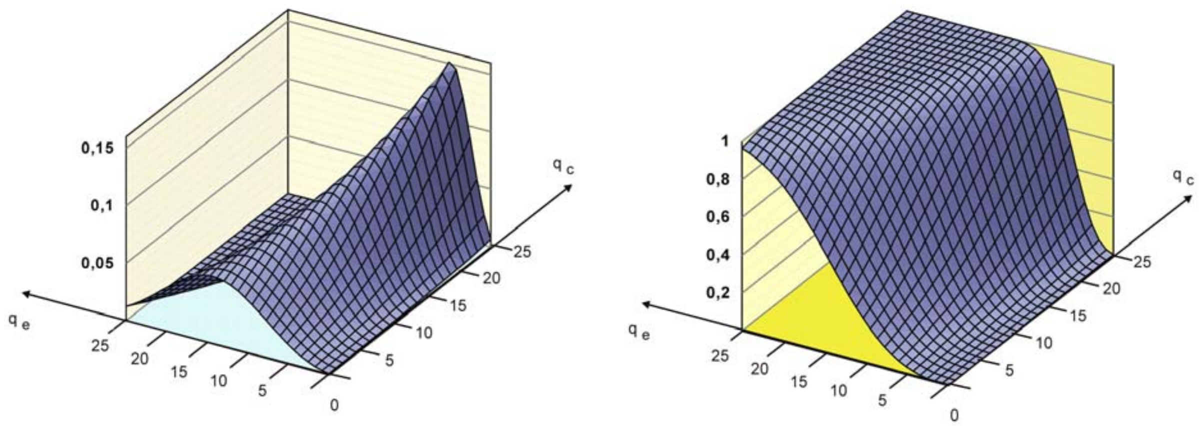


*fig. 14:* *Distribution of the roundabout entry capacity, observed in 1-minute intervals, according to a Weibull-distribution expressed as density function $f(q_e)$ and distribution function $F(q_e)$ (eq. 3) depending on volume $q_k$ (= $q_c$ in this plot, will be corrected in the final version; volumes in veh/min).*

It becomes clear that the German capacity estimation methods are different from those in other countries. Experience shows that the capacity of roundabouts is significantly influenced by basic driver behavior patterns formed by different traffic rules, traditions, and cultural attitudes. Therefore, one should not transfer capacity calculation formulas from one country to another without empirical evidence generated in the country where the method is meant to be applied. The special German attitudes e.g. are characterized by a culture of driving in lanes and an always clear definition of the fact who has priority and who has to give way. It is also a basic rule of behavior here, that a road user who has the right of way, should make made use of his priority.

In addition to capacity the quality of traffic operation at the roundabout is of primary interest. For the assessment of traffic flow performance, the average delay for vehicles entering the intersection is used as it is the case in other countries, e.g. [*24*]. This delay usually is calculated by the set of equations given by Kimber, Hollis [*25*]. This method is also recommended by the German guideline HBS [*20*]. Meanwhile, however, some doubts have been raised to which extend these equations can estimate realistic delays. For comparisons with measured delays and with simulated data, first of all, the basic definitions of average delay must be matched between derivation of the theory and data analysis. Here practitioners usually prefer a kind of definition which is in accordance with the Akcelik, Troutbeck equation [*26*] which is also used in the HCM (as eq. 17-38) [*24*]. These questions are, at present, also a matter of more detailed investigation.

## 7. Conclusions

Roundabouts have become one of the most attractive type of intersections in Germany. Reasons are the rather high traffic safety, low delays, and the popularity among politicians and in the public. Meanwhile there is much practical experience, which leads to well sophisticated set of rules for roundabout design. Also the capacity can rather well be described. There is, however, still some concern in Germany to which extend also larger roundabouts should again be used. As the state of the art documentation, a new comprehensive guideline for roundabouts in Germany as a new version of [*2*], including warrants for application and design rules, is going to be published in 2005, a draft of which has been submitted to the responsible committees at the end of 2004.

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