Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
1–11

DOI: 10.1177/03611981211030258
journals.sagepub.com/home/trr
SAGE

Capacity of Mini-Roundabouts: A New Model

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Abstract

Estimation of the capacity of mini-roundabouts is under discussion. Existing methods treat mini-roundabouts as analogous to larger roundabouts, assuming independence between operation of the entries. They fail to acknowledge the specific way that traffic operates at these narrow intersections. This study proposed a new model, which aimed to accommodate the peculiarities of mini-roundabouts: priority for upstream entry, capacity increasing effects of exiting vehicles, and heavy vehicle operation. The model resulted in a set of equations that can be solved iteratively. It was applied to a set of examples in which the model parameters were estimated according to existing guidelines. Test calculations showed: compared to the current German guidelines the model leads to a reduced total intersection capacity. Further calibration and tests for practicability are recommended.

Mini-roundabouts were first developed in the UK (*1*), and were standardized in line with the design standards for roundabouts (*2*). Their wide dissemination in the UK from 1970 onwards proved a great success (*3*). Other countries have treated mini-roundabouts more reluctantly. In Germany, the first experiments were undertaken in the federal state of Nordrhein-Westfalen (*4*, *5*). This research evaluated this type of intersection very positively and made recommendations for design details. This led to the first federal state-edited guidelines (*6*), the content of which was later implemented into an FGSV (*Forschungsgesellschaft für Straßen- und Verkehrswesen*) guideline (*7*) with validity for Germany as a whole.

According to these standards, a mini-roundabout has a diameter between 13 m and 22 m. In general, the central island is either just painted markings, or an area that is only slightly elevated to enable large vehicles to turn. In contrast to the UK, German standards require a physical central island that is elevated 5 cm above the asphalted circular lane, which has a width between 4 and 6 m. The slightly elevated central island proved to be essential for motivating car drivers to follow the circular lane instead of crossing the island.

Traffic rules at mini-roundabouts are the same as at normal compact roundabouts, that is, the circulating traffic has priority over the entering traffic. However, because of the short distance between two adjacent entries in the roundabout, a driver can overlook the whole intersection. At each entry drivers must observe all vehicles approaching from the left-hand entry to avoid conflicts on the circular lane. In many cases, a driver on an entry might be forced to stop and wait for an approaching vehicle from the left-hand entry, which itself is not yet on the circular lane. Thus, the operation of a mini-roundabout may convert from roundabout priority into a kind of "left-hand-side priority" rule, that is, a vehicle from the left-hand entry may get priority over vehicles at the subject entry. Thus, because of this interrelated priority constellation at a mini-roundabout, it could – theoretically – come to a deadlock, where the priority is not clearly defined, which can also occur at intersections with "right-hand-side priority," applied at almost all uncontrolled intersections in countries that drive on the right (*8*). By a certain probability, there could be approaching or waiting vehicles at all entries and a stalemate situation (deadlock) might occur. In these situations, nobody would be able to enter the mini-roundabout safely.

Very good overviews of international experiences with mini-roundabouts are given in papers by Kennedy (*9*, *10*). All capacity estimation methods for mini-roundabouts – as for larger roundabouts – treat the intersection as a sequence of independent T-junctions of entries into the circular lane. A pragmatic approach

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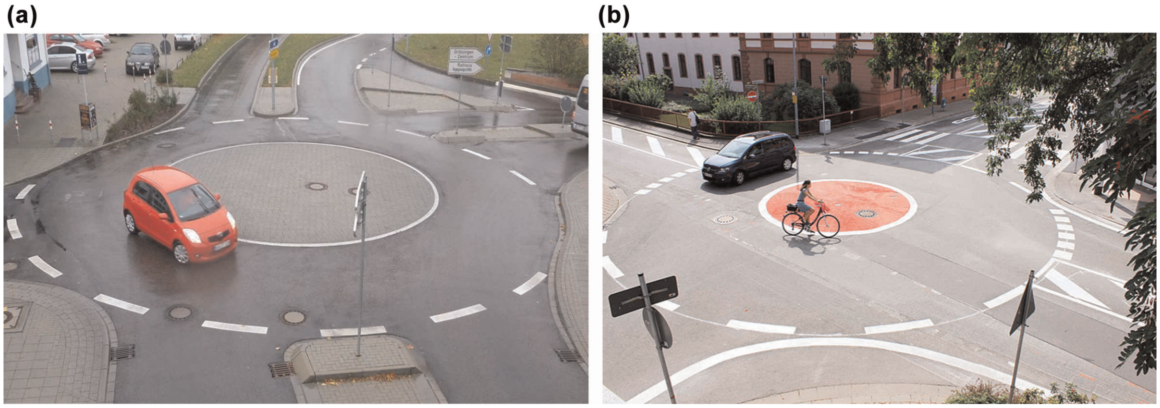

Figure 1. Examples of mini-roundabouts.

proposed by Sawers stated that the sum of entering and circulating traffic could be a maximum of 1,200 pcu/h (passenger car units per hour) at each entry (*11*). This simple rule of thumb has proven to be quite reliable.

The capacity of mini-roundabouts in the United States was studied by Taylor et al. (*12*). The authors proposed two linear equations for the entry capacity as this depends on circular flow. The paper explains the peculiarities of traffic operation at mini-roundabouts quite well, but ultimately, retained the traditional way of treating each entry as an independent unit. Heavy vehicles (HVs) were incorporated by a pcu value of 1.7. The study is not primarily based on empirical data, but used microscopic simulation as a means of producing data for regression analysis. The resulting equations differed significantly from findings by other authors.

The *Highway Capacity Manual* (HCM) (*13*) does not treat mini-roundabouts.

The most recent method for Germany was developed by Schmotz (*14*). Based on empirical research and simulation he developed a capacity calculation method based on gap-acceptance theory. A modified version of this was introduced by Baier et al. (*15*), which has found its way into the German version of the HCM, *Handbuch für die Bemessung von Straßen* (HBS) (*16*). Among several other solutions, a report by Buehlmann et al. who proposed a linear regression equation based on empirical research in Switzerland should be mentioned (*17*). In addition, Baier et al. developed linear regression equations for entry capacity at mini-roundabouts based on capacity observations in Germany (*15*). A different approach was proposed by Schmotz and Maier based on a conflict analysis model; this model led to quite complex formulas (*18*).

All these capacity estimation concepts treat the entries of a mini-roundabout like a combination of isolated T-junctions, which operate independently from each other. These solutions calculate the capacity of the subject entry depending on the circulating flow, which results from the demand at all other entries. However, in doing so, the solutions do not check whether these other demand volumes can be accommodated in the limited capacity of the entries, nor do the solutions consider deadlock. The actual mechanisms of traffic operation at mini-roundabouts are completely disregarded by these models. For example, the risk of gridlocks or deadlocks is not addressed. Also neglected is the operations of HVs that cross mini-roundabouts – especially during turning maneuvers – on a direct route, not following the circular lane. Therefore, a model that more realistically represents traffic operation at mini-roundabouts is required. This paper is an attempt to get closer to achieving that objective.

Model

At first, we consider traffic consisting of only light vehicles (LVs). LVs we define all vehicles that can and thus must turn around the central island of a mini-roundabout. These might be passenger cars and vans, but also small trucks.

In this study, pedestrian traffic was assumed to be very low or that it had to yield to the exiting vehicular traffic.

We address a four-arm mini-roundabout. Mini-roundabouts with more than four arms are unusual and may not even exist since a fifth arm would be difficult to accommodate in a mini-roundabout owing to limited space. A mini-roundabout with three arms could be treated as a special case, with zero entering and exiting traffic at one of the four arms.

We look at one entry (index *i*) to the mini-roundabout (Figure 2*a*). This entry would have a basic capacity, C_0,

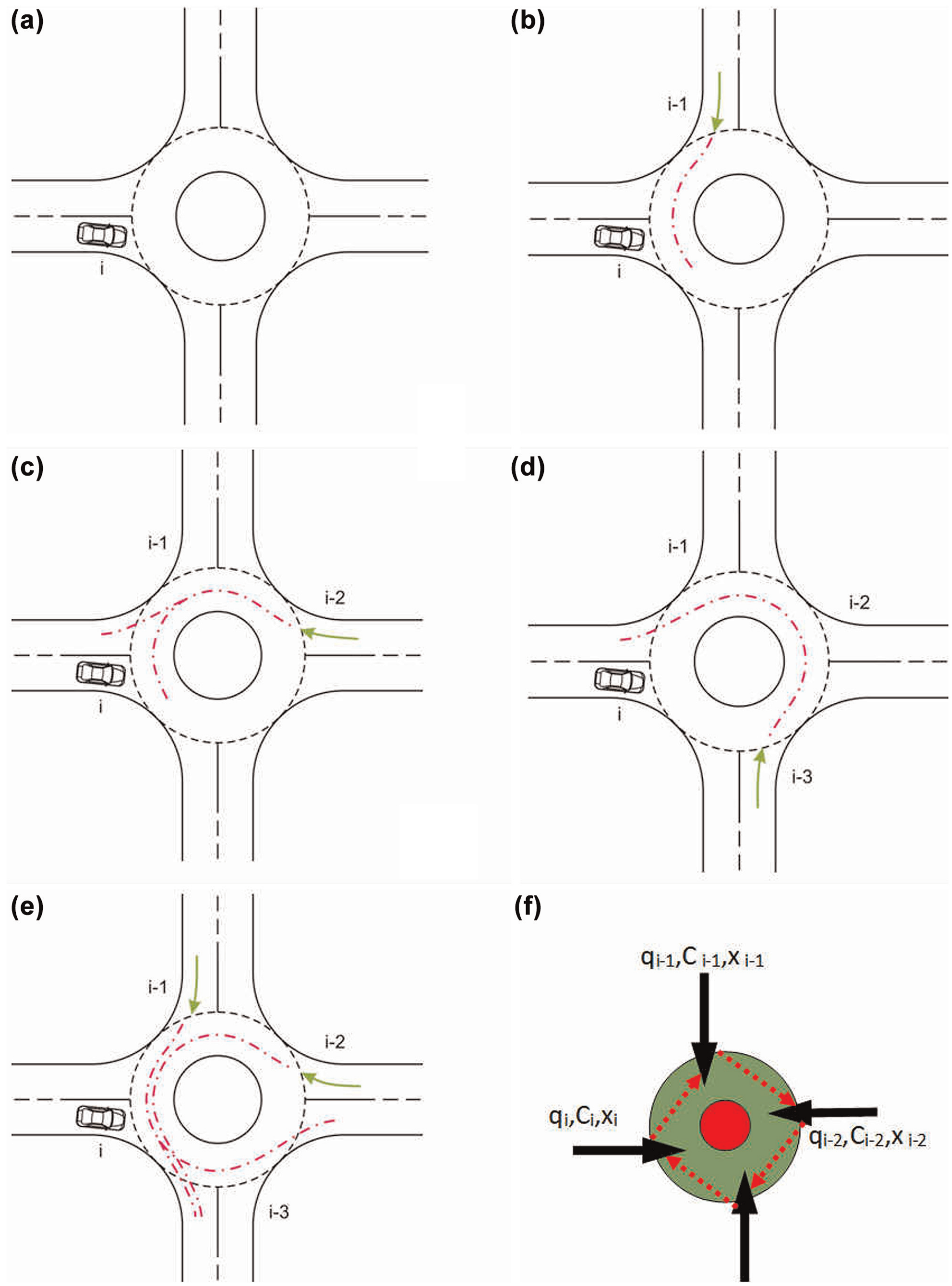

Figure 2. Illustration of the model.

in the case where no other vehicles are near or on the mini-roundabout. In this case, an uninterrupted flow of vehicles could enter the mini-roundabout. We call the average headway between two vehicles within such a stream the follow-up time, Δt .

$$\Delta t = \frac{3600}{C_{0,\ LV}}\ [\mathrm{s}] \tag{1}$$

where Δt = follow-up time = average headway between entering vehicles [s], $C_{0,LV}$ = basic capacity (LV/h). For ease of further derivations, we assume that $C_{0,LV}$ is the same for each of the four entries.

The basic capacity, $C_{0,LV}$, is reduced to the real capacity at times when other vehicles, which have priority over vehicle *i*, are approaching. Here we have to distinguish between vehicles from different movements.

Case 1: A Vehicle is Approaching or Waiting at the Left-Hand Entry (Figure 2b)

It is a peculiarity of the mini-roundabout that a vehicle approaching on the left-hand entry usually impedes the driver at the subject entry scanning for entry gaps – even if that vehicle is not yet on the circular lane. The reason is that, if a fast vehicle is approaching the left-hand entry, i–1 it may come into potential conflict with vehicles at the subject entry, i. In that case the i–1 vehicle would have priority even if, at the time of the i-vehicle's decision, it has not yet reached the circular lane. Observation also showed that a vehicle that is waiting at entry i–1 would be prioritized over a vehicle at the subject entry, i. Because of this, a reduced time is available for the i-vehicle. The proportion of the time remaining for the i-vehicle to enter the circular lane is

$$p_{0,\ i-1} = 1 - x_{i-1} = 1 - \frac{q_{i-1}}{C_{i-1,LV}} \qquad [-] \qquad (2)$$

where

i–1 = index of the entry left from the subject entry i (i–1 = 4 in the case of i = 1),

$p_{0,i-1}$ = probability that no vehicle is approaching or waiting at the entry i–1 (-),

q_{i-1} = traffic volume entering the circular lane at entry i–1, (LV/h) subject to q_{i-1} = Min{demand volume v_{i-1}, capacity $C_{i-1,\ LV}$},

$C_{i-1,LV}$ = capacity of entry i–1 (LV/h), and

x_{i-1} = degree of saturation of entry i–1 (-) = q_{i-1} / $C_{i-1,LV}$.

Note: Here and also later in this paper the volume, q_i, means the flow of vehicles that enter the circular lane from an entry, i, a value that is identical to demand volume v_i as long as $v_i \leqslant C_i$, and $q_i = C_i$ otherwise.

Thus, the capacity of the subject entry, i, accounting for vehicles approaching or waiting at the entry i–1 is

$$C_{i,LV} = C_{0,LV} \cdot (1 - x_{i-1}) = C_{0,LV} \cdot \left(1 - \frac{q_{i-1}}{C_{i-1,LV}}\right) \quad [\text{LV/h}] \qquad (3)$$

The degree of saturation x_{i-1} represents the impedance probability that a vehicle at entry i–1 prevents a vehicle at the subject entry, i, from entering the roundabout.

If there are vehicles at all four entries of the mini-roundabout at the same time, no vehicle can safely enter the roundabout. The probability of this stalemate/deadlock situation, $P_{deadlock}$, is the product of the impedance probabilities for all entries, that is,

$$P_{deadlock} = \prod\nolimits_{i\,=\,1\ldots4} x_i \qquad [-] \qquad (4)$$

Like at uncontrolled intersections with the right-hand-side priority rule, the probability of deadlock (Equation 4) at mini-roundabouts could be up to 8% (cf. the following calculation examples). However, due to exiting vehicles at the subject arm, i, the probability of deadlock is much smaller in reality (see the following section).

Case 2: Exiting Vehicles (Figure 2, c and d)

The capacity reduction of Case 1 (Equation 3) is, however, avoided if a vehicle from an entry $\neq i$–1, leaves the mini-roundabout by exit i. In that case the exiting vehicle closes the mini-roundabout to vehicles from entry i-1 without impeding vehicles from entry i. That means the proportion of time during which a vehicle from entry i-1 can impede the i-vehicle must be reduced by the proportion of time during which exiting vehicles are passing by entry i–1. This proportion can be estimated as

$$b_{i-1} = y_{i-2} \cdot a_{T,\ i-2} + y_{i-3} \cdot a_{L,\ i-3} \qquad [\text{s}] \qquad (5)$$

where

b_{i-1} = proportion of time during which vehicles exiting by exit i are blocking entry i–1 (-),

y_j = proportion of time during which vehicles from entry j are occupying a point on the circular lane (-) = $q_j/C_{c,ln}$,

$C_{c,ln}$ = capacity of the circular lane (LV/h) = 3,600/ $t_{\min}$,

$t_{\min}$ = minimum headway between vehicles on the circular lane (s),

q_j = traffic flow from entry j (LV/h) = min{demand volume v_j in entry j, capacity C_j},

$a_{T,j}$ = proportion of vehicles on entry j that drive through the roundabout in the opposite direction (through vehicles) (-), and

$a_{L,j}$ = proportion of vehicles at entry j that turn left at the roundabout (-).

j can be i - 2 or i – 3; and q_j and C_j as above (LV/h).

By this effect, the capacity-reducing effect of movement i–1 is decreased. Thus, the actual capacity of subject entry i accounting for vehicles approaching or waiting at the entry i–1 is

$$C_{i,\ LV} = C_{0,\ LV} \cdot (1 - x_{i-1} \cdot b_{i-1}) \qquad [\text{LV/h}] \qquad (6)$$

In this case, the term $x_{i-1} \cdot b_{i-1}$ represents the impedance probability that a vehicle at entry i– 1 is preventing a vehicle at subject entry i from entering the roundabout. The probability of the deadlock situation, $P_{deadlock}{}^{*}$ (cf. Equation 4) then is

$$P_{deadlock}{}^{*} = \prod\nolimits_{i\,=\,1\ldots4} (x_i \cdot b_i) \qquad [-] \qquad (7)$$

To reiterate, deadlock occurs if there is a vehicle approaching or waiting at each of the entries. Then – according to the assumption for Case 1 – none of the vehicles would be able to enter due to the fact that they all have a prioritized vehicle to their left. This is a theoretical case since, in reality, drivers will find a way to resolve this situation. Moreover, for realistic conditions with $x < 1$ and $b < 1$ this deadlock probability, $P_{deadlock}^{*}$, is very small (cf. the following calculations). Deadlock probability values are always below 0.03%, thus, the deadlock probability at mini-roundabouts can be considered irrelevant.

Obviously, considering parameter b_i for exiting vehicles at subject arm i will enhance the capacity significantly. Therefore, due to this operational mechanism, the capacity at mini-roundabouts is much higher than at an uncontrolled intersection with right-hand-side priority, where exiting vehicles at subject arm i are irrelevant. The total intersection capacity (TIC) of a mini-roundabout can be double that of an uncontrolled intersection, which in general is below 900 veh/h (cf. [*8*, *16*]).

Case 3: Priority Vehicles (Figure 2e)

A vehicle at subject entry i is impeded from entering the mini-roundabout during times when turning vehicles are passing by or approaching the entry point of the circular lane. Therefore, the capacity, C_i, derived so far must be reduced by the proportion of time during which vehicles (other than vehicles from entry i–1 that have already been considered in Cases 1 and 2) are passing by or approaching the entry point on the circular lane. This proportion of time is

$$p(\text{circulating vehicle}) = y_{i-2} \cdot a_{L,\, i-2} \qquad [-] \qquad (8)$$

where $a_{L,i\text{-}2}$ = proportion of left-turn vehicles on entry i - 2 (the opposite approach) (-).

Only periods that are free of circulating vehicles are available to the i-vehicle. That is,

$$p(\text{no circulating vehicle}) = 1 - y_{i-2} \cdot a_{L,\, i-2} \qquad [-] \quad (9)$$

In addition, the driver of the i-vehicle may be in doubt as to whether a vehicle exiting by arm i will really leave the circular lane. As a consequence, he may not fully use the gaps offered to him during this maneuver. We denote the proportion of cases in which this happens as z and we assume that there is no systematic difference in this value between the arms of a mini-roundabout. The value of z was analyzed at five mini-roundabouts in Germany by Baier et al. (*15*). The values for z varied between 0.13 and 0.36 with an average of 0.22.

From these considerations, we obtain an extension of Equation 6 for the final capacity of the subject entry i as follows:

$$\begin{aligned} C_{i,LV} = {} & C_{0,\, LV} \cdot (1 - x_{i-1} \cdot b_{i-1}) \cdot \\ & (1 - y_{i-2} \cdot a_{L,\, i-2} - y_{e,i} \cdot z) \qquad [\text{LV/h}] \end{aligned} \qquad (10)$$

where

$y_{e,i}$ = proportion of time during which vehicles exit into arm i (-) = $q_{e,j} \,/\, C_{c,ln}$,

$q_{e,i}$ = flow rate of vehicles leaving the mini-roundabout into arm i (LV/h),

$C_{c,ln}$ = capacity of the circular lane (LV/h) = 3,600/ $t_{\min}$, and

z = proportion of cases where the entering driver abstains from entering because of an exiting vehicle (-).

This equation describes the final capacity of entry i . The x-term depends on the capacity of the next upstream entry. Moreover, all y- and x-values depend on the capacity of the relevant entries by the limitation $q_i \leqslant C_i$ for all entries i . Thus, we get a system of four equations for i = 1, …, 4 where the results of each equation are mutually dependent on the results of the other equations (cf. Figure 2*f*). To get the solution for subject C_i, the values of all v_j (here, demand volumes), $a_{T,j}$, and $a_{L,i}$ (with j = 1, …, 4 for the number of all entries) and the parameters $t_{\min}$ and Δt must be given.

This equation system can only be solved iteratively because of the interrelated equations. To test the operational performance of a mini-roundabout in a case with given demand volumes, the four equations (Equation 10, for i = 1, …, 4) must be solved. This can easily be performed with an Excel spreadsheet using the Iterative Calculations option. Should the solution result in a capacity $C_i < v_i$ at one of the entries, then the mini-roundabout is overloaded. If C_i - v_i > 60 LV/h at each of the entries, sufficient performance of the intersection can be expected. A 60 LV/h margin was used here as a standard value that would provide an average delay below 50 s using one of the usual delay equations.

Within the system of equations established by Equation 10, $t_{\min}$ and Δt are the only model parameters. Their values must be obtained from field observations. Values have been estimated for Germany by Schmotz (*14*). These were originally intended for the HBS, where they were implemented into the capacity estimation procedure (*16*). With some fine-tuning, these values were used here for the following calculations: $t_{\min}$ = 2.8 s and Δt = 3.1 s.

Heavy Vehicles

To take into account very large vehicles, passenger car units instead of vehicles could be used in the equations. Then, the passenger car equivalents (pc-equivalent) for this model would have to be defined. As a first step, the pc-equivalent for a single-unit truck or bus might be 1.5,

Figure 3. Examples of HVs crossing a mini-roundabout by driving over the central island.

and for an articulated truck or bus a pc-equivalent of 2 might be used, as recommended by HBS (*16*). This approach would not, however, be in line with the kind of traffic operations at mini-roundabouts.

At a mini-roundabout, HVs, like buses or large articulated trucks, are forced to drive over the central island (see Figure 3). In doing so, they close the mini-roundabout to all other traffic. Thus, these large vehicles have another capacity-reducing effect, which is very different from the impact of smaller vehicles. Therefore, the model could be enhanced by the following considerations.

A HV entering a mini-roundabout prevents all vehicles from the other entries from going ahead. We assume that an HV needs a time of t_{HV} to finish its maneuver and to clear the intersection completely. These times, t_{HV}, summed for all entries, are not available for other vehicles coming from the entries. Thus, the impedance factor from HVs is

$$f_{HV} = \left(1 - \frac{t_{HV}}{3600} \cdot \sum_{all\ entries\ j} q_{j,\ HV}\right) \qquad [-] \qquad (11)$$

Of course, t_{HV} is a parameter that requires calibration from field measurements. Based on preliminary observations we assume $t_{HV} = 6\,s$ for the following calculation examples.

One might argue that a HV going straight over a mini-roundabout would not prevent the opposite through traffic or right-turners from proceeding into the mini-roundabout and that, thus, Equation 11 would overestimate the influence of HVs. However, observation suggests that drivers from those movements hesitate to enter the roundabout when HVs are crossing the intersection. Therefore, as a simplification, it is proposed to continue with Equation 11. If, however, this concern ought to be addressed, the volume of through – and especially right-turning – HV-traffic could be omitted in the summation of Equation 11; this, however, would increase the complexity of the equations significantly.

It should be noted that LV traffic has to be managed during HV-free time, which has a proportion of f_{HV} of the total time. As a consequence, the basic parameters $C_{0,LV}$ and $C_{c,ln}$ in Equation 1 to 10 must be reduced by a factor, f_{HV}. That is, using $C_{0,LV}{}^{*} = C_{0,LV} \times f_{HV}$ and $C_{0,ln}{}^{*} = C_{c,ln} \times f_{HV}$ to perform the calculations in Equation 10 to obtain the capacity $C_{i,LV}{}^{*}$ to account for the influence of HVs. It is assumed that the demand volume for HVs could always be accommodated. Thus the total capacity, $C_{i,}$ of entry i in veh/h is the sum of $C_{i,LV}{}^{*} + q_{i,HV}$. However, this assumption is only justified as long as the whole system is operating below or at most at capacity.

Total Roundabout Capacity

Sometimes, it is desirable to know the capacity of the intersection as a whole. TIC is reached as soon as $q_i = C_i$ at one of the entries, i . To test the operational performance of a mini-roundabout with given demand volumes, the four entry capacities (Equation 10 for $i = 1, \ldots, 4$) must be solved. This can easily be performed using the Solver tool within Excel.

Example Calculations

The following examples consider a four-arm mini-roundabout at the cross point of a major and a minor street. It is assumed that on both the major and minor street both directions carry the same traffic volumes. For our examples, the proportions for the turning movements were chosen as 20%, 60%, and 20% for the major street and 33%, 34%, and 33% for the minor street (right/through/left turners).

The proportion of minor to major street volume was chosen as a variable. This parameter is varied from 0% to 100%: 100% means that the minor street carries the same traffic volume as the major street.

Actual Capacity of Entries

The actual capacity of an entry is calculated from Equation 10 using the given traffic demand volumes for all entries.

Calculations for the major/minor entry capacities with a given total intersection demand $v_{inter} = 1{,}480$ veh/h were conducted (Figure 4). This total demand was balanced between the four entries according to a variable

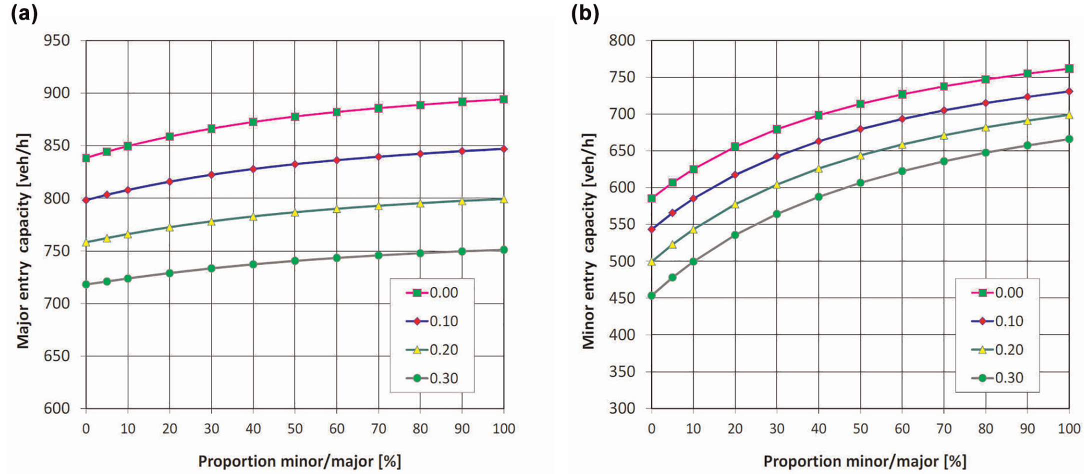

Figure 4. (*a*) Capacities at the major entries and (*b*) capacities at the minor entries (for different values of z with v_{inter} = 1,480 veh/h and $a_{HV,major}$ = 0.10).

proportion of minor to major street volumes. The proportion of HVs on the major street is allways $a_{HV,major} = 0.10$ and on the minor street $a_{HV,minor} = 0.05$. Four values of z (0.00, 0.10, 0.20, and 0.30), which is the proportion of entering drivers impeded by vehicles leaving the mini-roundabout by the same arm, are used. With these assumptions, Figure 4*a* describes the entry capacity for the major street entries whereas Figure 4*b* shows the entry capacity for the minor street entries.

From these results, it can be concluded that the entry capacities are sensitive to the directional distribution of traffic. The rate of capacity reduction as it is caused by increasing z is nearly independent of the distribution of traffic volumes over the two intersecting streets.

For the same input parameters, the deadlock probabilities of the mini-roundabout, accounting for exiting vehicles by entry i, $P_{deadlock}^{*}$ (Equation 7), are illustrated in Figure 5*a*. Those probabilities are very small. Those small probabilities can be considered as irrelevant. Thus, a deadlock of a mini-roundabout – under the assumption of no pedestrians at the exits – can be excluded. Without taking account of the exiting vehicles at the subject arm i - this is rather unrealistic at mini-roundabouts - the deadlock probabilities $P_{deadlock}$ (Equation 4) of the mini-roundabout are much larger. They can get values of up to 8% (cf. Figure 5*b*). The remarkable difference between both values underlines the impact of exiting vehicles toward effective operation of mini-roundabouts.

To study the influence of HVs, several values to denote the proportion of HVs (0.0, 0.05, 0.10, and 0.15) on the major street, $a_{HV,major}$, were used (Figure 6). Again, it is assumed that the proportion of HVs on the minor street is half that of the major street value and an average value of $z = 0.22$ (found to be typical [*15*]) was used.

For comparison, the actual entry capacities for the same input parameters were calculated according to the model in the HBS (*16*) (see Figure 7). The differences relative to the entry capacities from the proposed model (Figure 6) could be clearly identified. This was expected because the HBS model does not consider the mode of operation at mini-roundabouts realistically.

Once the actual capacities are calculated, the delays and therefore the traffic qualities at the entries can be estimated together with the corresponding traffic volumes of the entries from standardized delay functions, for example, Equations 22-17 in the HCM (*13*).

Total Intersection Capacity

TIC is the maximum traffic volume of the whole intersection that can be maintained without oversaturation at any entry. It can be obtained by stepwise rising of the traffic volume, q_i, at all entries proportionally. TIC is reached as soon as $q_i = C_i$ at one of the entries. TIC, then, is the sum of the corresponding traffic flows, q_i, across all entries.

For TIC, calculations were made using different values of of z and $a_{HV,major}$. With a constant value of $a_{HV,major} = 0.10$, calculations for the four values of z (0.0, 0.1, 0.20, and 0.3) are conducted (Figure 8*a*). Accounting for the influence of HVs four values for the proportion of HVs (0.0, 0.05, 0.1, and 0.15) on the major street, $a_{HV,major}$, are used with a value of $z = 0.22$ (Figure 8*b*). In each case, it is assumed that the proportion of HVs on the minor street is always half that of the major street value. The discontinuity in the curves of Figure 8 is related to the specific street that caused the limitation in capacity. On the left side of the breakpoint,

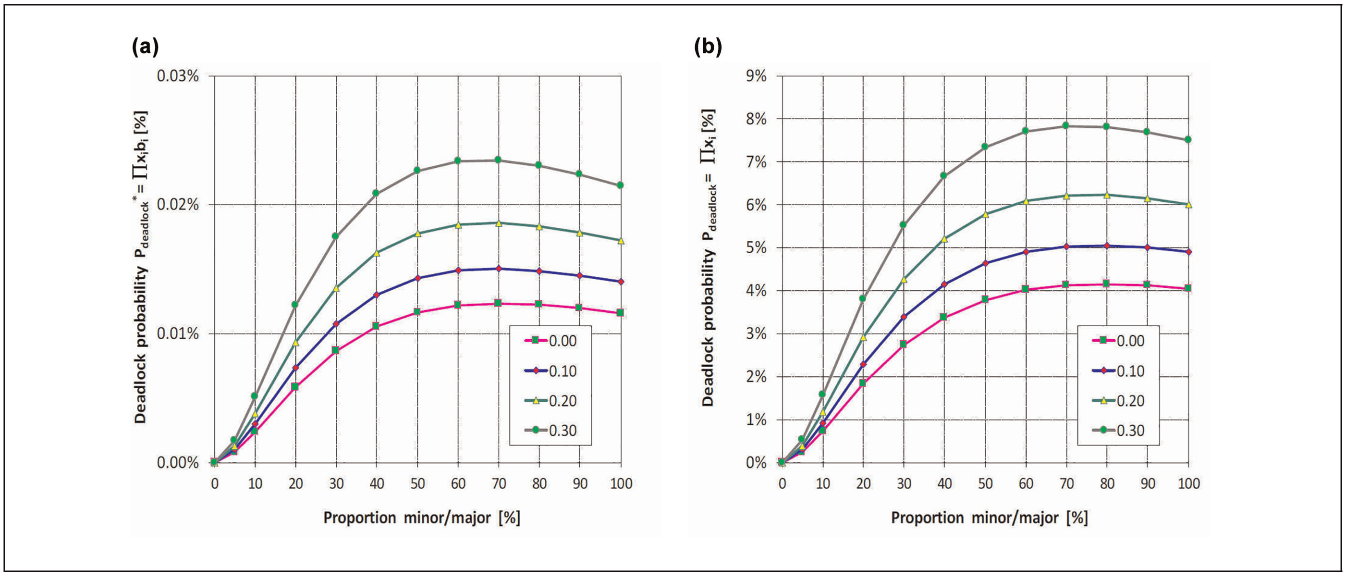

Figure 5. (*a*) Deadlock probability, $P_{deadlock}{}^*$ (Equation 7), accounting for vehicles exiting by entry *i* and (*b*) deadlock probability, $P_{deadlock}{}^*$ (Equation 4), not accounting for exiting vehicles (for different values of *z* with v_{inter} = 1,480 veh/h and $a_{HV,major}$ = 0.10).

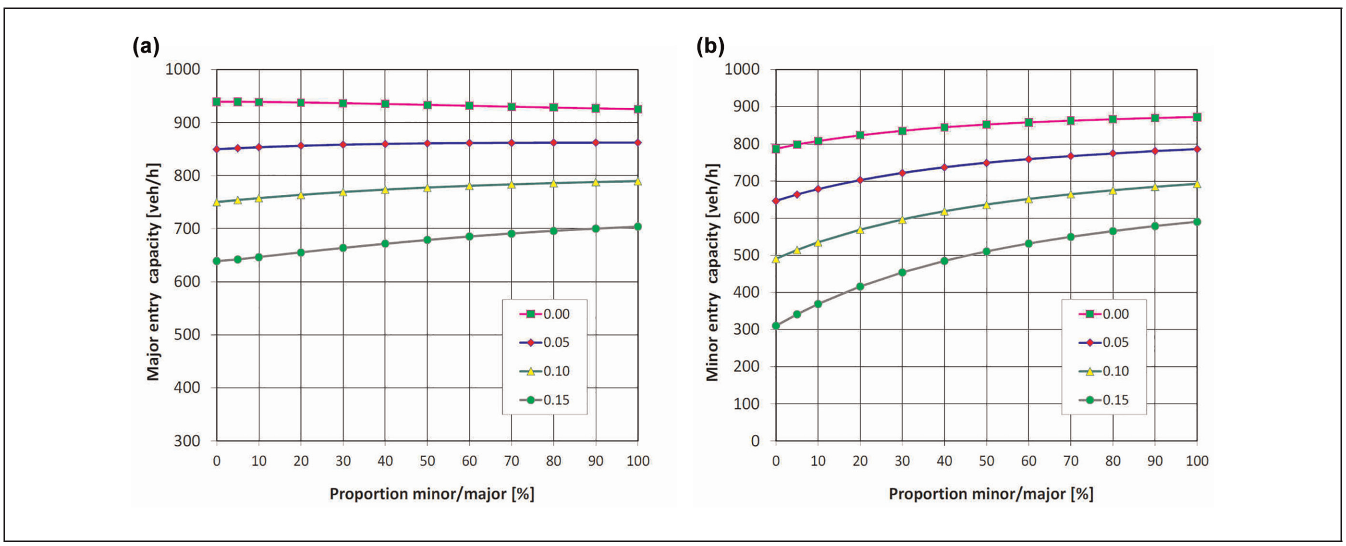

Figure 6. (*a*) Capacities at the major street entries and (*b*) capacities at the minor street entries (for different values of $a_{HV,major}$ with v_{inter} = 1,480 veh/h and z = 0.22).

the major street entries generate the limitation, whereas on the right side, the minor streets entrances reach capacity.

It can clearly be concluded that the TIC of the mini-roundabout is very sensitive to the directional distribution of traffic. The TIC of a mini-roundabout reaches its maximum in an area where the traffic volumes of both streets are on a nearly similar level. With $a_{HV,major}$ = 0.00 and *z* = 0.22 (cf. Figure 8*b*) we obtained a TIC of about 2,200 veh/h for the given turning volume proportions. For $a_{HV,major}$ = 0.10, TIC was about 1,850 veh/h.

Conclusion

A new model for capacity calculation for mini-roundabouts has been developed. On the one hand, it is based on quite simplified assumptions. On the other, it is better adapted to the mechanisms of traffic operation at mini-roundabouts than existing methods. The model includes a feature that focuses on the specific operational conditions of larger vehicles at such compact intersections. Also the effect that exiting vehicles may create opportunities for vehicles on the entry to start into the the mini-roundabout has been incorporated. The

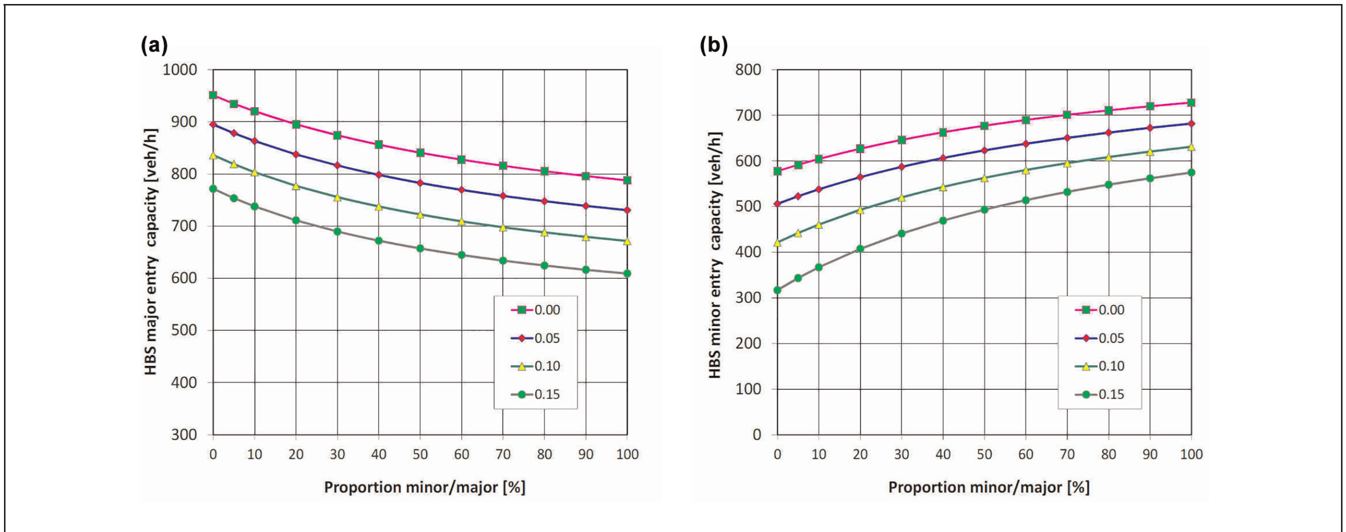

Figure 7. (*a*) Capacities at the major entries from HBS (*16*) and (*b*) capacities at the minor entries from HBS (*16*) (for different values of $a_{HV,major}$ with v_{inter} = 1,480 veh/h).

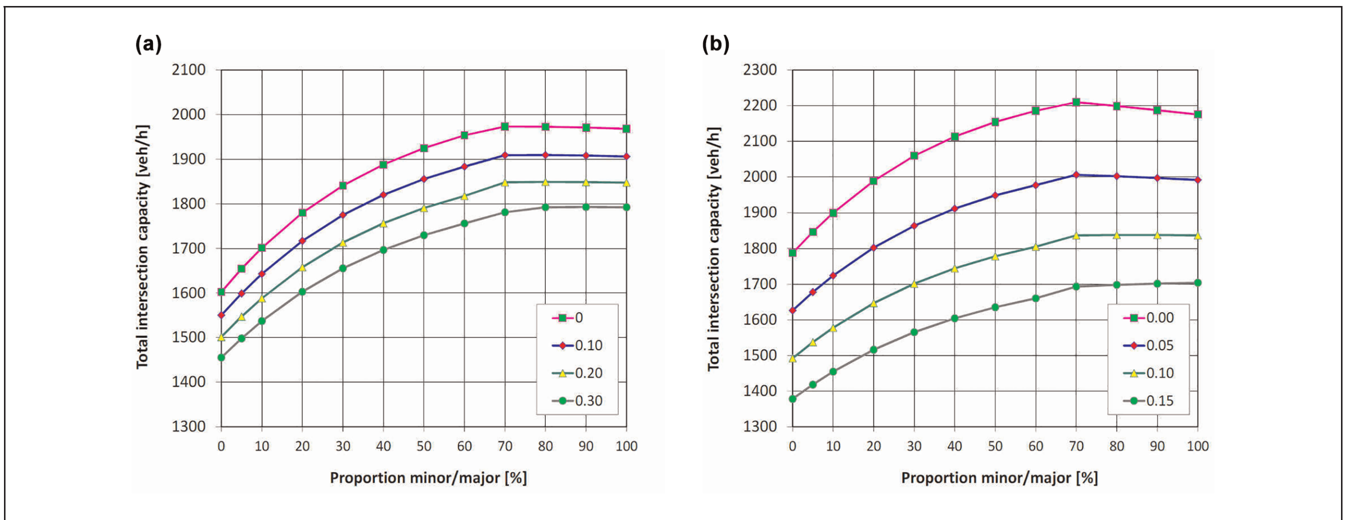

Figure 8. (*a*) Total intersection capacity of a mini-roundabout for different values of z (0, …, 0.30) with $a_{HV,major}$ = 0.10 and (*b*) total intersection capacity of a mini-roundabout for different values of $a_{HV,major}$ (0, …,0.15) with z = 0.22.

derivations led to a set of linear equations that could be solved iteratively. The model was used with parameters adapted for German guidelines for several examples.

The model could be further modified to capture specific cases of HV-operation at mini-roundabouts (right turning, through traffic, etc.), and attempts in that direction have been made. This would, however, lead to a level of complexity that does not seems justified since, usually, the proportion of very large trucks at urban roundabouts is quite small and, thus, the results in real cases will not be sensible to these specific characteristics.

Pedestrians crossing the arms of mini-roundabouts have not been addressed in this model to date. Under this premise the deadlock probability at mini-roundabouts is very small. Thus, for real world situations, the risk of a deadlock can be considered irrelevant. In cases of significant pedestrian movement, the technique published by the authors might be applied (*19*, *20*).

At this moment, the new method is only a proposal for further improvement of traffic performance analysis at mini-roundabouts. Using the parameters given here, the magnitude of results is rated as being realistic. However, more empirical research is required to calibrate the parameters within the model and to test the potential for further adaption to reality by dropping some of the restrictive assumptions (e.g., identical basic capacity $C_{0,LV}$ at all entries, an HV blocks all entries simultaneously). The technique also requires additional testing to confirm applicability in practice.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: W. Brilon, N. Wu; analysis and interpretation of results: W. Brilon, N. Wu; draft manuscript preparation: W. Brilon, N. Wu. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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