Capacity of Mini-Roundabouts

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ABSTRACT

A new calculation method based on the concept of Additive Conflict Flows (ACF procedure) was developed for the determination of capacities of mini-roundabouts. This method was adapted from the method BRILON/ WU (2002) developed for two-way stop-controlled intersections. The new method makes it possible to calculate the capacities of mini-roundabout entries and exits while taking crossing pedestrian streams into account. The deterministic model was calibrated with the help of survey data observed by video recordings at ten urban mini-roundabouts. Therefore, empirical capacities were derived from thirty-second periods under conditions of steady queuing. By traffic observations it was also possible to quantify the entry capacity reducing influence of vehicles exiting at the same branch. This fact was considered by means of the calibration. The calibrated calculation method was verified by microscopic traffic flow simulations. The adaption of the ACF procedure for mini-roundabouts, the calibration by survey data and the conformity of the new deterministic model to the simulation results are described in this paper.

1 INTRODUCTION

In case where little space is available, mini-roundabouts present an alternative to conventional roundabouts or intersections without traffic lights. They can also be considered as an alternative to signalized intersections with low traffic density. Due to the small diameter of a mini-roundabout (13 to 22 meters in Germany), its central island has to be traversable to allow heavy vehicles to pass the intersection in each direction. In Germany mini-roundabouts are only supposed to be used in cases of insufficient space for small roundabouts with non-traversable central island (RASt 2006).

So far there is no empirically verified analytic method for predicting entry capacities of mini-roundabouts in Germany. However those capacities are obligatory for average control delay computation and Level of Service (LOS) determination. Therefore the German Federal Highway Research Institute (BASt) initiated and funded a research project in order to fill this gap (BAIER et. al. 2010). As a major part of this study the capacities of ten urban mini-roundabouts were measured and analyzed.

Based on this research project a new method for the analysis of mini-roundabouts operations is derived. The new method bases on the concept of Additive Conflict Flows (ACF). This method was first developed for signalized intersections (GLEUE 1972) and was later modified for two-way stop-controlled intersections (BRILON/ WU 2002). The adaptation of this method for mini-roundabouts is described in this paper.

The new procedure makes it possible to consider the effect of crossing pedestrians and the degree of priority (i.e. the degree of acceptance of right of way) given to them by car drivers. The procedure was calibrated using empirical survey data and its practicality subsequently verified and evaluated by means of a simulation study.

2 ACF PROCEDURE

2.1 BASICS

In order to illustrate the basics of Additive Conflict Flows method (*ACF procedure*), a simplified intersection of two one-way roads, where two streams can pass over, will be examined (Fig. 1). A conflict is treated as the intersection of several movements which have to pass the same area within the intersection. The vehicles from these movements have to pass the area one after the other. The set of movements which are involved in the same conflict is called a conflict group (BRILON/ WU 2002).

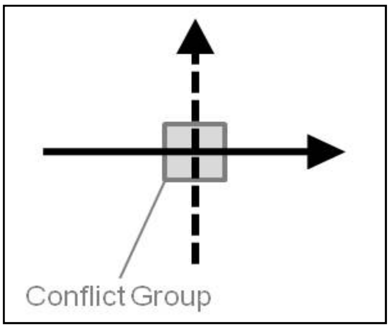


Fig. 1: Conflict in Case of two crossing One-Way Roads

The shared conflict area can only be used by minor-stream vehicles, when the conflict area is not occupied by stationary or discharging major-stream vehicles (probability $p_{0,s}$) or rather by approaching major-stream vehicles (probability $p_{0,a}$). The probability p_0 that the area is not blocked by the priority traffic stream is estimated by the relationship:

$$p_0 = p_{0,s} \cdot p_{0,a} \tag{1}$$

If the time $t_{s,i}$ which is needed by a competing vehicle of the stream i to pass over the conflict area and the traffic volume of that stream v_i are known, the proportion of occupancy of the conflict area $B_{s,i}$ by the traffic stream i and therefore the probability $p_{0,s}$, that the area is not blocked by queuing or discharging major-stream vehicles, can be characterized as follows:

$$p_{0,s} = 1 - B_{s,i} = 1 - \frac{v_i \cdot t_{s,i}}{3600} \tag{2}$$

Assuming a time period $t_{a,i}$, during which the conflict area is blocked by an approaching major stream vehicle, the probability $p_{0,a}$ of blockage due to approaching vehicles in major streams can be derived if the distribution of gaps in the major streams is given. This probability distribution can be defined via the gap-acceptance-theory as a function of the priority stream volume v_i, which is based on the assumption that the gaps in the major stream are exponentially distributed.

$$p_{0,a} = e^{-B_{a\,i}} = e^{-\frac{v_i \cdot t_{a,i}}{3600}} \tag{3}$$

The capacity of a minor stream j results from the theoretical maximum number of minor stream vehicles that can pull into the intersection (C_{max}) and the probability p_0, that the conflict area is not blocked by vehicles which have right of way. C_{max} results from the average time t_b required for a side stream vehicle to freely flow off. This time value can be estimated by the follow-up time value based on the gap-acceptance theory.

$$C = C_{max} \cdot p_0 = \frac{3600}{t_b} \cdot p_0 \tag{4}$$

2.2 DETERMINISTIC MODEL FOR MINI-ROUNDABOUTS

In the following, a calculation method for mini-roundabouts on the basis of ACF procedure will be described using the example of a four-arm mini-roundabout. For this purpose it is necessary to convert the intersection into the vehicle circulation flows 1 to 12, as well as the crossing pedestrian flows at the entry PEN1 to PEN4 and the crossing pedestrian flows at the exit PEX1 to PEX4, as shown in Fig. 2. Crossing bicycle streams will not be considered because, due to the limited space at mini-roundabouts, bicycle traffic and motor traffic share the circulatory roadway. The capacity for bicycle traffic will therefore be determined along with that for motor vehicle streams. According to the German Highway Code crossing pedestrians do not have priority over vehicles at the entries but do have priority at the exits if there are no crosswalks. When crosswalks exist, pedestrians have priority over vehicular traffic both at the entries and at the exits.

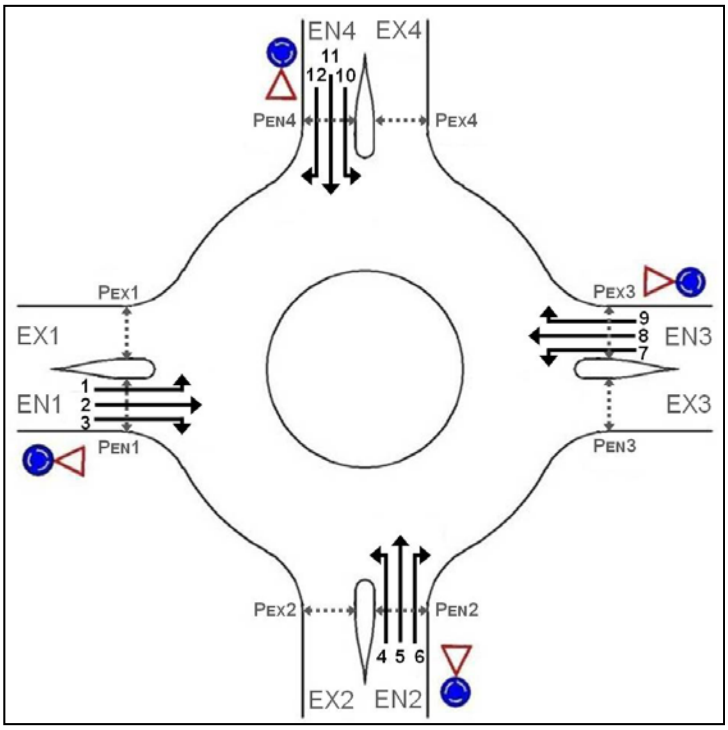


Fig. 2: Flow Stream Definitions

At three-arm mini-roundabouts the calculation algorithm is simplified – the traffic streams 10, 11, 12, PEN4 and PEX4 cease to apply.

Conflict Matrix

A matrix is used to depict the right of way at mini-roundabouts. This conflict matrix displays the degree of acceptance of right of way of a stream compared to another stream. The basis for the design of the conflict matrix for roundabouts is the conflict matrix for intersections according to MILTNER (2003). In accordance with the definition proposed in Fig. 2, the traffic in a roundabout is divided into 20 streams. Fig. 3 shows the conflict matrix for mini-roundabouts without crosswalks in the approach roads and exits. The entering streams have to give way to the traffic within the roundabout. A conflict factor A_{ji} = 1 implies total inferior of stream j to the stream i within the roundabout. If there are vehicles of a traffic stream already in the circle lane, these have priority over the traffic streams in the entrances. Hence, a change takes place in the priority of a traffic stream between the entry and the circulatory roadway. Therefore, the condition “if A_{ji}=1 then A_{ij}=0”, which applies to two-way stop-controlled intersections, does not apply to the conflict matrix for roundabouts (cf. HANTSCHEL (2009)).

Conflict-factor A_{ij}	**Conflict-Matrix for Mini-Roundabouts** without crosswalk																			
	analyzed flow j																			
	EN1			EN2			EN3			EN4										
conflicting flow i	1	2	3	4	5	6	7	8	9	10	11	12	P_{EN1}	P_{EN2}	P_{EN3}	P_{EN4}	P_{EX1}	P_{EX2}	P_{EX3}	P_{EX4}
1				1	1	1	1	1	1	*0*	*0*	*0*	1							0
2				1	1	1	*0*	*0*	*0*				1						0	
3				*0*	*0*	*0*							1					0		
4	*0*	*0*	*0*				1	1	1	1	1	1		1			0			
5							1	1	1	*0*	*0*	*0*		1						0
6							*0*	*0*	*0*					1					0	
7	1	1	1	*0*	*0*	*0*				1	1	1			1			0		
8	*0*	*0*	*0*							1	1	1			1		0			
9										*0*	*0*	*0*			1					0
10	1	1	1	1	1	1	*0*	*0*	*0*							1			0	
11	1	1	1	*0*	*0*	*0*										1		0		
12	*0*	*0*	*0*													1	0			
P_{EN1}	0	0	0																	
P_{EN2}				0	0	0														
P_{EN3}							0	0	0											
P_{EN4}										0	0	0								
P_{EX1}				1				1				1								
P_{EX2}			1				1				1									
P_{EX3}		1				1				1										
P_{EX4}	1				1				1											

Fig. 3: Conflict Matrix for Mini-Roundabouts without Crosswalks

If the real degree of acceptance of right of way is known, the conflict factors A_{ji} can be adapted for the corresponding movement (proportion from 0 to 1). Thus the effect of exiting vehicles on those entering at the same arm can also be considered in the conflict matrix (values printed in italics in Fig. 3).

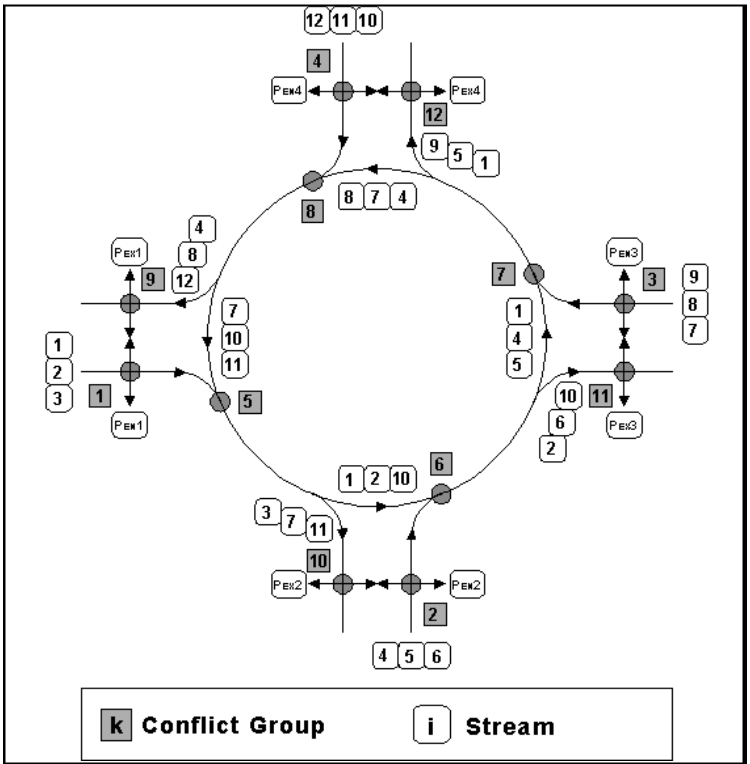
Determination of Capacity

If the classification of the intersection area into 12 independent conflict groups according to BRILON/ WU (2002) is applied to mini-roundabouts, the area of a roundabout can also be divided into 12 conflict groups (cf. Fig. 4). The streams i are separately assigned to the conflict groups k for the entering and exiting traffic.

The calculation instructions of ACF procedure explained in section 2.1 apply to every conflict group. Thus, a road user in a minor stream cannot enter the roundabout until the conditions for freedom of both the first (probability $p_{0,s}$ according to equation (2)) and the second kind (probability $p_{0,a}$ according to equation (3)) are satisfied.

Furthermore, it is assumed that for a road user entering the mini-roundabout only the conflict areas in the access roads are relevant. This means that a road user will enter the circulatory roadway even if in the exit at which he wishes to leave the roundabout, pedestrians are crossing. Consequently, two steps are required for determining the quality of the traffic flow. The first step is to determine the capacity of the entry C_{EN} and the second step is to establish the capacity of the exit C_{EX}. The minimum of both capacities constitutes the total capacity C of the stream under consideration:

$$C = min \begin{Bmatrix} C_{EN} \\ C_{EX} \end{Bmatrix} \tag{5}$$



Entry				Exit	
k	i	k	i	k	i
1	1, 2, 3, $P_{EN}1$	5	1, 2, 3, 7, 10, 11	9	4, 8, 12, $P_{EX}1$
2	4, 5, 6, $P_{EN}2$	6	1, 2, 4, 5, 6, 10	10	3, 7, 11, $P_{EX}2$
3	7, 8, 9, $P_{EN}3$	7	1, 4, 5, 7, 8, 9	11	2, 6, 10, $P_{EX}3$
4	10, 11, 12, $P_{EN}4$	8	4, 7, 8, 10, 11, 12	12	1, 5, 9, $P_{EX}4$

Fig. 4: Conflict Groups at Mini-Roundabouts and assignment of Streams i to Conflict Groups k

Entry Capacity

Since the capacities of the three streams of an entry road are subject to the same dependencies and these therefore also show the same conflict factors A_{ij} (cf. Fig. 3), it is possible to conduct a combined calculation of the traffic stream capacities of one entry road. However, the capacity calculation needs to take account of different $t_{b,j}$ values because of the differing vehicle fleet mix. This leads to different maximum capacities (C_{max}) for the various streams. The formula developed by HARDERS (1968) for the calculation of shared lanes makes allowance for the differing vehicle fleet mix in the individual traffic streams in one entry road. This results in four universally valid formulas for calculating entry capacities for all 12 vehicle streams at mini-roundabouts (see (6) to (9)).

$C_{EN1}=3600\cdot p_{0,123}\cdot\frac{v_1+v_2+v_3}{v_1\cdot t_{b,1}+v_2\cdot t_{b,2}+v_3\cdot t_{b,3}}$ and $p_{0,123}=\left(1-A_{PEN1,123}\cdot B_{s,PEN1}\right)\cdot\left(1-\left(A_{7,123}\cdot B_{s,7}+A_{10,123}\cdot B_{s,10}+A_{11,123}\cdot B_{s,11}\right)\right)$ $\cdot e^{-\left(A_{4,123}\cdot B_{a,4}+A_{7,123}\cdot B_{a,7}+A_{8,123}\cdot B_{a,8}+A_{10,123}\cdot B_{a,10}+A_{11,123}\cdot B_{a,11}+A_{12,123}\cdot B_{a,12}\right)}$		(6)
$C_{EN2}=3600\cdot p_{0,456}\cdot\frac{v_4+v_5+v_6}{v_4\cdot t_{b,4}+v_5\cdot t_{b,5}+v_6\cdot t_{b,6}}$ and $p_{0,456}=\left(1-A_{PEN2,456}\cdot B_{s,PEN2}\right)\cdot\left(1-\left(A_{1,456}\cdot B_{s,1}+A_{2,456}\cdot B_{s,2}+A_{10,456}\cdot B_{s,10}\right)\right)$ $\cdot e^{-\left(A_{1,456}\cdot B_{a,1}+A_{2,456}\cdot B_{a,2}+A_{3,456}\cdot B_{a,3}+A_{7,456}\cdot B_{a,7}+A_{10,456}\cdot B_{a,10}+A_{11,456}\cdot B_{a,11}\right)}$		(7)
$C_{EN3}=3600\cdot p_{0,789}\cdot\frac{v_7+v_8+v_9}{v_7\cdot t_{b,7}+v_8\cdot t_{b,8}+v_9\cdot t_{b,9}}$ and $p_{0,789}=\left(1-A_{PEN3,789}\cdot B_{s,PEN3}\right)\cdot\left(1-\left(A_{1,789}\cdot B_{s,1}+A_{4,789}\cdot B_{s,4}+A_{5,789}\cdot B_{s,5}\right)\right)$ $\cdot e^{-\left(A_{1,789}\cdot B_{a,1}+A_{2,789}\cdot B_{a,2}+A_{4,789}\cdot B_{a,4}+A_{5,789}\cdot B_{a,5}+A_{6,789}\cdot B_{a,6}+A_{10,789}\cdot B_{a,10}\right)}$		(8)
$C_{EN4}=3600\cdot p_{0,101112}\cdot\frac{v_{10}+v_{11}+v_{12}}{v_{10}\cdot t_{b,10}+v_{11}\cdot t_{b,11}+v_{12}\cdot t_{b,12}}$ and $p_{0,101112}=\left(1-A_{PEN4,101112}\cdot B_{s,PEN4}\right)\cdot\left(1-\left(A_{4,101112}\cdot B_{s,4}+A_{7,101112}\cdot B_{s,7}+A_{8,101112}\cdot B_{s,8}\right)\right)$ $\cdot e^{-\left(A_{1,101112}\cdot B_{a,1}+A_{4,101112}\cdot B_{a,4}+A_{5,101112}\cdot B_{a,5}+A_{7,101112}\cdot B_{a,7}+A_{8,101112}\cdot B_{a,8}+A_{9,101112}\cdot B_{a,9}\right)}$		(9)
and: $t_{b,j}$	discharging service time for movement j according to equation (14)	[s]
$A_{i,j}$	conflict factor according to Fig. 3	[-]
$B_{s,i}$	occupancy by queuing movement i according to equation (2)	[-]
$B_{a,i}$	occupancy by an approaching vehicle in major movement i according to equation (3)	[-]

Exit Capacity

The capacity of the exit roads depends on the potential follow-up time between the vehicles of the traffic streams under consideration ($t_{b,j}$), as well as on the pedestrian streams crossing the exit (P_{EX1} to P_{EX4}). Since it is assumed that pedestrians approaching the conflict area have no capacity-reducing influence on the vehicular streams, it is not necessary to determine the probability for freedom of the second kind (probability $p_{0,a}$). As for the calculation of entry capacities, there are also four universally valid formulas for determining the exit capacities – see equations (10) to (13).

$C_{EX1}=\left(3600\text{-}A_{PEX1,4812}\cdot B_{s,PEX1}\right)\cdot\frac{v_4+v_8+v_{12}}{v_4\cdot t_{b,4}+v_8\cdot t_{b,8}+v_{12}\cdot t_{b,12}}$	(10)
$C_{EX2}=\left(3600\text{-}A_{PEX2,3711}\cdot B_{s,PEX2}\right)\cdot\frac{v_3+v_7+v_{11}}{v_3\cdot t_{b,3}+v_7\cdot t_{b,7}+v_{11}\cdot t_{b,11}}$	(11)
$C_{EX3}=\left(3600\text{-}A_{PEX3,2610}\cdot B_{s,PEX3}\right)\cdot\frac{v_2+v_6+v_{10}}{v_2\cdot t_{b,2}+v_6\cdot t_{b,6}+v_{10}\cdot t_{b,10}}$	(12)
$C_{EX4}=\left(3600\text{-}A_{PEX4,159}\cdot B_{s,PEX4}\right)\cdot\frac{v_1+v_5+v_9}{v_1\cdot t_{b,1}+v_5\cdot t_{b,5}+v_9\cdot t_{b,9}}$	(13)
and: $t_{b,j}$ discharging service time for movement j according to equation (14) $A_{i,j}$ conflict factor according to Fig. 3 $B_{s,i}$ occupancy by queuing movement i according to equation (2)	[Fz/h] [-] [-]

Adaption of Time Values t_b and t_s

For determining the capacity of the entries and exits, the time values are of key importance in the ACF procedure. Basically it is assumed that the time value t_b is equivalent to the follow-up time. However, the t_s and t_a values are not directly measurable time values and have to be calibrated on the basis of empirical data (cf. 2.3).

In order to take account of the vehicle fleet mix in the various vehicle streams, it is necessary to adjust the time values t_b and t_s. Using the ACF procedure, the time values have to be adjusted to correspond to the influence of the different types of vehicles, analogously to the conversion of traffic volume figures from veh/hr into pcu/hr described in the German Highway Capacity Manual, HBS (2001). There is no conversion of the approach time t_a because the gap choice of a road user in a minor stream is independent of the type of the approaching major-stream vehicle. The conversion is carried out using the equation (14).

$t_{s,i}=f_{PE,i}\cdot t^*_{s,i}$ $t_{b,i}=f_{PE,i}\cdot t^*_{b,i}$	(14)
and: $t_{s,j}$ service time for a road user of movement i passing over a conflict group under consideration of vehicle fleet mix $t_{b,i}$ discharging service time for a road user of movement i under consideration of vehicle fleet mix $f_{PE,i}$ factor representing vehicle fleet mix of movement i according to equation (15) $t^*_{s,j}$ service time for a road user of movement i passing over a conflict group $t^*_{b,i}$ discharging service time for a road user of movement i	[s] [s] [-] [s] [-]
$f_{PE,i}=\frac{0{,}5\cdot q_{i,Bicyle}+q_{i,Motorbike}+q_{i,Passenger\ Vehicle}+1{,}7\cdot q_{i,Heavy\ Vehicle}}{q_{i,Bicyle}+q_{i,Motorbike}+q_{i,Passenger\ Vehicle}+q_{i,Heavy\ Vehicle}}$	(15)
and: $q_{i,k}$ volume of traffic mode k of movement i	[Fz/h]

2.3 CALIBRATION OF THE DETERMINISTIC MODEL

Time Values

The calibration was based on traffic surveys conducted at 10 mini-roundabouts. Using video observation it was possible to analyze a total of 20 hours of traffic movements. The traffic flows that formed the basis of this study are the entry flow under conditions of steady queuing in the entry and the corresponding conflict flow rate. The conflict flow rate takes account of the circulation flow across the entry as well as vehicles exiting into the same arm. The entry flow counts were measured on a thirty-second basis. Owing to the rare occurrence of capacity overload on mini-roundabouts, the utilization of one-minute periods did not result in a statistically verified database. By means of capacity analyses of two-lane roundabouts, BRILON/ GEPPERT (2010) have demonstrated that the capacity of roundabouts can also be estimated reliably using thirty-second periods under conditions of steady queuing. In all, the study provided 923 thirty-second periods of capacity data from a total of 10 mini-roundabouts.

By minimizing square deviation between the empirical capacities and the capacities calculated on the basis of ACF procedure, the time values t_s and t_a were calibrated. The time value t_b was measured directly as the interval between the front of a vehicle leaving the entry and the front of the immediately following vehicle arriving at the entry (under conditions of steady queuing). The time-value t_s for pedestrian streams was also measured, this being the time taken by pedestrians to cross the entry or exit of a mini-roundabout. The results are shown in Fig. 5.

flow	Time Value		
	t_b [s]	t_s [s]	t_a [s]
Vehicle (1 to 12)	3,0	2,6	0,8
Pedestrians crossing entry (PEZ1 to PEZ4)	-	2,6	-
Pedestrians crossing exit (PEX1 to PEX4)	-	3,0	-

Fig. 5: Calibrated t-Values

Conflict Matrix

Owing to the short distances between entry and exit at mini-roundabouts, it can be assumed that waiting road users do not always recognise in good time the intention of the vehicle in the circle lane approaching from the left (cf. BOVY 1991). In order to determine the extent to which exiting vehicles using the same arm as the entering vehicles have an influence on the entering vehicles or rather entry capacity, behaviour observation surveys were conducted at the mini-roundabouts involved in the study. Using video recordings, it was observed how often drivers waiting in the entry

(i) drove into the roundabout without any influence from exiting vehicles,
(ii) recognised exiting vehicles in good time as such and then drove into the roundabout,
(iii) did not drive into the roundabout because of an exiting vehicle, despite there being a sufficient gap in the stream having direct right of way.

Using this method, it was found that on average the influence of exiting vehicles amounted to 20%. Significant differences in the proportional influence of exiting vehicles at 3- and 4-arm roundabouts, as described by BOVY (1991), were not confirmed. The influence of exiting vehicles established in this way was taken into account when adjusting the conflict matrix in the calculation model based on ACF concept (cf. Fig. 6).

Conflict-factor Aij	**Conflict-Matrix for Mini-Roundabouts** with crosswalk/without crosswalk analyzed flow j																			
	EN1			EN2			EN3			EN4										
conflicting flow i	1	2	3	4	5	6	7	8	9	10	11	12	PEN1	PEN2	PEN3	PEN4	PEX1	PEX2	PEX3	PEX4
1				1	1	1	1	1	1	0,2	0,2	0,2	0/1							0
2				1	1	1	0,2	0,2	0,2				0/1						0	
3				0,2	0,2	0,2							0/1					0		
4	0,2	0,2	0,2				1	1	1	1	1	1		0/1			0			
5							1	1	1	0,2	0,2	0,2		0/1						0
6							0,2	0,2	0,2					0/1					0	
7	1	1	1	0,2	0,2	0,2				1	1	1			0/1			0		
8	0,2	0,2	0,2							1	1	1			0/1		0			
9										0,2	0,2	0,2			0/1					0
10	1	1	1	1	1	1	0,2	0,2	0,2							0/1			0	
11	1	1	1	0,2	0,2	0,2										0/1		0		
12	0,2	0,2	0,2													0/1	0			
PEN1	1/0	1/0	1/0																	
PEN2				1/0	1/0	1/0														
PEN3							1/0	1/0	1/0											
PEN4										1/0	1/0	1/0								
PEX1				1				1				1								
PEX2			1				1				1									
PEX3		1				1				1										
PEX4	1				1				1											

Fig. 6: Adapted Conflict Matrix for Mini-Roundabouts

2.4 VERIFYING MEASUREMENTS AND SIMULATIONS

Entry Capacity at Mini-Roundabouts without Crosswalks

Fig. 7 depicts the capacity function calculated on the basis of the calibrated time values and the adjusted conflict matrix along with the 923 individual values for the capacities measured at thirty-second periods with steady queuing. Since in ACF procedure the time values are adjusted in order to take the vehicle fleet mix into account, and there is no conversion into passenger cars, the capacity calculation using equations (6) to (9) must be based on the traffic volume of the priority streams measured directly in vehicles per hour. The capacities calculated according to ACF procedure are also calculated directly in vehicles per hour. Hence, in ACF procedure the situation of the capacity function changes depending on the vehicle fleet mix in the priority streams (shift along the x-axis) and of the entering stream (shift along the y-axis). In order to take account of this effect, and also to ensure comparability with the empirically measured capacities (thirty-second periods), the traffic volumes of the priority streams, as well as the capacities, were converted into passenger car units for the depiction of the calculation model in Fig. 7.

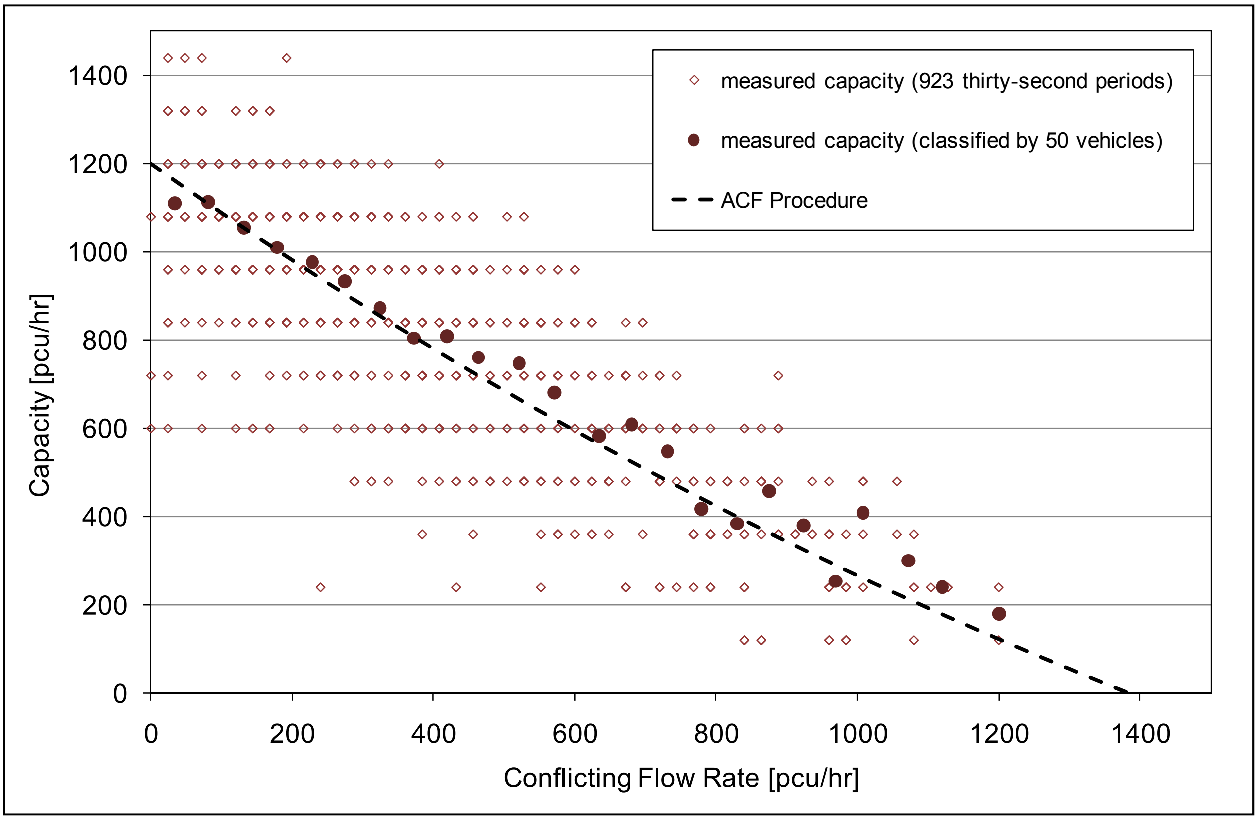


Fig. 7: Comparison of measured and calculated Entry Capacities

The statistical verification of the relationship between the capacity function established by the deterministic calculation model (ACF procedure) and the empirically determined capacities (923 thirty-second periods of capacity data) results in a coefficient of determination of B = 0.63. Since the observed individual values in Fig. 7 are relatively widely distributed, the traffic volume of the priority streams was classified into groups of 50 vehicles and the mean capacities for the individual classes determined, in order to evaluate the goodness of fit of the calculation model to the observed capacities. The comparison of these mean capacities with the calculation model provided by ACF procedure revealed a very high degree of goodness of fit of the deterministic calculation model to real conditions, the coefficient of determination being B = 0.98.

The developed calculation method was further verified and validated by means of microscopic traffic simulation. For this purpose, a simulation model of a four-arm mini-roundabout was created using the VSSIM simulation system (PTV AG) and was calibrated on the basis of measured travel times. Using the simulation model, capacities were measured for 1,200 simulation hours with different traffic volumes and varying proportions of heavy goods vehicles, ranging from 0% to 5%. In Fig. 8 the simulated capacities are compared with the capacities determined on the basis of ACF procedure.

The simulated capacities between 150 veh/hr and 900 veh/hr show a very high degree of conformity to the calculated values. This is confirmed by the findings presented in Fig. 7, which show that the developed calculation model provides valid results for this range. In the higher capacity range (C > 900 veh/hr) the calculated capacities are systematically lower than the simulated values (maximum deviation $\Delta C_{SIM\text{-}CALC}$ = 174 veh/hr). Such high capacities in the approach road arise when the priority traffic stream consists of fewer than 300 veh/hr. However, the empirically determined capacities for the thirty-second periods with steady queuing shown in Fig. 7 also indicate a high degree of goodness of fit in relation to the deterministic calculation model. It is therefore surmised that the reason for the observed deviations in the higher capacity range lies in the calibration of the simulation model. The travel times on which the calibration was based were determined for the capacity range of 400 veh/hr up to 1,000 veh/hr. Consequently, the simulated capacities of more than 1,000 veh/hr are data extrapolated from the simulation, for which there was no direct basis for calibration. The deviations observed in this capacity range therefore probably result from insufficient adaptation of the simulation model to real conditions.

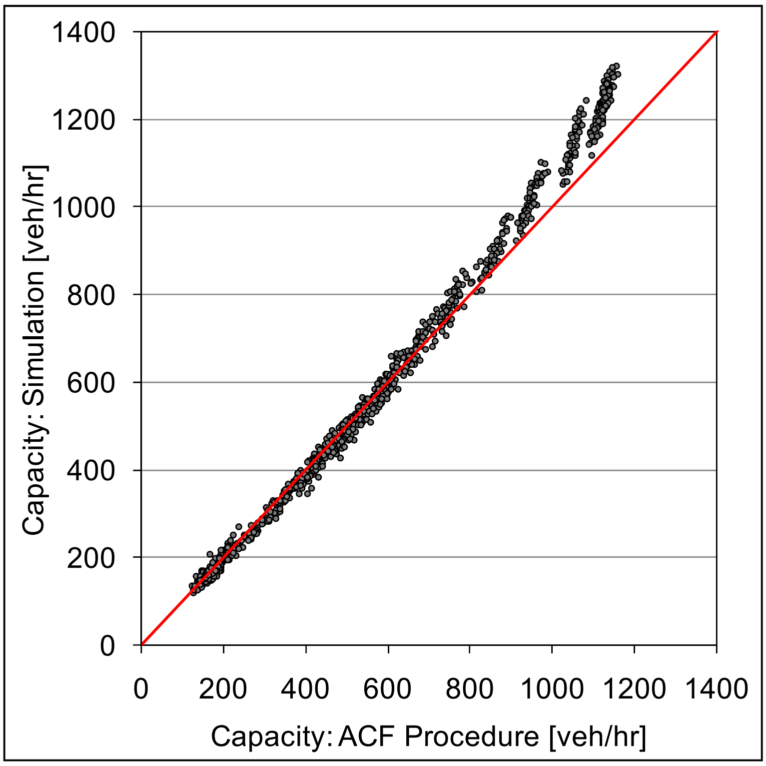


Fig. 8: Comparison of simulated and calculated Entry Capacities

The comparison between the newly developed calculation model (based on ACF procedure) and the empirically determined capacities (cf. Fig. 7) and the simulation results (cf. Fig. 8) show that traffic flows at mini-roundabouts can be described well using ACF procedure. However, in studies conducted so far, the influence of crossing pedestrians has been neglected. Therefore, the following section will examine the extent to which the approach used in the calculation model for taking account of priority pedestrian streams provides an accurate reflection of real conditions.

Entry Capacity at Mini-Roundabouts with Crosswalks

Pedestrians crossing the entries to a roundabout only have priority over the vehicle traffic if there is a crosswalk at the entry. If there is no crosswalk at the entry, pedestrians are obliged to wait, and vehicles entering the roundabout only have to give way to the priority-stream vehicles in the circle lane. This fact is taken into account in ACF procedure by using the adapted conflict matrix shown in Fig. 6. This section will only consider the influence of crossing pedestrians under the assumption that they have priority, and hence that there are crosswalks at the entries to the roundabout. Using traffic flow simulations, the influence on vehicle flow capacities resulting from pedestrians crossing at the entry was tested with varying volumes of pedestrian traffic (from 0 ped/hr to 500 ped/hr).

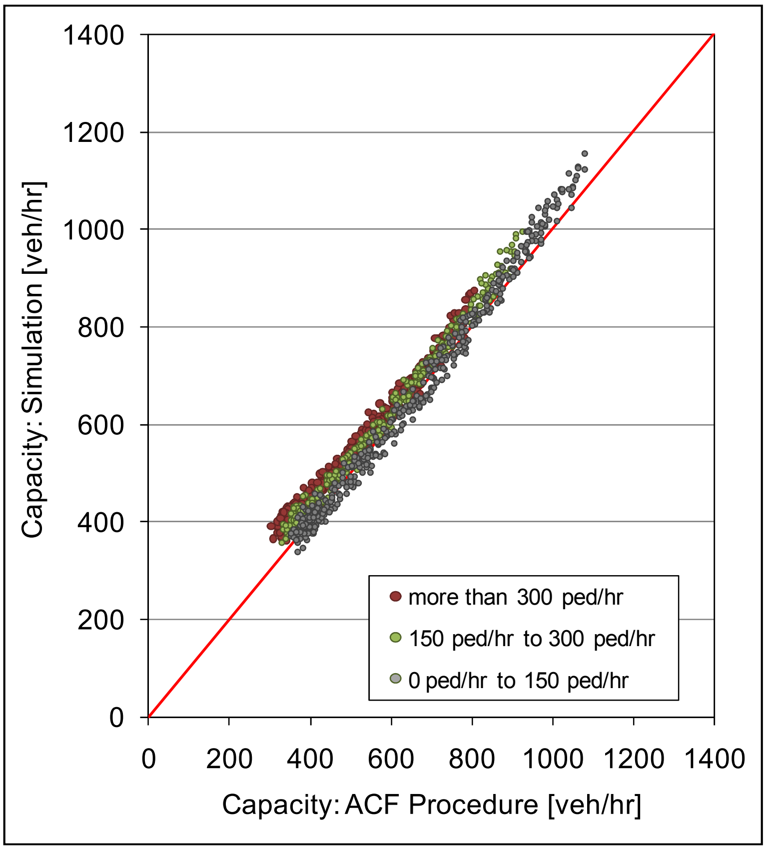


Fig. 9: Comparison of simulated and calculated Entry Capacities influenced by crossing Pedestrians

Fig. 9 shows the simulated and calculated capacities for different volumes of pedestrian traffic. For pedestrian traffic volumes of up to 300 ped/hr there is a high degree of conformity between the simulated and the calculated capacities. As already explained in connection with Fig. 8, the systematic deviations where capacities exceed 900 veh/hr are ascribable to the characteristics of the simulation model. For pedestrian volumes of more than 300 ped/hr the calculation model produces a systematic underestimate of the simulated capacities. From 300 ped/hr upwards, the deviation between the simulated and calculated capacities amounts, on average, to 50 veh/hr. The differences in capacity with heavy volumes of pedestrian traffic can be explained by the fact that at these volumes it is usual for several pedestrians to occupy the crossing at once. This effect is not taken into account in the calculation method developed on the basis of ACF concept. However, in reality, pedestrian streams exceeding 300 ped/hr crossing at the entry to a roundabout are only observed in exceptional cases, so that it was not considered necessary to make further allowance for this effect.

Furthermore, it is evident from Fig. 9 that the deviations between the simulated and calculated capacities are greatest in the lower capacity range (C < 600 veh/hr). Capacities of less than 600 veh/hr mean that the volume of priority traffic within the roundabout is more than 500 veh/hr. Such high volumes of traffic in the conflicting flow in the circle lane frequently result in tailbacks in the approach roads. Consequently, pedestrians can cross between the waiting vehicles, so that the capacity-reducing influence of the pedestrians decreases (cf. HBS 2001). This effect is not accounted for in the ACF procedure. This explains the increasing differences in capacity at low capacities and high volumes of pedestrian traffic. In order to limit the influence of this error on the calculation of capacity according to ACF procedure, crossing pedestrians should no longer be taken into account when calculating the capacity of a roundabout entry if the volume of priority traffic exceeds 800 veh/hr.

Exit Capacity at Mini-Roundabouts with and without Crosswalks

The ACF procedure described above also makes it possible to calculate the capacity of exits from mini-roundabouts (cf. equations (10) to (13)). Since according to the German Highway Code pedestrians crossing the exit of a mini-roundabout have priority over exiting vehicles (regardless of whether there is a crosswalk or not), the volume of pedestrian traffic has a major influence on the capacity of the exit. This influence is taken into account when determining the capacity of the exits from mini-roundabouts by ACF procedure. The capacity of an exit is also influenced by the vehicle fleet mix in the exiting traffic streams, since heavy goods vehicles require more time to exit owing to their greater length and slower rate of acceleration. This effect is also taken into account in ACF procedure.

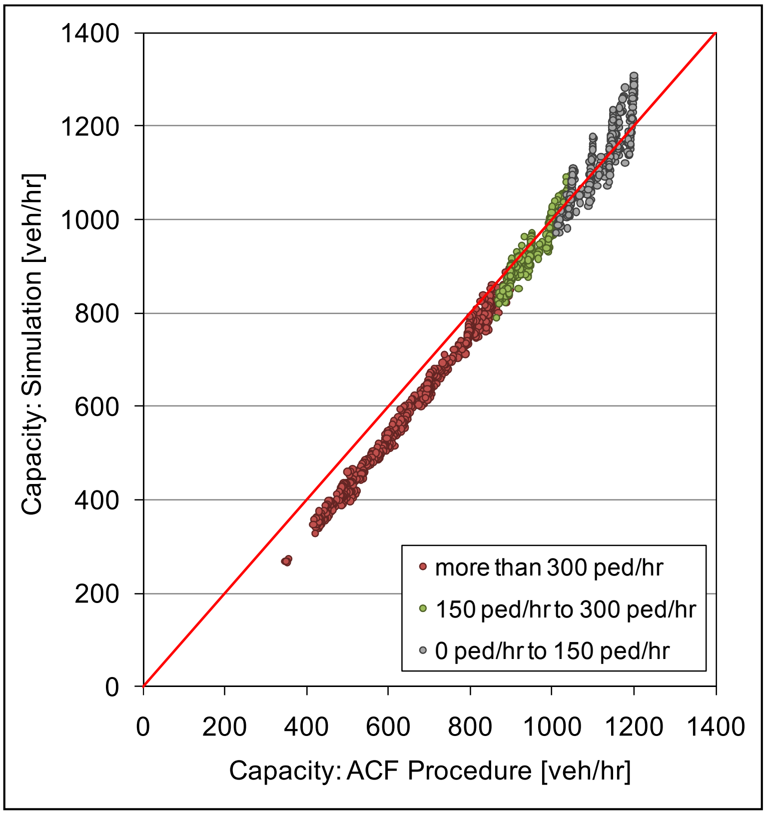


Fig. 10: Comparison of simulated and calculated Exit Capacities influenced by crossing Pedestrians

In order to verify the capacity formulas described in equations (10) to (13), microscopic traffic flow simulations were carried out. Simulation tests were conducted to determine the maximum flow rate of vehicles leaving the roundabout at an exit with different volumes of pedestrian traffic (from 0 ped/hr to 800 ped/hr) and different proportions of heavy goods vehicles, ranging from 0% to 5%. In Fig. 10 the results of this simulation test are compared with the deterministic calculation model (ACF procedure). The simulated and calculated capacities for different volumes of pedestrian traffic are shown.

Fig. 10 demonstrates that, in principle, the assumption frequently encountered in the literature that the maximum capacity of an exit is around 1,200 veh/hr (e.g. HBS 2001) is confirmed by the results of the simulation test. The calibrated calculation method based on ACF procedure also establishes a maximum capacity of 1,200 veh/hr at exits where there are no pedestrians and no heavy goods traffic. In the range of low and medium volumes of pedestrian traffic (up to 300 ped/hr) there is a high degree of conformity between the simulated capacities and the calculated predictions (Fig. 10). With volumes of pedestrian traffic in excess of 300 ped/hr it is evident that the simulated capacities systematically fall below the calculated values. This effect can be explained by the fact that in calculating the capacities according to ACF procedure a linear correlation is assumed to exist between the exit capacity and the pedestrian stream, which has right of way. Thus, the capacity of the exit decreases by 0.08% per pedestrian. When the volume of pedestrian traffic is very high, the time periods available for the exiting vehicle stream between successive pedestrians become increasingly small. In the case of very high volumes of pedestrian traffic, some of these periods can no longer be used by exiting vehicles. This increasing loss of usable exit time is not taken into account in the developed calculation method. However, it must be assumed, on the other hand, that when the volume of pedestrian traffic is significantly in excess of 300 ped/hr, the pedestrians increasingly cross the entry in groups. In turn, this has a capacity-increasing effect on the vehicle streams. The occurrence of larger groups of pedestrians is not taken into account in the simulation model, so that it must also be assumed that the capacity under real conditions is underestimated by the simulation where such high volumes of pedestrian traffic are concerned. In order to be able to assess this effect with a sufficient degree of certainty, it would have been necessary to conduct further traffic surveys at mini-roundabouts with very large volumes of pedestrian traffic. However, in reality mini-roundabouts with such high volumes of pedestrian traffic (more than 300 ped/hr) hardly occur, because in such cases traffic signals are employed in order to meet the needs of the pedestrians.

To summarise, it can be stated that in the range that is of practical relevance (up to 300 ped/hr) the calculation method developed on the basis of ACF concept provides a good reflection of the capacities of exits at mini-roundabouts. In the case of very high volumes of pedestrian traffic, the calculation method may result in an overestimation of capacity. However, low roundabout exit capacities resulting from high volumes of pedestrian traffic mean that there are increasing tailbacks in the circle lane even if the volume of exiting vehicle traffic is only moderate. This leads to reciprocal effects on the neighbouring entry and hence to traffic conditions which cannot be described using the calculation method presented here. It is therefore not recommended that this calculation method be applied in cases of pedestrian traffic volumes in the exit exceeding 300 ped/hr. The reciprocal effects brought about by such heavy pedestrian traffic volumes can only be reflected in very complex calculation models, and so assessment in such cases should be conducted using microscopic traffic flow simulations.

3 CONCLUDING REMARKS

The calculation method developed by BRILON/ WU (2002) on the basis of ACF concept for two-way stop-controlled intersections was adapted for the determination of the capacity of mini-roundabouts. Like all the known calculation methods for roundabouts, this method is based on an analysis of traffic movements focusing on the individual entry points, with the roundabout being regarded as a series of independent junctions.

The developed method makes it possible to calculate the capacities of mini-roundabout entries and exits while taking crossing pedestrian streams into account. Depending on whether crosswalks exist, the changing right-of-way relationships are depicted in a conflict matrix. The conflict matrix also describes the extent of the indirect influence exerted by exiting vehicles. Through traffic observations it was possible to establish that the influence on entering vehicles by vehicles exiting at the same arm amounts to 20%. This effect, which in Germany has only been observed at mini-roundabouts, can be attributed to the shorter distance – compared with roundabouts with a non-traversable center island – between the conflict points of the entries and exits. As a result, it is not always possible for the waiting road user to recognise the intention of vehicles approaching from the left in the circle lane in good time.

The time values t_b, t_s and t_a constitute the calibration parameters of the calculation method. The time value t_b was established directly by means of measurements conducted in traffic surveys at 10 mini-roundabouts. It can be compared to the follow-up time used in gap-acceptance theory. The time values t_s and t_a, on the other hand, are not measurable values. They were calibrated using the capacities determined for thirty-second periods with steady queuing.

In order to verify the calibrated calculation model, microscopic traffic flow simulations were conducted. Overall, the simulation results showed a good degree of conformity with the calculated capacities. Significant deviations occurred in the range of very high capacities, i.e. with low volumes of traffic in the roundabout and with high volumes of pedestrian traffic in excess of 300 ped/hr. The deviations in the range of very high capacities could be attributed to the characteristics of the simulation model. The differences between the simulation and the calculated results that were observed in respect of high volumes of pedestrian traffic were caused by various factors. However, empirical verification of these influences was not possible because mini-roundabouts with pedestrian traffic volumes in excess of 300 ped/hr in an entry hardly occur in reality. At this point there is potential for further empirical verification of the calculation method. Particularly when very high volumes of pedestrian traffic occur in exits from mini-roundabouts this may lead to tailbacks onto the circle lane, resulting in conditions (such as the blocking of the neighbouring entry by queuing vehicles) which cannot be depicted using the calculation method described here.

The calculation method presented in this paper is generally suitable for determining the capacity of mini-roundabouts. The method can be employed for mini-roundabouts both with and without crosswalks in the entries and exits. The influence of crossing pedestrian streams is taken into account directly in the calculation algorithm. A further advantage of ACF procedure over alternative calculation methods (e.g. gap-acceptance theory) is its simplicity in determining capacities for mini-roundabout exits.

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