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ACF PROCEDURE FOR TWSC INTERSECTIONS - EXTENSIONS AND MODIFICATIONS

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Introduction

Capacity of Two-Way Stop-Controlled (TWSC) intersections is normally analyzed by the so-called gap-acceptance procedures (GAP) which originally was developed in Germany. This method is used in many countries of the world (cf. Brilon *et al*, 1995) such as in the USA (HCM, 1997 and 2000). Other countries, like Sweden or Germany, also use the GAP method in their own capacity manuals. The theory of gap-acceptance is the predominant concept for capacity analysis at TWSC intersections in the world.

However, this concept has a couple of shortcomings for practical application. For example, the determination of the critical gap is complicated (cf. Brilon *et al*, 1997; Tian *et al*, 2000). The estimation of critical gaps is a source of uncertainty within the GAP method. The subsequent calculation methods of the GAP look like rigorous mathematics (cf. Wu, 2001) but, in reality, they are based on many pragmatic simplifications. Overall the calculation produces produce results of a correct magnitude but they are of approximate nature. Thus, there could be a much simpler approximation which would make the application of an estimation method much easier without loosing too much reliability.

The gap-acceptance theory does not apply to driver behavior not exactly complying with the rules of priority such as gap forcing or polite behavior of priority drivers (priority reversal). The gap-acceptance theory needs a clearly defined ranking of priorities with the assumption that each road user will exactly comply with these rules. The gap-acceptance theory cannot deal with pedestrians or cyclists properly because of the complicated and confusing priority rules between pedestrians and motorists. As a consequence, the real behavior both of pedestrians and motorists is of great variability which cannot be taken into account by the gap-acceptance theory. Based on the concept of the so-called Additive Conflict Flows (ACF), which has first been developed by Gleue (1972) for signalized intersection analysis and modified by

Wu (2000a, b) for All-Way-Stop-Controlled (AWSC) intersections, a new concept was developed for application on TWSC intersections (cf. Brilon and Wu, 2001, 2002). The new procedure makes it easy to take into account 1) the number of lanes of the subject, the opposite, and the conflict approach, 2) the distribution of traffic flow volumes on the different approaches, 3) the pedestrian volumes crossing the legs of the intersection, and 4) flared approaches.

However, according to the recent (TU Dresden, 2008) investigations, the exiting ACF procedure still has some crucial shortcomings. For example, the capacities of movements of ranks 3 and 4 are systematically over-estimated compared to the measurements. The deviations are biased significantly. The main reason for these deviations is the fact that the queue-free states in the major-left turn movements is not properly considered. In this paper, some enhancements for taking into account the probability of those queue-free states are constructed in order to extent and modify the exiting ACF procedure. First of all, the so-called $t_{B.a}$ values (comparable to the critical gaps in the gap-acceptance theory) are applied - like the gap-acceptance procedure - to the subject minor movements instead to the major movements. The procedure is modifies in such a way that it is simplified and more accurate. In addition, the queue-free states in shared major left-turn movements are considered in the same way as in the HCM 2000 and in the proposed new HBS2011 (Brilon and Wu, 2009). Furthermore, the conflict groups for T-junctions are redefined according to the realistic movement configurations. With those extensions and modifications, the ACF procedure can use the microscopic parameters such as the critical gaps and the following-up times from the gap-acceptance theory directly. The deviations to the measurements can be reduced.

Departure mechanisms at TWSC intersections

The departure mechanisms at TWSC intersections for the ACF procedure were introduced in details by Brilon and Wu (2001, 2002). Here they are only explained briefly in following.

Vehicles from different movements passing a conflict area one after the other are defined in a conflict group. Conflict groups are defined according to the concept of Additive Conflict Flows (ACF) from Gleue (1972).

In general the capacity of a minor movement can be expressed as

$$C_m = C_{max,m} \cdot p_0 = \frac{3600}{t_{B,q,m}} \cdot p_0 \qquad \text{[veh/h] (1)}$$

where

C_m = capacity for movement m [veh/h]

$C_{max,m}$ = maximal possible capacity for movement m (= $3600/t_{B,q,m}$) [veh/h]

$t_{B,q,m}$ = discharging service time for movement m [s]

p_0 = Pr(no blockage)
= probability for the case that the conflict area is not occupied by other vehicles [-]

The probability p_0 for the case that the conflict area is not occupied by other vehicles can be calculated as the product of the probability that the conflict area is not blocked by a standing or discharging of queue of major movement vehicles and the probability that the conflict area is not blocked by approaching major vehicles. That is

$$\begin{aligned} p_0 &= \Pr(\text{no blockage}) \\ &= \Pr(\text{no queueing/discharging of a queue of major movement vehicles}) \cdot \\ &\qquad \cdot \Pr(\text{no approaching major vehicles}) \\ &= p_{0,q} \cdot p_{0,a} \end{aligned} \tag{2}$$

The probabilities $p_{0,q}$ and $p_{0,a}$ are derived and modified separately in the following sections. The probability $p_{0,q}$ of no blockage during queue and queue discharge can be derived from the ACF technique. The probability $p_{0,a}$ of no blockage due to approaching vehicles can be derived from the probability theory. The derivation in this paper is different from the exiting ACF model from Brilon and Wu (2001, 2002). The modifications are introduced in details in the following sections.

Definition of Conflict Groups and Reduction of Conflict Groups at T-Junctions

The Conflict groups are defined according to the concept of Additive Conflict Flows (ACF) from Gleue (1972).

Looking at a simple intersection of two streets, the conflict groups for the ACF procedure are defined in Fig. 1 and Table 1 (cf. Brilon and Wu, 2001, 2002).

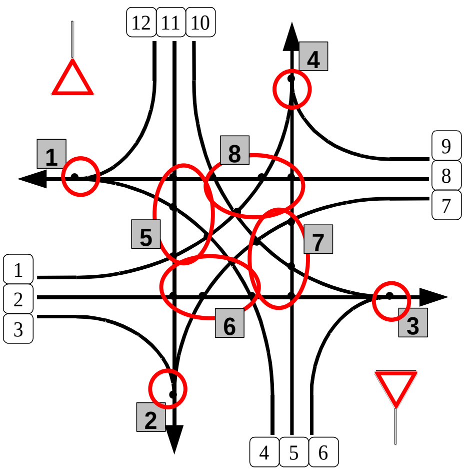

Fig. 1: Arrangement of conflict groups at a simple cross intersection
k Conflict group i Movement

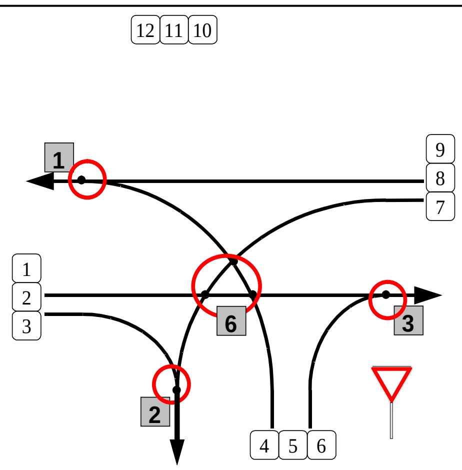

Fig. 2: Arrangement of conflict groups at simple a T-junction
k Conflict group i Movement

Table 1: Conflict groups and conflicting movements at the intersection

Subject movement		**movements of higher ranks**	**Conflict group**	**conflicting movements**				
				higher priority ranking rank :			**lower rank**	
No.	**rank**			**1**	**2**	**3**		
i	**r**	**hr**	**k**	**a**	**b**	**c**		
1	2	8, 9	5	8			4	11
			8	8			5	10
			4	9			5	
2	1	priority						
3	1		2				7	11
4	4	2, 7, 11	6	2	7	11		
		8, 1, 12	5	8	1	11		
			1	8	12			
5	3	2, 7, 8 1, 9	7	2	7		10	
			8	8	1		10	
			4	9	1			
6	2	2	3	2			10	
7	2	2, 3	7	2			5	10
			6	2			4	11
			2	3			11	
8	1	priority						
9	1		4				1	5
10	4	8, 1, 5	8	8	1	5		
		2, 7, 6	7	2	7	5		
			3	2	6			
11	3	8, 1, 2, 7, 3	5	8	1		4	
			6	2	7		4	
			2	3	7			
12	2	8	1	8			4	
i	**r**	**hr**	**k**	**a**	**b**	**c**		

Table 2: Conflict groups and conflicting movements at T-junctions

Subject movement		**movements of higher ranks**	**Conflict group**	**conflicting movements**				
				higher priority ranking rank :			**lower rank**	
No.	**rank**			**1**	**2**	**3**		
i	**r**	**hr**	**k**	**a**	**b**	**c**		
1	N.N.							
2	1	priority						
3	1		2				7	
4	3	2, 7	6	2	7			
		8	1	8				
5	N.N.							
6	2	2	3	2				
7	2	2, 3	6	2			4	
			2	3				
8	1	priority						
9	N.N.							
10	N.N.							
11	N.N.							
12	N.N.							
i	**r**	**hr**	**k**	**a**	**b**	**c**		

At T-junctions, the movements 1, 5, 9, 10, 11, and 12 do not exist. Those movements should be excluded from the corresponding conflict groups under consideration.

Hence, the conflict groups for T-junctions for the ACF procedure must be reduced and redefined as presented in Fig. 2 and Table 2.

Derivation and modification for probability $p_{0,a}$ of blockage due to approaching vehicles in major movements

In the ACF model developed earlier (Brilon and Wu, 2001, 2002), the values of $t_{B,a}$ are selected according to the subject major movements (Brilon and Wu, 2002, eq.(8)). Thus, for a single minor movement m (i.e. movement 5), several different $t_{B,a,i}$ values (i.e. for movements 1, 2, 7, 8, and 9) are applied. This is an unnecessary complication. It is evident, that the probability $p_{0,a}$ just corresponds to concept of the gap-acceptance theory. Thus, the $t_{B,a}$ values should be applied to the subject minor movement as it is the case in the gap-acceptance procedure. Therefore, for a minor movement m we have:

$$p_{0,a,m}^{\ *} = \prod_{\substack{\text{i for all}\\ \text{major}\\ \text{movements}}} p_{0,a,i} = \prod_{\substack{\text{i for all}\\ \text{major}\\ \text{movements}}} \exp(-B_{a,i}) = \exp(-\sum_{\substack{\text{i for all}\\ \text{major}\\ \text{movements}}} B_{a,i})$$

$$= \exp\left(-t_{B,a,m}^{\ *} \cdot \sum_{\substack{\text{i for all}\\ \text{major}\\ \text{movements}}} \left(\frac{Q_i}{3600}\right)\right) \qquad [-] \qquad (3)$$

$$= \exp\left(-\left(t_{B,a,m} - \Delta\right) \cdot \sum_{\substack{\text{i for all}\\ \text{major}\\ \text{movements}}} \left(\frac{Q_i}{3600}\right)\right)$$

with

$B_{a,i}$	=	$Q_i \cdot t_{B,a,m}^{\ *}/3600$ [-]
Q_i	=	volume of movement i [veh/h or ped/h]
	=	0, if the relevant cell in Table 1 or 2 is empty
$t_{B,a,m}$	=	duration of blocked time caused on average by one approaching vehicle in major movement for minor movement m
	≈	$t_{c,m} - t_{f,m}/2$
$t_{B,a,m}^{\ *}$	=	duration of blocked time caused on average by one approaching vehicle in major movement for minor movement m exclude the minimal headway Δ
	≈	$t_{c,m} - t_{f,m}/2 - \Delta$
Δ	=	minimal headway in major movement (normally = 2 s)

The index i corresponds to the index in column **hr** in Table 1 for intersections or in Table 2 for T-junctions. Here, it is to notice that none of the major movements should be double-counted.

In the equation above, we have to taken into account the minimal headway Δ here to avoid double-counting vehicles in the major movements (cf. Wu. 2001), because we also consider the minimal headway Δ in major movements q_2/q_8, q_3/q_9, and q_6/q_{12} for calculating $p_{0,q}$ of blockage during queue and queue discharge in major movements (cf. the following sections).

Derivation and modification for probability $p_{0,q}$ of blockage during queue and queue discharge in major movements

The concept of ACF is implemented in the calculation of probability $p_{0,q}$ of blockage during queue and queue discharge in major movements. As a modification, a value of the service time $t_{B,q,j}^*$ based on the potential capacity is defined here as the service time at the stop line for the subject movement j in contrast to a fixed service time $t_{B,q,j} \approx t_{f,j}$ (following-up time) in the exiting ACF procedure. In this way, the blockage of conflict areas by queuing/discharging vehicles is taken into account more realistically. This service time is then the reciprocal of the potential capacity G_j. G_j can be calculated according the common formulas. For example, using the HBS formula, we can calculate for any movement j the potential capacity

$$G_j = \frac{3600}{t_{B,q,j}} \cdot \exp\left(- t_{B,a,j} \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr}}} \frac{Q_i}{3600} \right) \approx \frac{3600}{t_{f,j}} \cdot \exp\left(-(t_{c,j} - \frac{t_{f,j}}{2}) \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr}}} \frac{Q_i}{3600} \right) \quad \text{[veh/h]} \qquad (4)$$

and

$$t_{B,q,j}{}^* = \frac{3600}{G_j} \quad \text{[s]} \qquad (5)$$

in advance and use the pre-calculated values for further computations.

For major movements we use a minimum time headway Δ for estimating the potential capacity G. That is,

$$G_{j,major} = \frac{3600}{\Delta} \quad \text{[veh/h]} \qquad (6)$$

and

$$t_{B,q,j,major}{}^* = \Delta \quad \text{[s]} \qquad (7)$$

From those service times we can easily obtain the queue-free probability in movement j of rank 2 as follows:

$$p_{0,q,j} = \frac{3600 - t_{B,q,j}{}^* \cdot Q_j}{3600} = 1 - \frac{Q_j}{G_j} = 1 - B_{q,j} \quad \text{[-]} \qquad (8)$$

The value of $p_{0,q,j}$ is subject to $0 \le p_{0,q,j} \le 1$.

Now $B_{q,j}$ is defined as

$$B_{q,j} = \frac{Q_j}{G_j} = t_{B,q,j}{}^{*} \cdot \frac{Q_j}{3600} \qquad [-] \qquad (9)$$

Thus, the probability of queue-free states in movements of higher ranks can be now correctly considered.

Consideration of Back-of-Queue in major left-turn movements

In the reality, there still more arrivals coming into the end of queue when the queue in front is being discharged. This effect is called the Back-of-Queue. This effect of Back-of-Queue (BOQ) is crucial in major approach with shared lane both for the left-turn and the through movements. The effect of Back-of-Queue can be taking into account by multiplying a factor (cf. also Harders 1968, and HCM 2000). If the right turn movement 9 also shares the same lane with the movement 7, the probability of the queue-free state in movement 7 is

$$p^{*}_{0,7} = 1 - \frac{g_7}{1 - g_8 - g_9} \qquad [-] \qquad (10)$$

with $0 \le p_{0,7}{}^{*} \le 1$.

In general, the effect of the so-called Back-of-Queue in a share turning movement (i.e. movement 7) can be considered by using the following equation:

$$p^{*}_{0,j} = 1 - \frac{Q_j}{C_j}\left(1 - \sum \frac{Q_n}{C_n}\right)^{-1} = 1 - \frac{Q_j}{C_j} \cdot f_{n,j} \qquad (11)$$

with $0 \le p_{0,j}{}^{*} \le 1$.

Here, Q_n and C_n are flow volume and capacity of the share through movement (i.e. movement 8). $f_{n,j}$ is the factor for the turning movement j and the through movement n in order to take into account the effect of Back-of-Queue. For major movements we have always $C_n = G_n$ and therefore

$$f_{n,j} = \left(1 - \sum \frac{Q_n}{C_n}\right)^{-1} = \left(1 - \sum \frac{Q_n}{G_n}\right)^{-1} = \left(1 - \sum B_{q,n}\right)^{-1} \qquad (2)$$

with $0 \le f_{n,j} \le 1$.

Queue-free state within a conflict group

Here we should distinguish between movements of the same rank and movements of different ranks under consideration.

For two movements j_2 and j_3 of the same rank 2 we have the queue-free probability

$$p_{0,j_2/j_3} = 1 - B_{q,j_2} - B_{q,j_3} = 1 - \frac{Q_{j_2}}{C_{j_2}} - \frac{Q_{j_3}}{C_{j_3}} = 1 - \frac{Q_{j_2}}{G_{j_2}} - \frac{Q_{j_3}}{G_{j_3}} \qquad [veh/h] \qquad (13)$$

For two movements j_2 of ranks 2 and j_3 of rank 3 we can approximately calculate the queue-free probability as the product of the queue-free probabilities from the movements j_2 and j_3. That is

$$p_{0,j_2/j_3} = p_{0,j_2} \cdot p_{0,j_3} = \left(1-\frac{Q_{j_2}}{C_{j_2}}\right)\left(1-\frac{Q_{j_3}}{C_{j_3}}\right) = \left(1-\frac{Q_{j_2}}{G_{j_2}}\right)\left(1-\frac{Q_{j_3}}{C_{j_3}}\right) \qquad [\text{veh/h}] \quad (3)$$

with

$$C_{j_3} = p_{0,j_2} \cdot G_{j_3} = G_{j_3}\left(1-\frac{Q_{j_2}}{G_{j_2}}\right) \qquad [\text{veh/h}] \quad (4)$$

Combining both equations yields

$$\begin{aligned} p_{0,j_2/j_3} &= p_{0,j_2} \cdot p_{0,j_3} = \left(1-\frac{Q_{j_2}}{G_{j_2}}\right)\cdot\left(1-\frac{Q_{j_3}}{C_{j_3}}\right) \\ &= 1-\frac{Q_{j_2}}{G_{j_2}}-\frac{Q_{j_3}}{G_{j_3}} \\ &= 1-B_{q,j_2}-B_{q,j_3} \end{aligned} \qquad [\text{veh/h}] \quad (5)$$

Thus, we have in a conflict group generally

$$p_{0,j_2/j_3} = 1-B_{q,j_2}-B_{q,j_3} = 1-\frac{Q_{j_2}}{G_{j_2}}-\frac{Q_{j_3}}{G_{j_3}} \qquad [\text{veh/h}] \quad (6)$$

And respectively

$$\begin{aligned} p_{0,j_2/j_3}{}^{*} &= 1-f_{n,j_2}\cdot B_{q,j_2}-f_{n,j_3}\cdot B_{q,j_3} \\ &= 1-B_{q,j_2}{}^{*}-B_{q,j_3}{}^{*} \end{aligned} \qquad [\text{veh/h}] \quad (7)$$

with

$$B_{q,j}{}^{*} = f_{n,j}\cdot B_{q,j}$$

Analogously we have for arbitrary many movement j in arbitrary (parallel or consecutive) ranks the queue-free probability

$$p_{0,j_2..j_{k-1}} = 1-\sum_{j=a}^{f}\left(B_{q,j}\right) \qquad [\text{veh/h}] \quad (8)$$

and

$$p_{0,j_2..j_{k-1}}{}^{*} = 1-\sum_{j=a}^{f}\left(f_{nj}\cdot B_{q,j}\right) = 1-\sum_{j=a}^{f}\left(B_{q,j}{}^{*}\right) \qquad [\text{veh/h}] \quad (20)$$

In general, for a minor movement m we obtain:

$$p_{0,q,m}{}^{*} = \prod_{\text{each } k}\left(1-\sum_{j=a}^{f}B_{q,j,k}{}^{*}\right) \qquad [\text{veh/h}] \quad (21)$$

with

$B_{q,j,k}{}^{*}$ = occupancy in conflict group k by queuing movement j

$= f_{nj} \cdot B_{q,j}^{*} = f_{nj} \cdot Q_j \cdot t_{B,q,j}^{*}/3600$ [-]

In this equation, all value in the bracket are queue-free probabilities and the must be set to values larger or equal to 0.

The index j corresponds to the index in columns **a** to **f** in Table 1 for intersections or in Table 2 for T-junctions.

Capacity of minor movements

The final equation for the capacity of a minor movement reads

$$C_m = C_{max,m} \cdot p_{0,q,m}^{*} \cdot p_{0,a,m}^{*} = G_m \cdot p_{0,q,m}^{*} \cdot p_{0,a,m}^{*}$$

$$= G_m \cdot \prod_{\text{each } k} \left(1 - \sum_{j=a}^{f} B_{q,j,k}^{*}\right) \cdot \exp\left(-\sum_{\substack{\text{i for all} \\ \text{number in hr}}} B_{a,i}\right) \quad \text{[veh/h]} \quad (22)$$

$$= G_m \cdot \prod_{\text{each } k} \left[1 - \sum_{j=a}^{f} \left(\frac{Q_j \cdot f_{n,j}}{G_j}\right)\right] \cdot \exp\left(\Delta \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr}}} \frac{Q_i}{3600}\right)$$

where

C_m	=	capacity for movement m [veh/h]
$B_{q,j,k}^{*}$	=	occupancy in conflict group k by queuing movement j with Back-of-Queue = $f_{nj} \cdot B_{q,j,k}$ [-]
$B_{q,j,k}$	=	occupancy in conflict group k by queuing movement j without Back-of-Queue = $Q_j / G_j = Q_j \cdot t_{B,q,j}^{*}/3600$ [-]
$B_{a,i}$	=	$\left(t_{B,a,m} - \Delta\right) \cdot \frac{Q_i}{3600}$
Q_j, Q_i	=	volume of movement j or i [veh/h or ped/h]
	=	0, if the relevant cell in Table 1 or 2 is empty
G_j	=	Potential capacity of movement j
	=	$\frac{3600}{t_{B,q,j}} \cdot \exp\left(-t_{B,a,j} \cdot \sum_{\text{i for all number in hr}} Q_i\right)$ [veh/h]
$f_{n,j}$	=	factor for the turning movement j and the through movement n in order to take into account the effect of Back-of-Queue (applies only to movements 1 and 7)
	=	$\left(1 - \sum \frac{Q_n}{G_n}\right)^{-1} = \left(1 - \sum B_{q,n}\right)^{-1}$ (f_{nj}=1, if Back-of-Queue is neglected)
$t_{B,q,j}$	=	average discharge service time for one vehicle in movement j
	=	duration of blocked time caused on average by one vehicle for queue discharge [s]
$t_{B,a,i}$	=	duration of blocked time caused on average by one approaching vehicle in major movement i
Δ	=	minimal headway in movement movement (normally = 2 s)

a, f, k : see bottom line of Table 1 or 2

In this equation, all value in the square bracket are queue-free probabilities and the must be set to values larger or equal to 0.

The capacities of the twelve movements of a cross-road can be written out directly as following (cf. Fig. 1 and Table 1).

Potential capacities of the movements:

$$G_1 = \frac{3600}{t_{B,q,1}} \cdot e^{[-t_{B,a,1}(Q_8+Q_9)/3600]} \quad \text{[veh/h]} \quad (9)$$

$$G_2 = \frac{3600}{\Delta} \quad \text{[veh/h]} \quad (10)$$

$$G_3 = \frac{3600}{\Delta} \quad \text{[veh/h]} \quad (11)$$

$$G_4 = \frac{3600}{t_{B,q,4}} \cdot e^{[-t_{B,a,4}\cdot(Q_2+Q_7+Q_{11}+Q_8+Q_1+Q_{12})/3600]} \quad \text{[veh/h]} \quad (12)$$

$$G_5 = \frac{3600}{t_{B,q,5}} \cdot e^{[-t_{B,a,5}\cdot(Q_2+Q_7+Q_8+Q_1+Q_9)/3600]} \quad \text{[veh/h]} \quad (13)$$

$$G_6 = \frac{3600}{\Delta} \quad \text{[veh/h]} \quad (14)$$

The potential capacities for movements 7 through 12 can be calculated correspondingly to movements 1 through 6.

Movement capacities for intersection with single lane major approaches:

$$C_1 = G_1 \cdot \left[1 - \frac{Q_8}{3600} \cdot \Delta\right] \cdot \left[1 - \frac{Q_9}{3600} \cdot \Delta\right] \cdot e^{\Delta\cdot(Q_8+Q_9)/3600} \quad \text{[veh/h]} \quad (29)$$

$$C_2 = G_2 \quad \text{[veh/h]} \quad (30)$$

$$C_3 = G_3 \quad \text{[veh/h]} \quad (31)$$

$$C_4 = G_4 \cdot \left[1 - \left(\frac{Q_2}{3600} \cdot \Delta + \frac{\frac{Q_7}{G_7}}{1 - \frac{Q_8}{G_8} - \frac{Q_9}{G_9}} + \frac{Q_{11}}{G_{11}}\right)\right] \cdot \left[1 - \left(\frac{Q_8}{3600} \cdot \Delta + \frac{\frac{Q_1}{G_1}}{1 - \frac{Q_2}{G_2} - \frac{Q_3}{G_3}} + \frac{Q_{11}}{G_{11}}\right)\right] \cdot \left[1 - \left(\frac{Q_8}{3600} \cdot \Delta + \frac{Q_{12}}{G_{12}}\right)\right] \cdot e^{\Delta \cdot (Q_2 + Q_7 + Q_{11} + Q_8 + Q_1 + Q_{12}) / 3600} \quad \text{[veh/h]} \quad (32)$$

$$C_5 = G_5 \cdot \left[1 - \left(\frac{Q_2}{3600} \cdot \Delta + \frac{\frac{Q_7}{G_7}}{1 - \frac{Q_8}{G_8} - \frac{Q_9}{G_9}}\right)\right] \cdot \left[1 - \left(\frac{Q_8}{3600} \cdot \Delta + \frac{\frac{Q_1}{G_1}}{1 - \frac{Q_2}{G_2} - \frac{Q_3}{G_3}}\right)\right] \cdot \left[1 - \left(\frac{Q_9}{3600} \cdot \Delta + \frac{\frac{Q_1}{G_1}}{1 - \frac{Q_2}{G_2} - \frac{Q_3}{G_3}}\right)\right] \cdot e^{\Delta \cdot (Q_2 + Q_7 + Q_8 + Q_1 + Q_9) / 3600} \quad \text{[veh/h]} \quad (15)$$

$$C_6 = G_6 \cdot \left[1 - \frac{Q_2}{3600} \cdot \Delta\right] \cdot e^{\Delta \cdot Q_2 / 3600} \quad \text{[veh/h]} \quad (16)$$

All value in the square brackets are queue-free probabilities and the must be set to values larger or equal to 0.

The capacities for movements 7 through 12 can be calculated correspondingly to movements 1 through 6.

Respectively, we have for a T-junction (cf. Fig. 2 and Table 2):

Potential capacities of the movements:

$$G_2 = \frac{3600}{\Delta} \quad \text{[veh/h]} \quad (17)$$

$$G_3 = \frac{3600}{\Delta} \quad \text{[veh/h]} \quad (18)$$

$$G_4 = \frac{3600}{t_{B,q,4}} \cdot e^{\left[-t_{B,a,4} \cdot (Q_2 + Q_7 + Q_1) / 3600\right]} \quad \text{[veh/h]} \quad (19)$$

$$G_6 = \frac{3600}{\Delta} = 1800 \qquad \text{[veh/h]} \quad (20)$$

$$G_7 = \frac{3600}{t_{B,q,7}} \cdot e^{\left[-t_{B,a,7} \cdot Q_2 / 3600\right]} \qquad \text{[veh/h]} \quad (21)$$

$$G_8 = \frac{3600}{\Delta} = 1800 \qquad \text{[veh/h]} \quad (40)$$

Movement capacities for T-junctions intersection with single lane major approaches:

$$C_2 = G_2 \qquad \text{[veh/h]} \quad (41)$$

$$C_3 = G_3 \qquad \text{[veh/h]} \quad (42)$$

$$C_4 = G_4 \cdot \left[1 - \left(\frac{Q_2}{3600} \cdot \Delta + \frac{\frac{Q_7}{G_7}}{1 - \frac{Q_8}{G_8}}\right)\right] \cdot \left[1 - \frac{Q_8}{3600} \cdot \Delta\right] \cdot e^{\Delta \cdot (Q_2 + Q_7 + Q_{11} + Q_8 + Q_1 + Q_{12}) / 3600}$$

$$\text{[veh/h]} \quad (22)$$

$$C_6 = G_6 \cdot \left[1 - \frac{Q_2}{3600} \cdot \Delta\right] \cdot e^{\Delta \cdot Q_{,2} / 3600} \qquad \text{[veh/h]} \quad (23)$$

$$C_7 = G_7 \cdot \left[1 - \frac{Q_2}{3600} \cdot \Delta\right] \cdot \left[1 - \frac{Q_3}{3600} \cdot \Delta\right] \cdot e^{\Delta \cdot (Q_2 + Q_3) / 3600} \qquad \text{[veh/h]} \quad (24)$$

$$C_8 = G_8 \qquad \text{[veh/h]} \quad (25)$$

Again, all value in the square brackets are queue-free probabilities and the must be set to values larger or equal to 0.

Capacity of minor movements with pedestrian influence

Other groups of conflicts have to be regarded if also pedestrians are admitted at the intersection (see Fig.3 and 4). The pedestrians have to be added to the conflict groups 1, 2, 3, and 4 at the intersection exits. Moreover they become of importance at the entries to the intersection (conflict groups 9, 10, 11, and 12).

The German Highway Code (StVO, 2001) does not describe a definitive priority between the pedestrian and motor movements. For each vehicle movement pedestrians – in case of a conflict – get priority only in a specific proportion A of cases (Czytich and Boer, 1999). That means: In A per cent of conflicting situations the pedestrian is going first and the car driver waits. These percentage values of A are given in column **hr** in Table 4 and 5 for pedestrian movements.

Table 3 : Suggestions for parameters use (t_c- and t_f-values from Weinert, 2000, 2001; $t_{B,a}$, $t_{B,q}$, and Δ for pedestrians and bicycles from Miltner, 2003).

minor movement m	critical gap t_c	follow-up time t_f	resulting $t_{B,a}$ $=t_c-t_f/2$	resulting $t_{B,a}^*$ $=t_c-t_f/2-\Delta$	resulting $t_{B,q}$ $=t_f$
1	5.5	2.6	4.2	2.2	2.6
2	-	-	-	-	$2.0^{1)}$
3	-	-	-	-	$2.0^{1)}$
4	6.6	3.4	4.9	2.9	3.4
5	6.5	3.5	4.8	2.8	3.5
6	6.5	3.1	5.0	3.0	3.1
pedestrian	6.5	3.0	5.0	$3.0^{3)}$	3.0
bicycle	6.0	2.0	5.0	$3.0^{3)}$	2.0
all m vs. pedestrian	N.N.	3.0	0.0	$0.0^{2)}$	$3.0^{2)}$
all m vs. bicycle	N.N.	2.0	0.0	$0.0^{2)}$	$2.0^{2)}$
movements 7 through 12 correspond to movements 1 through 6					
	s	s	s	s	s

$^{1)}$ value used for Δ, $^{2)}$ from Miltner (2003), 3) presumed values

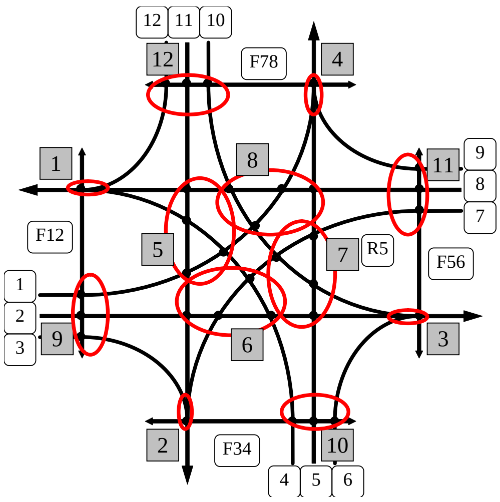

Fig. 3: Arrangement of conflict groups at a simple cross intersection including pedestrians

k	**conflict group**
i	**veh-movement**
Fi	**ped-movement**

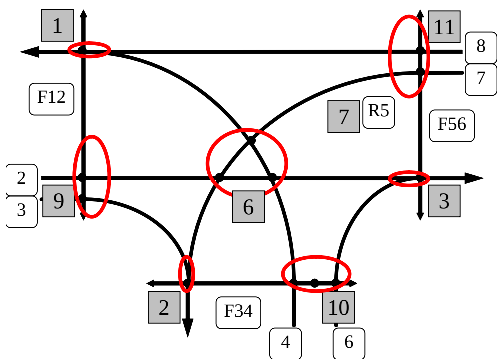

Fig. 4: Arrangement of conflict groups at a T-junction including pedestrians

k	**conflict group**
i	**veh-movement**
Fi	**ped-movement**

Table 4: Conflict groups at the intersection including pedestrians

Subject movement		movements of higher ranks	Conflict group	conflicting movements								
				of higher priority ranking rank r					lower rank			
i	**r**	**hr**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**m**
No.	**rank**			**1**	**2**	**3**	**4**	**5**				
1	3	8, 9	9						F2			
		F7 (30%)	5	8						4	11	
			8	8						5	10	
			4		9			F7		5		
2	1	priority	9						F2	4		
			6							5	7	11
			7							6	7	10
			3						F5		10	
3	2	F3 (70%)	9						F2			
			2	F3						7	11	
4	5	2, 7, 11	10						F4			
		8, 1, 12	6	2		7	11					
		F1 (30%)	5	8		1	11					
		F4 (50%)	1	8	F1	12						
5	4	2, 7 ,8 ,1 ,9	10						F4			
		F4 (50%)	7	2		7				10		
		F7 (10%)	8	8		1				10		
			4		9	1			F7			
6	3	2	10						F4			
		F5 (70%)	3	2	F5					10		
7	3	2, 3	11						F6			
		F3 (30%)	7	2						5	10	
			6	2						4	11	
			2		3			F3		11		
8	1	priority	11						F6			
			8							1	5	10
			5							1	4	11
			1						F1			
9	2	F7 (70%)	11						F6			
			4	F7						1	5	
10	5	8, 1 ,5	12						F8			
		2, 7, 6	8	8		1	5					
		F5 (30%)	7	2		7	5					
		F8 ((50%)	3	2	F5	6						
11	4	8, 1, 6, 7,3	12						F8			
		F8 (50%)	5	8		1				4		
		F3 (10%)	6	2		7				4		
			2		3	7			F3			
12	3	8	12						F8			
		F1 (70%)	1	8	F1					4		
F1	2		1	8						4	12	
F2	4		9	2	3	1						
F3	5 / 1		2				11			3	7	
F4	6		10			6	5	4				
F5	2		3	2						6	10	
F6	4		11	8	9	7						
F7	5 / 1		4				5			1	9	
F8	6		12			12	11	10				
i	**r**	**hr**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**m**

Table 5: Conflict groups at a T-junction including pedestrians

Subject movement		**movements of higher ranks**	**Conflict group**	**conflicting movements of higher priority ranking rank r**					**lower rank**			
i	**r**	**hr**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**M**
No.	**rank**			**1**	**2**	**3**	**4**	**5**				
1	N.N.											
2	1	Priority	9						F2	4		
			6								7	
			3						F5			
3	2	F3 (70%)	9						F2			
			2	F3						7		
4	4	2, 7, 8	10						F4			
		F1 (30%)	6	2		7						
		F4 (50%)	1	8	F1							
5	N.N.											
6	3	2	10						F4			
		F5 (70%)	3	2	F5							
7	3	2, 3	11						F6			
		F3 (30%)	6	2						4		
			2		3			F3				
8	1	priority	11						F6			
			5								4	
			1						F1			
9	N.N.											
10	N.N.											
11	N.N.											
12	N.N.											
F1	2		1	8						4		
F2	3		9	2	3							
F3	1		2							3	7	
F4	5		10			6	4					
F5	2		3	2						6		
F6	4		11	8		7						
F7	N.N.											
F8	N.N.											
i	**r**	**hr**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**m**

For the calculation, Fig.3 and Table 4 should be used for cross-roads and Fig.4 and Table 5 for T-junctions (cf. Brilon and Wu, 2000, 2001). Because a pedestrian or a bicycle does not have the same influence on the minor movement vehicles, the values of $t_{B,a}$ are to be considered different from the values in Table 3 for minor movements with pedestrians and bicycles as major movements. The probability $p_{0,a}$ of blockage due to approaching vehicles in major movements can be spitted into different parts for vehicles and pedestrians due to its exponential expression. That is, for taking account major pedestrian movements (for major bicycle movements respectively),

$$p_{0,a,m,p}{}^{*} = p_{0,a,m}{}^{*}\Big|_{veh} \cdot p_{0,a,m}{}^{*}\Big|_{ped}$$
$$= \exp\left(-t_{B,a,m}{}^{*} \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right) \cdot \exp\left(-t_{B,a,m,p}{}^{*} \cdot \sum_{\substack{\text{i for all} \\ \text{F in hr}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right)$$

[veh/h] (26)

According to Miltner (2003), the values of $t_{B,q}$ can be set to 3.0s and 2.0s for pedestrians and bicycles and the blockage effect of B_a in the approaching phase can be neglected (that is, $t_{B,a,m,p}{}^{*}=0$, $\Delta_p=0$ and $p_{0,a,m,p}=1$). As a consequence, the parameters in Table A3* should be used. Thus, we have

$$p_{0,a,m,p}{}^{*} = p_{0,a,m}{}^{*}\Big|_{veh} \cdot p_{0,a,m}{}^{*}\Big|_{ped}$$
$$= \exp\left(-t_{B,a,m}{}^{*} \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right) \cdot \underbrace{\exp\left(-\underbrace{t_{B,a,m,p}{}^{*}}_{=0} \cdot \sum_{\substack{\text{i for all} \\ \text{F in hr}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right)}_{=1}$$
$$= \exp\left(-t_{B,a,m}{}^{*} \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right)$$

[veh/h] (27)

Therefore, the final equation for the capacity of a minor movement with pedestrian influence reads then

$$C_{m,p} = C_{max,\,m,p} \cdot p_{0,a,m,p}{}^{*}$$
$$= C_{max,\,m,p} \cdot \prod_{\text{each k}} \left[1 - \sum_{j=a}^{f} \left(\frac{A_j}{100} \cdot B_{q,j,k}{}^{*} \right) \right] \cdot \exp\left(-t_{B,a,m}{}^{*} \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right)$$
$$= C_{max,\,m,p} \cdot \prod_{\text{each k}} \left[1 - \sum_{j=a}^{f} \left(\frac{A_j}{100} \cdot B_{q,j,k}{}^{*} \right) \right] \cdot \exp\left(-\left(t_{B,a,m} - \Delta \right) \cdot \sum_{\substack{\text{i for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right)$$

[veh/h] (28)

Setting all corresponding parameters yields

$$C_{m,p} = G_m \cdot \prod_{\text{each } k} \left[1 - \sum_{j=a}^{f} \left(\frac{A_j}{100} \cdot \frac{Q_j \cdot f_{n,j}}{G_j} \right) \right] \cdot \exp\left(\Delta \cdot \sum_{\substack{i \text{ for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right)$$

[veh/h] (50)

where

$C_{m,p}$ = capacity for movement m including the influence of pedestrians [veh/h]

A_j, A_i = 100 if j or i is a vehicle movement (parameter for "limited priority")

= values in **hr** if j or i is a pedestrian movement f (cf. Table 4 or 5)

$B_{q,j,k}^*$ = occupancy in conflict group k by queuing movement j with Back-of-Queue = $f_{nj} \cdot B_{q,j,k}$ [-]

$B_{q,j,k}$ = occupancy in conflict group k by queuing movement j without Back-of-Queue = $Q_j / G_j = Q_j \cdot t_{B,q,j}^*/3600$ [-]

$B_{a,i}$ = $\left(t_{B,a,m} - \Delta\right) \cdot \frac{Q_i}{3600}$

Q_j, Q_i = volume of movement j or i [veh/h or ped/h]

= 0, if the relevant cell in Table A4 or A5 is empty (if i or j is a pedestrian movement, Q_i or Q_j represents the number of pedestrian groups)

$t_{B,q,j}^*$ = $\frac{3600}{G_j}$ [s]

G_j = Potential capacity of movement j

$$= \frac{3600}{t_{B,q,j}} \cdot \exp\left(-t_{B,a,j} \cdot \sum_{\substack{i \text{ for all} \\ \text{number in hr} \\ \text{except F}}} \left(\frac{A_i}{100} \cdot \frac{Q_i}{3600} \right) \right) \text{ [veh/h or ped/h]}$$

$f_{n,j}$ = factor for the turning movement j and the through movement n in order to take into account the effect of Back-of-Queue (applies only to movements 1 and 7)

$$= \left[1 - \sum \frac{Q_n}{G_n} \right]^{-1} = \left[1 - \sum B_{q,n}\right]^{-1}$$ (f_{nj}=1, if Back-of-Queue is neglected)

$t_{B,q,j}$ = average discharge service time for one vehicle in movement j [s]

= duration of blocked time caused on average by one vehicle for queue discharge $\approx t_{f,j}$

$t_{B,a,j}$ = duration of blocked time caused on average by one approaching vehicle in major movement j $\approx t_{c,j} - t_{f,j}/2$

$t_{B,a,j}^*$ = duration of blocked time caused on average by one approaching vehicle in major movement j for minor movement m exclude the minimal headway $\Delta = t_{B,a,j} - \Delta \approx t_{c,j} - t_{f,j}/2 - \Delta$

Δ = minimal headway in major movement (normally = 2 s)

Δ_p = minimal headway in major pedestrian movement (= 0 s)

a, f, k : see bottom line of Table 4 for cross-roads or 5 for T-junctions
All value in the square brackets are queue-free probabilities and the must be set to values larger or equal to 0.

In the reality, there may be situations, where car drivers typically give priority to other drivers; e.g. a minor right turner (i=6) is polite enough to give priority to opposite minor left turners (i=10) to improve their chance to depart. This "limited priority" (Troutbeck and Kako, 1997) can be handled by using A-values less than 100% also for vehicle traffic.

Conclusions

To cover the shortcomings in the existing ACF procedure for TWSC intersections, some crucial extensions and modifications are made. First at all, the queue-free states in movements of higher ranks are properly considered now. Also the share lane situations in major left-turn movements including the effect of Back-of-Queue can be taken into account. Furthermore, the $t_{B.a}$ values (corresponding to the critical gaps in the gap-acceptance theory) are applied - like the gap-acceptance procedure - to the subject minor movements instead to the major movements. The ACF procedure for TWSC intersections is now simplified and is more accurate. The modified ACF procedure can use the parameters from the gap-acceptance theory directly and delivers also comparable results. The robustness and the capability to taking into account pedestrian/bicycle influence, the main advantages of the ACF model, remain.

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