UNSIGNALIZED INTERSECTIONS - A THIRD METHOD FOR ANALYSIS

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INTRODUCTION

Capacity of Two-Way Stop-Controlled (TWSC) intersections is either analyzed by the empirical regression method, which is mainly applied in the context of British research results (Kimber and Coombe, 1980), or by the so-called gap-acceptance procedures (GAP). The latter is used in many countries of the world (cf. Brilon *et al*, 1995) such as in the USA (HCM, 1997 and 2000). For the HCM procedures a comprehensive investigation has been performed by Kyte *et al* (1994). A rather recent state of the art for this stream of theories is also documented in Kyte (1997). Other countries, like Sweden or Germany, also use the GAP method in their own capacity manuals. Thus it is correct to say that the theory of gap-acceptance is the predominant concept for TWSC intersection analysis in the world.

However, on a closer look this concept has a couple of drawbacks which could become a problem for practical application. These are:

- The determination of the critical gap is rather complicated (cf. Brilon *et al*, 1997). Some details of the practical aspects of critical gap estimations are also described in Tian *et al* (2000), and in former publications by these authors. In fact, looking into details of the determination, it turns out that for the determination a couple of definitions must be made which are not self-explanatory and which contain elements of arbitrariness. Their impact on the results is not clear. Thus, it is justified to say, that 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). However, in reality, they are based on pragmatic simplifications. This applies for the whole treatment of the hierarchy of four ranks of priorities at an intersection. Here some

movements are accounted for twice, an approach which is based on suggestions from Harders (1968) and were confirmed through simulations by Grossmann (1991). Overall these calculations produce results of a correct magnitude. They are, however, only of approximative 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 which is not exactly complying with the rules of priority such as gap forcing or polite behavior of priority drivers (priority reversal). This can be stated even if some approaches to deal with this problem have been published (Troutbeck *et al*, 1997; Kita, 1997).
- The gap-acceptance theory fails when pedestrians or cyclists share the use of the intersection. For pedestrians, at least on the European continent, rather complicated rules of priority apply: pedestrians sometimes have the right of way over cars and sometimes they do not. The whole set of rules is neither written explicitly in the highway code nor is it known to many road users. As a consequence, the real behavior both of pedestrians and motor vehicle drivers is of great variability. This variability is, however, not a framework which fits the gap-acceptance theory, which needs a clearly defined ranking of priorities with the assumption that each road user will exactly comply with these rules. This aspect will be discussed in more detail in this paper. The same aspects apply also to cyclists who can drive either on the roadway, on separate cycle paths, or in some illegal manner.

Therefore, it could be of interest to derive a third basic approach to the analysis of TWSC intersection operations. As a basis, the concept of Additive Conflict Flows (ACF) seems to be usable, which has first been developed by Gleue (1972) for signalized intersection analysis. It has been modified by Wu (2000a, b) to be applied on All-Way-Stop-Controlled intersections (AWSC). The same concept was developed for application on Two-Way-Stop-Controlled intersections (TWSC) (cf. Brilon and Wu, 2001). For this case the results are even easier to develop and apply than for the AWSC case. In this paper the ACF method applied to TWSC intersections is developed for more detailed geometric and traffic conditions at TWSC intersections.

The new procedure makes it easy to take into account a) the number of lanes of the subject, the opposite, and the conflict approach, b) the distribution of traffic flow rates on the different approaches, c) the number of pedestrians crossing the arms of the intersection, and d) flared approaches.

DEPARTURE MECHANISMS AT TWSC INTERSECTIONS

We start our derivations looking at a conflict between several movements (Fig. 1). As a conflict we treat the intersection of several movements which have to pass the same area within

an intersection. Consequently the vehicles from these movements have to pass the area one after the other. The set of movements which are involved into the same conflict is called a conflict group. In general the capacity of a minor stream can be expressed as

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

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	[-]

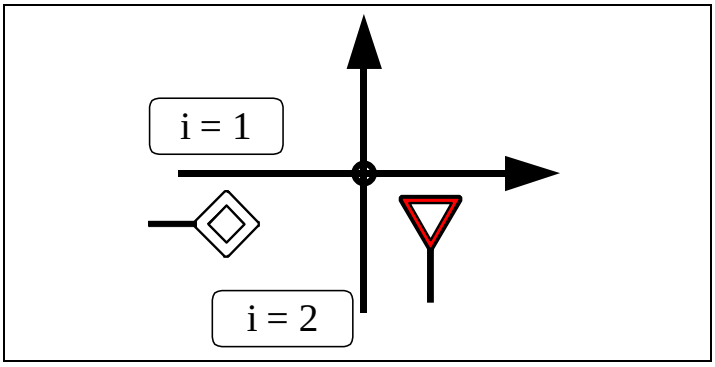

Fig. 1: Conflict between two movements

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 stream vehicles s and the probability that the conflict area is not blocked by approaching major vehicles. That is

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

The probabilities $p_{0,q}$ and $p_{0,a}$ are derived 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.

Probability $p_{0,q}$ of blockage during queue and queue discharge for traffic streams in a conflict group

First we concentrate on the easy case of two conflicting streams (Fig. 1). One of these movements (i=1) is assumed to have priority over the other, established by a yield sign or a stop sign for the minor movement. Then we assume that the conflict area is comparable to a

queuing system where each vehicle from movement i - passing this point - is consuming on average a service time $t_{B,q,i}$. The proportion of time occupied by queuing/discharging vehicles from stream 1 is

$$B_{q,1} = \frac{Q_1 \cdot t_{B,q,1}}{3600} \qquad \text{[veh/h]} \qquad (3)$$

where

Q_i	=	traffic demand for movement i	[veh/h]
$t_{B,q,i}$	=	discharging service time for movement i	[s]
$B_{q,i}$	=	proportion of occupancy by queuing/discharging movement i	[-]

with the restriction

$$Q_1 \cdot t_{B,q,1} \leq 3600$$

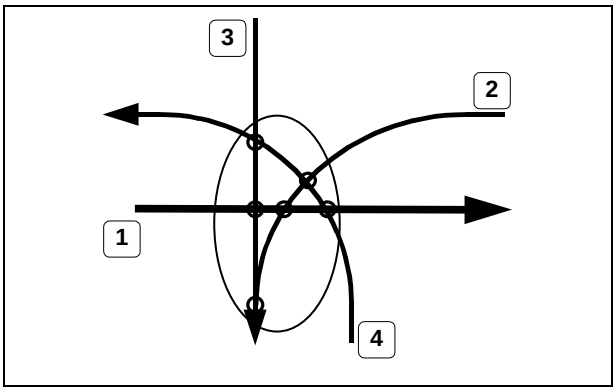

Fig. 3: Conflicts between four movements

$B_{q,i}$ is the proportion of time during which the conflict area is occupied by queuing/discharging vehicles from movement i ("i-vehicles"). Thus (1 - $B_{q,i}$) is the proportion of time during which the conflict area is free from queuing/discharging i-vehicles. Therefore, (1 - $B_{q,i}$) can be interpreted as an estimation for the probability $p_{0,q,i}$; i.e. the probability that no queuing/discharging i-vehicle is occupying the conflict zone. In analogy to these considerations we get the probability $p_{0,q}$ that the conflict area is not occupied by major stream 1:

$$p_{0,q} = p_{0,q,1} = \left(1 - B_{q,1}\right) = \left(1 - \frac{Q_1 \cdot t_{B,q,1}}{3600}\right) \qquad \text{[veh/h]} \qquad (4)$$

where $p_{0,q,i}$ is the probability that the conflict area is not occupied by queuing/discharging movement i.

Extending the same technique to a conflict group consisting of four movements (Fig. 3) we get the probability $p_{0,q}$ that the conflict area is not occupied by major stream 1, 2, and 3:

$$p_{0,q} = p_{0,q,1/2/3} = 1 - \frac{\left(Q_1 \cdot t_{B,q,1} + Q_2 \cdot t_{B,q,2} + Q_3 \cdot t_{B,q,3}\right)}{3600} = \left[1 - \left(B_{q,1} + B_{q,2} + B_{q,3}\right)\right]$$

[veh/h] (5)

where $p_{0,q,1/2/3}$ is the probability that the conflict area is neither occupied by queuing/discharging vehicles from stream 1 nor from stream 2 nor from stream 3.

More movements than four can not occur within a standard cross intersection.

Probability $p_{0,q}$ of blockage during queue and queue discharge for traffic streams in more than one conflict group

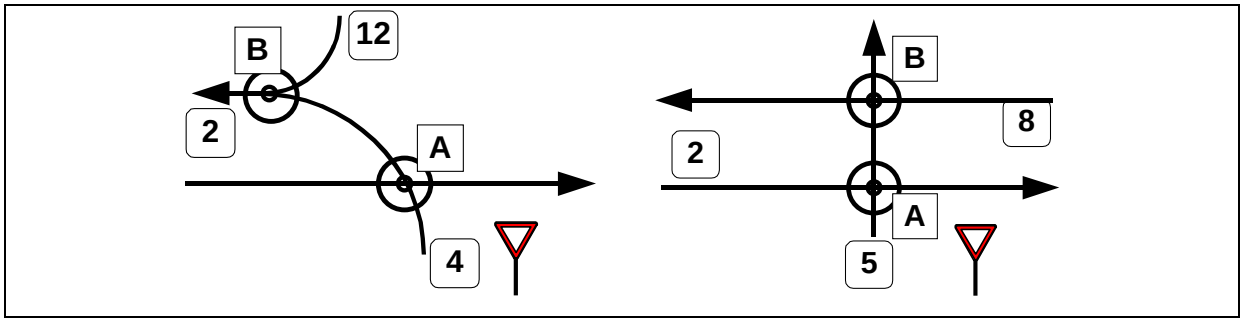

Fig. 4: One movement passing through two subsequent conflict groups

At a TWSC-intersection we have different traffic rules. Priority movements operate independently from each other. The major stream vehicles occupy the conflict area as soon as they arrive at the intersection. A minor stream vehicle, however, can only depart in the case that all conflict groups, which it needs to cross, are free of blockage at the same moment. The probability that both conflict areas are free from queuing/discharging simultaneously, is the product of the individual $p_{0,q}$-values. With that in mind we find for the cases from Fig. 4:

$$p_{0,q}^{*} = p_{0,q,A} \cdot p_{0,q,B}$$

For arbitrary n conflict groups, which have to be passed within a hierarchical system of priorities we get:

$$p_{0,q}^{*} = \prod_{k=1}^{n} p_{0,q,k} \tag{6}$$

where

$p_{0,q}^{*}$	=	probability that all conflict groups are free from queuing/discharging for the subject movement	[-]
k	=	index for conflict group	[-]
$p_{0,q,k}$	=	probability that conflict group k is free from queuing/discharging for the subject movement	[-]
n	=	number of conflict groups	[-]

Of course, mathematically speaking, eq. 6 is only valid, if all conflict groups would operate independently from each other, which is not necessarily the case for $n > 2$. Thus, for simplicity stochastic interdependencies between succeeding conflict groups are neglected when using eq. 6 for $n > 2$.

Probability $p_{0,a}$ of blockage due to approaching vehicles in major streams

For the case that the conflict area is not occupied by queuing/discharging vehicles from major streams, the conflict area can still be blocked by major stream vehicles approaching the intersection.

Assuming a time period $t_{B,a}$, 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 probability distribution of gaps (time headways) in the major streams is given. The probability $p_{0,a}$ can simply be expressed as the probability that a gap in major streams is larger than the time period $t_{B,a}$. Thus, we get

$$p_{0,a,i} = \Pr(t > t_{B,a,i}) = 1 - F(t_{B,a,i}) \qquad [-] \qquad (7)$$

where

$p_{0,a,i}$	=	probability that the conflict area is not blocked by approaching major vehicles from major movement i	[-]
t	=	duration of a gap in major movement i	[s]
$t_{B,a,i}$	=	time period, that the conflict is blocked by a approaching vehicle in major movement i	[-]
$F(t)$	=	probability distribution function for gap t	[-]

Because the traffic volume in streams at TWSC intersection is always much smaller than the lane capacity (≈ 1800 veh/h), the effect of bunching in major movements is neglected. Thus, with sufficient approximation, the gaps in the major streams can be assumed as exponentially distributed. Thus, we get

$$p_{0,a,i} = 1 - F(t_{B,a,i}) = \exp\left(-\frac{Q_i \cdot t_{B,a,i}}{3600}\right) = \exp(-B_{a,i}) \qquad [-] \qquad (8)$$

where $B_{a,i} = \dfrac{Q_i \cdot t_{B,a,i}}{3600}$

For a minor stream in a conflict group we then get:

$$p_{0,a} = \prod_{\substack{i \text{ for all} \\ \text{major} \\ \text{streams}}} p_{0,a,i} = \prod_{\substack{i \text{ for all} \\ \text{major} \\ \text{streams}}} \exp(-B_{a,i}) = \exp\Big(-\sum_{\substack{i \text{ for all} \\ \text{major} \\ \text{streams}}} B_{a,i}\Big) \qquad [-] \qquad (9)$$

For minor stream interfering with more than one conflict group we must take into account the major streams in all the conflict groups. Thus we get:

$$p_{0,a}^{*} = \prod_{\substack{i \text{ for all} \\ \text{major} \\ \text{streams} \\ \text{in all} \\ \text{groups}}} p_{0,a,i} = \exp\Big(-\sum_{\substack{i \text{ for all} \\ \text{major} \\ \text{streams} \\ \text{in all} \\ \text{groups}}} B_{a,i}\Big) \qquad [-] \qquad (10)$$

Here, it is to notice that none of the major streams should be double-counted.

Capacity of a minor stream involved in more than one conflict group

Finally we get from the eqs. 1 through 10 the capacity of a minor stream k involved in more than one conflict group:

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

$$= \frac{3600}{t_{B,q,m}} \cdot \prod_{\substack{\text{k fo1 all} \\ \text{groups}}} \left(1 - \sum_{\substack{\text{i for all} \\ \text{major} \\ \text{streams} \\ \text{in group k}}} \frac{Q_i \cdot t_{B,q,i}}{3600}\right) \cdot \exp\left(- \sum_{\substack{\text{i for all} \\ \text{major} \\ \text{streams} \\ \text{in all} \\ \text{groups}}} \frac{Q_i \cdot t_{B,a,i}}{3600}\right) \quad [-] \qquad (11)$$

In general the values of $t_{B,q}$ are comparable to the follow-up time t_f and the values of $t_{B,a}$ are comparable to the so-called zero time t_0 (t_0 = critical time t_c - follow-up time t_f / 2). These values can be achieved by measurements. It is to notice that the value of $t_{B,a}$ is - in contrast to gap-acceptance theory - a major stream related value not a minor stream related value.

CONFLICT GROUPS AT AN INTERSECTION

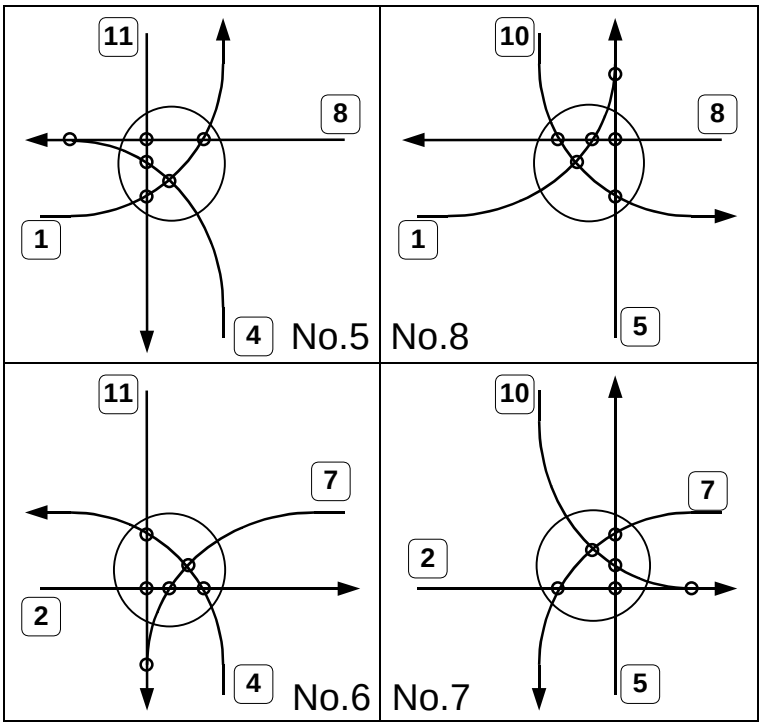

Fig. 5: Four typical conflict groups at an intersection

Motorized vehicle movements

We now look at a simple intersection of two streets. The whole configuration of traffic movements consists of twelve streams of motorized vehicle traffic. Here, as a first approach we assume that on the four approaches of the intersection there is exactly one lane available for each of the twelve movements. For this configuration the conflict groups outlined in Fig. 5 (valid for conflict groups 5 - 8) and Fig. 6 have been identified (Wu, 2000b). The strategy for

the definition was, that in conjunction with the considerations for eqs. 2 - 4 the hierarchical system of priorities according to traffic rules is represented.

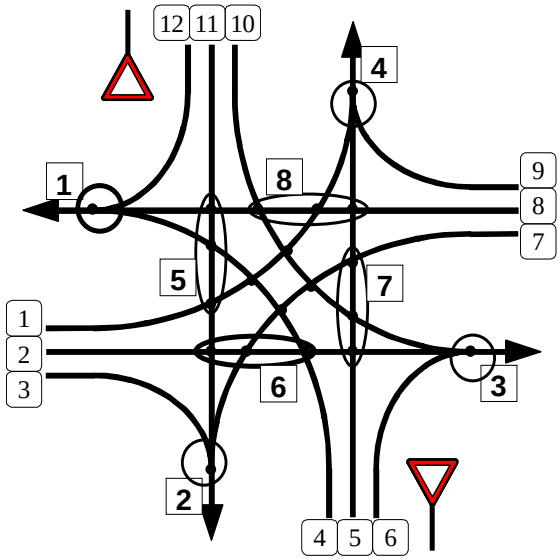

Fig. 6: Arrangement of conflict groups at a simple cross intersection (for conflict groups 5 - 8 : see fig. 5)

k **Conflict group** i **Movement**

For the further derivations an enumeration is needed for the 12 movements at the intersection. Here the system applied in the German guidelines is used (Fig. 6). Using the relations formulated in section 2 of this paper (cf. eqs. 2 - 4), we can now define the involvement of each movement into conflict groups and their conflicting movements as they are pointed out in Table 1. This formulation of conflict groups goes back on Wu (2000a). It has been derived from graph theory. This definition represents the traffic rules and the hierarchy of priorities in the most accurate way.

Based on these conflicts and on the derivations in section 2 the following set of equations turns out to be formulated very easily if the system obtained from Table 1 is applied.

$$C_1 = C_{max,1} \cdot (1 - B_{q,8}) \cdot (1 - B_{q,9}) \cdot \exp[-(B_{a,8} + B_{a,9})] \quad \text{[veh/h]} \quad (12)$$

$$C_2 = C_{max,2} \quad \text{[veh/h]} \quad (13)$$

$$C_3 = C_{max,3} \quad \text{[veh/h]} \quad (14)$$

$$C_4 = C_{max,4} \cdot [1 - (B_{q,2} + B_{q,7} + B_{q,11})] \cdot [1 - (B_{q,8} + B_{q,1} + B_{q,11})] \cdot [1 - (B_{q,8} + B_{q,12})] \cdot \cdot \exp(-(B_{a,2} + B_{a,7} + B_{a,11} + B_{a,8} + B_{a,1} + B_{a,12})) \quad \text{[veh/h]} \quad (15)$$

$$C_5 = C_{max,5} \cdot [1 - (B_{q,2} + B_{q,7})] \cdot [1 - (B_{q,8} + B_{q,1})] \cdot [1 - (B_{q,9} + B_{q,1})] \cdot \cdot \exp[-(B_{a,2} + B_{a,7} + B_{a,8} + B_{a,1} + B_{a,9})] \quad \text{[veh/h]} \quad (16)$$

$$C_6 = C_{max,6} \cdot (1 - B_{q,2}) \cdot \exp(-B_{a,2}) \quad \text{[veh/h]} \quad (17)$$

$$C_7 = C_{max,7} \cdot (1 - B_{q,2}) \cdot (1 - B_{q,3}) \cdot \exp[-(B_{a,2} + B_{a,3})] \quad \text{[veh/h]} \quad (18)$$

$$C_8 = C_{max,8} \quad \text{[veh/h]} \quad (19)$$

$$C_9 = C_{max,9} \quad \text{[veh/h]} \quad (20)$$

$$C_{10} = C_{max,10} \cdot \left[1 - \left(B_{q,8} + B_{q,1} + B_{q,5}\right)\right] \cdot \left[1 - \left(B_{q,2} + B_{q,7} + B_{q,5}\right)\right] \cdot \left[1 - \left(B_{q,2} + B_{q,6}\right)\right] \cdot \\ \cdot \exp\left[-\left(B_{a,8} + B_{a,1} + B_{a,5} + B_{a,2} + B_{a,7} + B_{a,6}\right)\right] \quad \text{[veh/h]} \quad (21)$$

$$C_{11} = C_{max,11} \cdot \left[1 - \left(B_{q,8} + B_{q,1}\right)\right] \cdot \left[1 - \left(B_{q,2} + B_{q,7}\right)\right] \cdot \left[1 - \left(B_{q,3} + B_{q,7}\right)\right] \cdot \\ \cdot \exp\left[-\left(B_{a,8} + B_{a,1} + B_{a,2} + B_{a,7} + B_{a,3}\right)\right] \quad \text{[veh/h]} \quad (22)$$

$$C_{12} = C_{max,12} \cdot \left(1 - B_{q,8}\right) \cdot \exp\left(-B_{a,8}\right) \quad \text{[veh/h]} \quad (23)$$

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	8 8 9			4 5 5	11 10
2	1	priority						
3	1		2				7	11
4	4	2, 7, 11 8, 1, 12	6 5 1	2 8 8	7 1 12	11 11		
5	3	2, 7, 8 1, 9	7 8 4	2 8 9	7 1 1		10 10	
6	2	2	3	2			10	
7	2	2, 3	7 6 2	2 2 3			5 4 11	10 11
8	1	priority						
9	1		4				1	5
10	4	8, 1, 5 2, 7, 6	8 7 3	8 2 2	1 7 6	5 5		
11	3	8, 1, 2, 7, 3	5 6 2	8 2 3	1 7 7		4 4	
12	2	8	1	8			4	
i	**r**	**hr**	**k**	**a**	**b**	**c**		

Table 1: Conflict groups and conflicting movements for each traffic stream at the intersection

With the denotation of the last line in Table 1 we can write these eqs. 12 - 23 in a more general way for a minor stream m:

$$C_m = C_{max,\,m} \cdot \prod_{\text{each } k} \left[1 - \left(B_{q,a} + B_{q,b} + B_{q,c}\right)\right] \cdot \exp\left(-\sum_{\substack{\text{i for all} \\ \text{numbers in hr}}} B_{a,i}\right) \quad \text{[veh/h]} \quad (24)$$

The relevant conflict groups k for each individual movement i are given in Table 1. If columns a, b, or c for a specific conflict group k in Table 1 are empty, then the corresponding $B_q = 0$.

At this point it should be noted: so far the model has not the qualities of a theoretically precise mathematical model. Instead it is a pragmatic representation of the traffic streams at the intersection and their mutual impediments according to traffic rules. Also the gap-acceptance theory, in principle, has not a higher qualification. The major advantage of the new model is that the capacity for any stream can be calculated as a function of traffic volumes of other streams in a single computational step. No capacities of higher ranked streams need to be computed in advance. The results are therefore more robust than the results from the gap-acceptance theory.

Pedestrian movements

Another group of conflicts has to be regarded if also pedestrians are admitted at the intersection (see Fig. 7). 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).

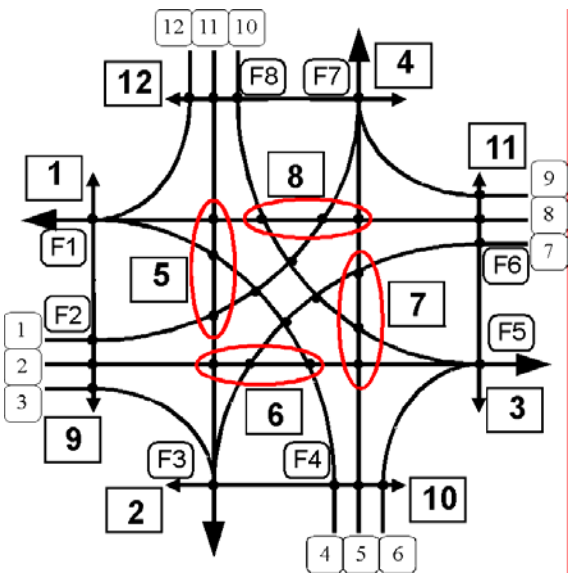

Fig. 7: Arrangement of conflict groups at a simple cross intersection including pedestrians

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

The question is to which degree these pedestrians have priority over car traffic. The answer may differ from country to country according to their specific traffic rules. The rules from the German highway code (StVO, 2001) stipulate that all turning movements have to give priority to pedestrians. This regulation results in some priority rules for pedestrian movements as expressed in Table 2. It needs some concentration

to understand these rules. Thus, they are also not really understood nor even known to street users – both to car drivers and pedestrians. Moreover, also jurisdictional literature in some cases expresses controversial opinions about these regulations.

conflict group k	**Pedestrian movement f**	**vehicle movements i in ( ) : $A_{k,f,i}$ - value in %**				
		Priority movements (i.e. peds have to give priority to vehicles from these movements)			**Priority to peds over vehicles from these movements**	
1	F1	8 (0)			4 (30)	12 (70)
2	F3	11 (10)			3 (70)	7 (30)
3	F5	2 (0)			6 (70)	10 (30)
4	F7	5 (10)			1 (30)	9 (70)
9	F2	1 (0)	2 (0)	3 (10)		
10	F4	4 (50)	5 (50)	6 (50)		
11	F6	7 (0)	8 (0)	9 (10)		
12	F8	10 (50)	11 (50)	12 (50)		

Table 2: Definition of pedestrian priority according to the German Highway Code (StVO, 1998); in ( ) : percentages $A_{k,f,i}$ of pedestrian priority for different conflicts

As a consequence, the usual practice is that these rules are not really applied. Instead motor vehicle drivers and pedestrians find their own arrangement in each individual situation. Some preliminary studies by Czytich and Boer (1999) found out that for each vehicle movement pedestrians – in case of a conflict – get priority in a specific proportion A of cases. That means: In A per cent of conflicting situations the pedestrian is going first and the car driver waits. Some estimations for A to be associated with the different conflicts are given in Table 2. These are obtained from Czytich and Boer (1999) and generalized into rounded values. More generalized values for A based on a larger sample size are going to be analyzed by the authors for German conditions in the next future within a research project funded by the German Federal DOT.

If we combine these rules from Table 2 into a table like the style of Table 1, we obtain Table 3. It needs quite a lot of concentration to follow through each detail. With Table 3 it becomes also obvious that the classical hierarchy of priority ranking is not longer easy to be applied if pedestrian crossings are included. We see that F3 (and F7) are of rank 5 with respect to movement 11 (and 5). With respect to movement 3 (and 9) the same movement F3 (and F7), however, is of rank 2. These movements 3 (and 9) have priority over 11 (and 5) (cf. Fig. 8). Thus a clearly structured consecutive ranking of priorities is not longer existing with pedestrian priorities in mind. This is another reason why the classical theory of gap-acceptance comes to an end when pedestrians are to be regarded at TWSC-intersections.

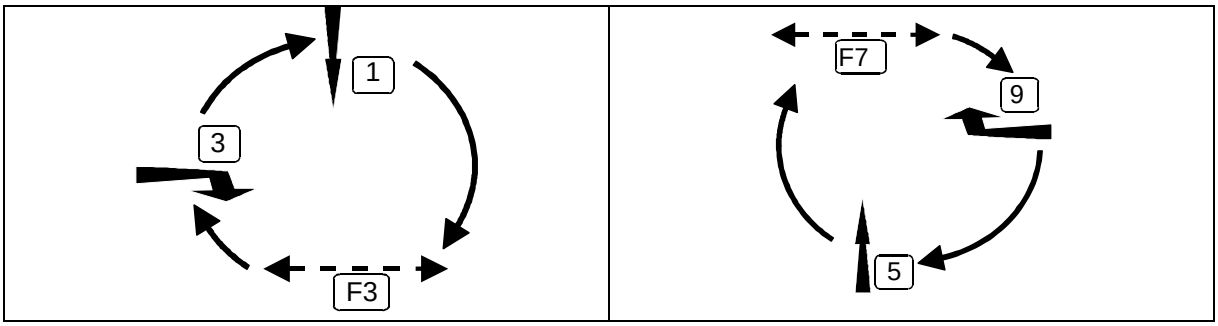

Fig. 8: Cycle of priorities: the round arrows are a symbol for "has priority over".

Regardless of this problem, in the new theory Table 3 together with eq. 24 gives us the framework to indicate an equation, which calculates the capacity for each of the vehicle movements, where also the influence of pedestrians is observed:

$$C_{m,p} = C_{max,m,p} \cdot \prod_{\text{each } k} \left[1 - \sum_{j=a}^{f} \left(\frac{A_j}{100} \cdot B_{q,j,k} \right) \right] \cdot \exp\left(- \sum_{\substack{i \text{ for all} \\ \text{number in hr}}} \left(\frac{A_i}{100} \cdot B_{a,i} \right) \right) \quad \text{[veh/h]} \quad (25)$$

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 (cf. remark "limited priority" below)	
	=	$A_{k,f,i}$, if j or i is a pedestrian movement f (cf. Table 2)	
$A_{k,f,i}$	=	probability of priority for pedestrians from movement f in conflict group k over vehicles from movement i	[%]
$B_{q,j,k}$	=	occupancy in conflict group k by queuing movement j	
	=	$Q_j \cdot t_{B,q,j}/3600$	[-]
$B_{a,i}$	=	$Q_i \cdot t_{B,a,i}/3600$	[-]
Q_j, Q_i	=	volume of movement j or i	[veh/h or ped/h]
	=	0, if the relevant cell in Table 3 is empty	
$t_{B,q,j}$	=	average discharge service time for one vehicle or pedestrian in movement j	[s]
	=	duration of blocked time caused on average by one vehicle or pedestrian for queue discharge	
$t_{B,a,i}$	=	duration of blocked time caused on average by one approaching vehicle in major stream i	
a, f, k	:	see bottom line of table 3	

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**				
71	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 3: Conflict groups and conflicting movements for each traffic stream at the intersection including pedestrians.

The time during which a crosswalk near an unsignalized intersection is occupied by one pedestrian may be depending on pedestrian volume as well as on width of the crosswalk. It can be estimated based on empirical observations. Czytich and Boer (1999) found from a limited sample of observations in Germany that for a single approaching pedestrian using the crosswalk on average a block time of $t_{B,a,i}$ = 3.2 s is consumed. The discharging service time of $t_{B,q,j}$ can be assumed as nearly 0 s. For further application, $t_{B,a}$ = 1 s is used. This value seems to be quite low. It has, however, also to take into account that pedestrians in many cases are grouped. Thus the average blocking time per pedestrian is lower than the time needed to cross the street. In the cases observed, the width of the crosswalks was not a limiting factor to pedestrian's freedom crossing the street.

By the way: eq. 25 would very easily allow to account for the effect of "limited priority" (Troutbeck and Kako, 1997) by using A-values less than 100% also for vehicle traffic. 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. If this would happen in 40 % of such conflicts then the $A_{j=6}$-value would be 60 in eq. 25. If this concept should be included into a future version of the model, then also the movements in column g, h, and m of Table 3 must be regarded for the sum in eq. 25.

INTERSECTION WITH SINGLE-LANE APPROACHES

Now we concentrate on an intersection where each approach has only one lane. This adds another degree of complication since we now have also a limitation of entry capacity due to the mutual interaction of movements on each of the entries to the intersection.

If one entry lane is used by several movements we call this - according to the usual concept of unsignalized intersections - a shared lane. The capacity of shared lanes can be determined according to a formula first developed by Harders (1968). This concept has been extended by Wu (1997) such that also additional lanes of limited length (short lane) can be taken into account. For the common case that all streams at an approach use the same shared lane the capacity of this shared lane, C_s, is given by

$$C_s = \frac{Q_{s,L} + Q_{s,T} + Q_{s,R}}{x_{s,L} + x_{s,T} + x_{s,R}} \qquad \text{[veh/h]} \quad (26)$$

where

C_s	=	capacity of the shared lane	[veh/h]
$Q_{s,L}$	=	volume for left turners using the shared lane	[veh/h]
		(in analogy: T : through movement / R : right turner)	

$C_{s,L}$ = capacity for left turners according to the equations mentioned above (i.e. for an exclusive lane) [veh/h]

$x_{s,L}$ = $Q_{s,L} / C_{s,L}$ = degree of saturation [-]

For the case of a single-lane approach with an additional short lane near the intersection (flared entry) offering space for one right-turning vehicle the capacity of the shared traffic lane can be calculated from (Wu, 1997) by

$$C_s = \frac{Q_{s,L} + Q_{s,T} + Q_{s,R}}{\sqrt{(x_{s,L} + x_{s,T})^2 + (x_{s,R})^2}} \quad \text{[veh/h]} \quad (27)$$

Using both equations (eq. 26 and 27) the following restriction has to be observed

$$(Q_{s,L} \cdot t_{B,q,s,L}) + (Q_{s,T} \cdot t_{B,q,s,T}) + (Q_{s,R} \cdot t_{B,q,s,R}) + (Q_F \cdot t_{B,q,F}) \leq 3600 \quad \text{[s]} \quad (28)$$

Again (s,L), (s,R), and (s,T) stand for the index of the left (L) and right turning (R) movement and the through movement (T) respectively, on the shared lane (s). F stands for the pedestrian movement involved into the entry conflict group.

A ROUGH CALIBRATION OF THE MODEL

move-ment	**critical gap t_c**	**follow-up time t_f**	**range of volume used for calibration**	**resulting $t_{B,a}$-values**	**corresponding $t_g^* = t_{B,a}+t_{B,q}/2$**	**resulting $t_{B,q}$-values**
1	5.5	2.6	0 - 200	5.0	6.3	2.6
2	-	-	0 - 400	2.4	3.4	2.0
3	-	-	0 - 250	2.1	3.1	2.0
4	6.6	3.4	0 - 120	-[1)]	-[1)]	3.3
5	6.5	3.5	0 - 150	3.1	4.8	3.5
6	6.5	3.1	0 - 350	5.5	7.1	3.2
movements 7 through 12 correspond to movements 1 through 6						
	s	s	veh/h	s	s	s

Table 4: Parameters used for the calibration process together with calibrated t_B-values (t_c- and t_f-values are obtained from Weinert, 2000). [1)] : no result through calibration

The t_B-values constitute the parameters of the model. By an appropriate selection of these values the model should receive the qualification to represent the real world with sufficient quality. For this model it is not useful to measure these values directly from field observations, since the beginning and the termination of each individual t_B can not clearly be defined. Thus, direct measurement could reveal quite a range of t_B-values depending on experimenter's

decisions for details of the measurement techniques. Instead the t_B-values should be estimated in the sense of statistical parameter estimation. Those t_B-values should be selected which give the best coincidence between specific traffic performance parameters (like capacities, average delays, or average queue lengths) and the corresponding model results. The coincidence could e.g. be assessed using minimized variances between measured values and estimated model results. For these parameter estimations the underlying observed demand volumes for all movements should be varied over a realistic range of magnitudes.

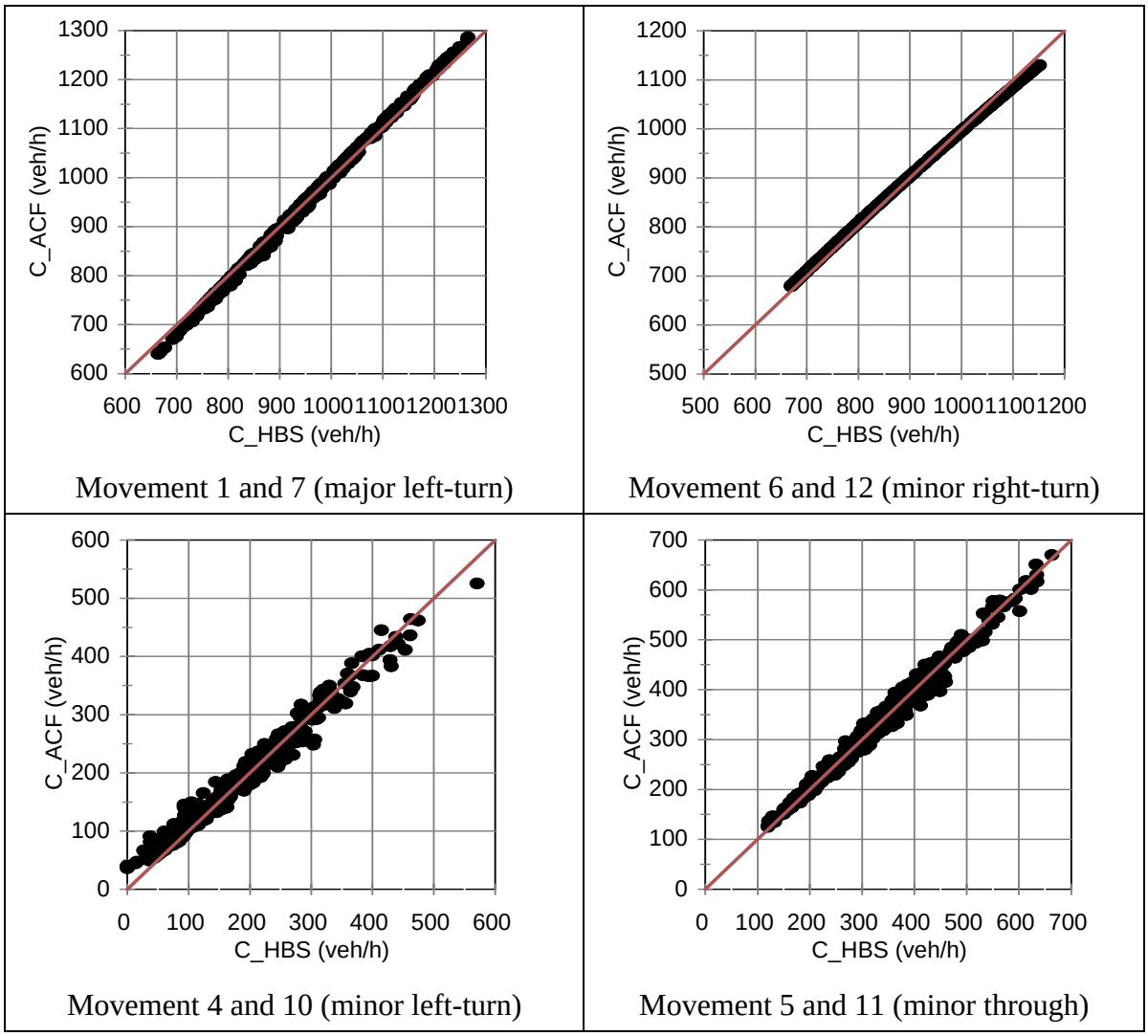

Fig. 9: Comparison of capacities from the new model (ACF) to the value of German HCM (HBS)

In this sense, to calibrate the model, only the set of 12*2 t_B-values (12 for $t_{B,q}$ and 12 for $t_{B,a}$) must be estimated. Due to the symmetry of movements coming from the north side or the south side the number of unknown t_B-values is reduced to 6*2=12. For the stream 4 and 10 the $t_{B,a}$-values are not used at all. Furthermore we set the $t_{B,q}$-value of streams 3 equal to the value of stream 2 and the $t_{B,q}$-value of streams 9 equal to the value of stream 8. Thus it is only necessary to calibrate 10 t_B-values. Of course, it would be desirable to produce the

t_B-estimation based on empirical studies. This will be made in the near future by the authors. As a preliminary estimate another solution is proposed, just to demonstrate the applicability of the new method and to give an idea for the size of the t_B-values.

To avoid interference from geometry conditions we use the idealized intersection in Fig. 6 for this calibration process. Here we assume one turning lane for each of the turning movements. The intersection is controlled by yield-signs on the minor street and it is assumed, that the site is at a rural intersection with a population of drivers being familiar with the situation. For this intersection an analysis has been made by the classical gap acceptance theory (cf. data in Table 4). It was performed on a spreadsheet using the German standardized procedure for unsignalized intersection analysis. This procedure is very similar to the procedures established in the HCM (1997, 2000). The critical gaps and follow-up times were obtained from a recent study performed for rural intersections in Germany (Weinert, 2000). For the calculations 400 different combinations of traffic volumes (which were generated randomly within a reasonable range of values, cf. Table 4) for motorized vehicle traffic were applied. Since only the influence between different vehicle movements had to be analyzed, no pedestrians were regarded in this step of calibration. For these 400 combinations of volumes the capacity of each minor movement has been determined based on the GAP solution. In addition the set of equations 7 - 24 has been programmed in a spreadsheet (Corel Quattro-Pro8). Here the optimizer tool has been used to adjust the capacities obtained from both methods as close as possible. For the optimization the sum of the quadratic errors was minimized. This optimization gave a first estimation of the t_B-values. These are those values, which reveal the best fit to the results of the GAP methodology with parameters, which are characteristic for Germany.

As a result the t_B-values given in Table 4 were obtained. They give an idea about the magnitude for these parameters. They may be used as a first very rough approach for applying this new ACF-technique. Of course, for a definite use of this new technique some more empirical evidence is needed. Then the parameters might also be calibrated based on an optimum approximation of observed and calculated delays, which would lead to a better performance of the whole procedure. Nevertheless, the simple calibration process, used here, shows the practicability of this new concept.

The values of $t_{B,q}$ are comparable to the measured following-up t_f time. Also the $t_{B,a}$-values are more or less in the same range as the measured values of $t_0 = t_c - t_f /2$. Because of the major stream related nature of the $t_{B,a}$-values, no direct comparison is possible.

In Fig. 9 the calibration results are compared with the capacities calculated from the German HCM (HBS 2001). It shows a very good correlation between the results from both models.

TESTS OF THE RESULTS BY MEASUREMENTS

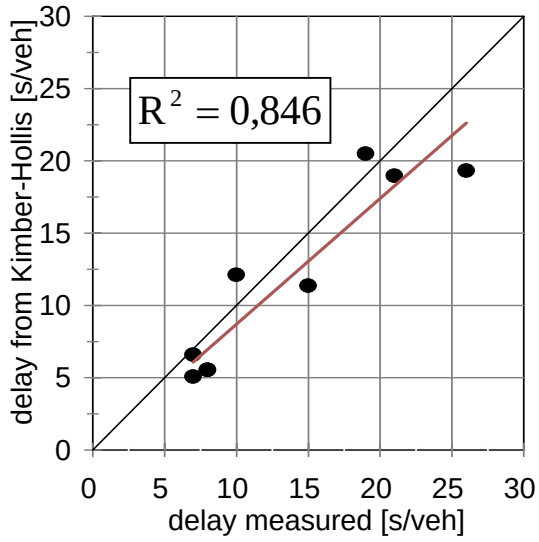

Fig. 10 Comparison of delays at TWSC intersections

In order to test the results of the new procedure field data collected at real TWSC intersections in Germany were employed. At four intersections 4 major left-turn and 4 shared minor approaches were measured. All intersections were intersections on rural highways. At the measured TWSC intersections, delays and queue lengths instead of capacities were measured. Against these data the new procedure was tested. The formulations of capacities in the previous sections and the calibrated t_B-values were used.

Fig. 10 shows the comparison between the measured and the calculated delays. Delays were calculated by the formula from Kimber and Hollis (1979) using capacities obtained from eq. 24 with parameters given in Table 4. It is obvious, that a good correlation between the measured delays and the estimated delays exists. It can be expected that the correlation would be much better using sites-related t_B-values

CONCLUSION

In addition to the classical methods for TWSC-intersection analysis (the empirical regression method and the critical gap method) a new technique has been developed. It is based on the procedure of Additive Conflict Flows (ACF) after Gleue. The background of this new method is easier to understand than the theory of gap-acceptance.

With this technique it is also possible to take into account the complicated regulations of pedestrian priority as they apply on the European continent. Also the real road user behavior which deviates from the rules, as they are established in the highway code, can rather easily and flexibly be taken into account. Thus the method makes it very easy to account for the so-called limited priority effects.

The t_B-values in the model are just parameters. It is not useful trying to measure these values in the field. They are only to be calibrated based on model results like capacities or average delays. There are various possibilities to calibrate the t_B-values as the parameters of the model. For this paper an estimation has been made to show the practicability of the concept and to

demonstrate the magnitude of these parameters. Of course, empirical evidence of the method must still be proven. Also the realization of the concept for each possible intersection layout must still be figured out in form of a suitable computer program, an exercise which is not of theoretical complication.

The major advantage of the new model is that the capacity for any stream can be calculated as a function of traffic volumes of other streams in a single step. No capacities of higher ranked streams need to be computed in advance. The results are therefore more robust than the results from the gap-acceptance theory.

The new concept is expected to have the potential to substitute the gap-acceptance theory to a great extend. Especially when also pedestrian movements have to be included into the analysis, the new technique provides significant advantages.

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