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CAPACITY AT UNSIGNALIZED INTERSECTIONS DERIVED BY CONFLICT TECHNIQUE

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Abstract

A new simplified theoretical approach for the determination of capacities at unsignalized intersections has been derived. This approach is based on the method of Additive Conflict Streams (ACS). The method is much easier to handle compared to the method of gap-acceptance. It avoids a lot of theoretical complications imbedded into the method of gap-acceptance which, under certain circumstances, seem to be rather unrealistic. The new method has been developed for application on each potential intersection configuration where one street has priority over the other. A calibration of the parameters within the model is given for German conditions. The new procedure can deal with shared lanes, short lanes and flared entries and also with cases of so-called limited priority. For the estimation of traffic performance measures - like average delay and queue lengths - the classical methods can be applied.

Keywords: Capacity, unsignalized intersection, traffic flow quality

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1 Introduction

Capacity of unsignalized intersections is either analysed by the empirical regression method, which is mainly applied in the context of British research results (Kimber, Coombe, 1980), or by the so-called gap-acceptance procedures (GAP). The latter is used in many countries of the world (cf. Brilon, Troutbeck, Tracz, 1995) such as in the USA (HCM, 1997 and 2000). For the HCM procedures a comprehensive investigation has been performed by Kyte e.a. (1994). A rather recent state of the art for this stream of theories is also documented in Kyte (1997). Also other countries, like Sweden, 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 unsignalized intersection analysis in the world.

On a closer look this concept has, however, 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, König, Troutbeck, 1997). Some details of the practical aspects of critical gap estimations are also described in Tian e.a. (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-explaining 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 very theoretical mathematics. However, they are more 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) 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 has no real good chance to apply on 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 this problem have been published (Troutbeck e.a., 1997; Kita, 1997).
- The gap-acceptance theory does completely loose its applicability when it should be extended to accounting for pedestrians or cyclists at the intersection. For pedestrians, at least on the European continent, rather complicated rules of priority apply, such that 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 to the sophistication of 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 figured out in more detail in this paper. The same aspects apply also for cyclists which 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 concept of analysis for unsignalized 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). In this paper the same concept is developed for application on Two-Way-Stop-Controlled intersections (TWSC). For this case the results are even easier to develop and apply than for the AWSC case.

The new procedure makes it easy to take into account

- the number of lanes of the subject, the opposite, and the conflict approach,
- the distribution of traffic flow rates on the different approaches,
- the number of pedestrians crossing the legs of the intersection,
- flared approaches.

2 Departure mechanisms at TWSC intersections

2.1 Capacity of traffic streams in a conflict group

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 the movements involved into one conflict 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.

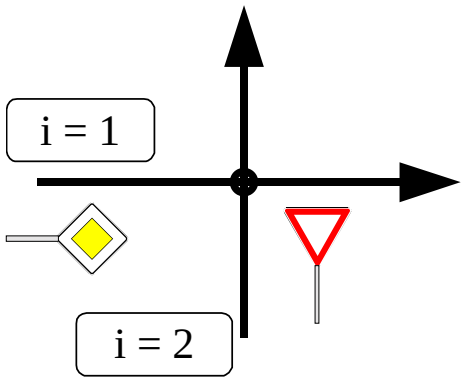


Fig. 1: Conflict between two movements

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 queueing system where each vehicle from movement i - passing this point - is consuming on average a service time $t_{B,\,i}$. The total time available for vehicles from both movements is 3600 s per hour. If we look at the situation where the intersection is oversaturated (i.e. $Q_2 > C_2$) we find that the relation is true

$$3600 = Q_1 \cdot t_{B,1} + C_2 \cdot t_{B,2} \qquad \text{[veh/h]} \quad (1)$$

where

Q_i	=	traffic demand for movement i	[veh/h]
C_i	=	capacity for movement i	[veh/h]
$t_{B,\,i}$	=	service time for movement i	[s]

with the restriction

$$Q_1 \cdot t_{B,1} \le 3600$$

Thus we get for the capacity of the minor street movement i=2 :

$$C_2 = \frac{3600 - Q_1 \cdot t_{B,1}}{t_{B,2}} = \frac{3600}{t_{B,2}} \cdot \left(1 - \frac{Q_1 \cdot t_{B,1}}{3600}\right) = C_{max,2} \cdot (1 - B_1) = C_{max,2} \cdot p_{0,1}$$

[veh/h] (2)

where

B_i = $\frac{Q_i \cdot t_{B,i}}{3600}$ = occupancy by movement i

$p_{0,i}$ = *(1 - B_i)* = probability that the conflict area is not occupied by movement i

$C_{max,\,j}$ = $\frac{3600}{t_{B,\,j}}$ = maximum capacity of movement 1 in case of no conflicting streams

B_i is the proportion of time during which the conflict area is occupied by vehicles from movement i ("i-vehicles"). Thus *(1 - B_i)* is the proportion of time during which the conflict area is free from i-vehicles. Thus *(1 - B_i)* can be interpreted as an estimation for the probability $p_{0,i}$; i.e. the probability that no i-vehicle is occupying the conflict zone. In analogy to these considerations further p_0 - values are to be defined below.

Now we look at a conflict group consisting of three movements (fig. 2). Here a hierarchy of priorities should be applicable like it is valid for conflicts at an unsignalized intersection; i.e. movement 1 has highest priority, movement 2 is of intermediate priority, and movement 3 has to yield to both of the other movements.

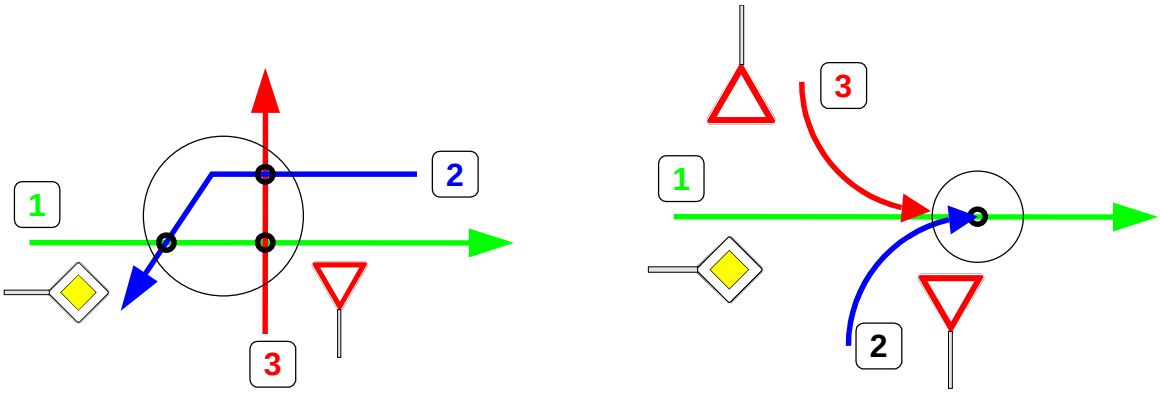


Fig. 2: Conflicts between three movements

With the same logic as described above we can again apply eq. 2 for the capacity of movement 2. For the capacity of movement 3 we can now derive:

$$C_3 = \frac{3600 - \left(Q_1 \cdot t_{B,1} + Q_2 \cdot t_{B,2}\right)}{t_{B,3}}$$
$$= C_{\max,3} \cdot \left[1 - \left(B_1 + B_2\right)\right] \qquad \text{[veh/h]} \quad (3)$$
$$= C_{\max,3} \cdot p_{0,1/2}$$

where

$p_{0,\,1/2}$ = [1 - (B_1 + B_2)] = probability that the conflict area is neither occupied by vehicles from stream1 nor from stream 2

Extending the same technique to a conflict group consisting of four movements (fig. 3) we get the capacity for a movement of rank 4:

$$C_4 = \frac{3600 - \left(Q_1 \cdot t_{B,1} + Q_2 \cdot t_{B,2} + Q_3 \cdot t_{B,3}\right)}{t_{B,4}}$$
$$= C_{\max,4} \cdot \left[1 - \left(B_1 + B_2 + B_3\right)\right] \qquad \text{[veh/h]} \quad (4)$$
$$= C_{\max,4} \cdot p_{0,1/2/3}$$

where

$p_{0,\,1/2/3}$ = [1 - (B_1 + B_2 + B_3)] = probability that the conflict area is neither occupied by vehicles from stream1 nor from stream 2 nor from stream 3

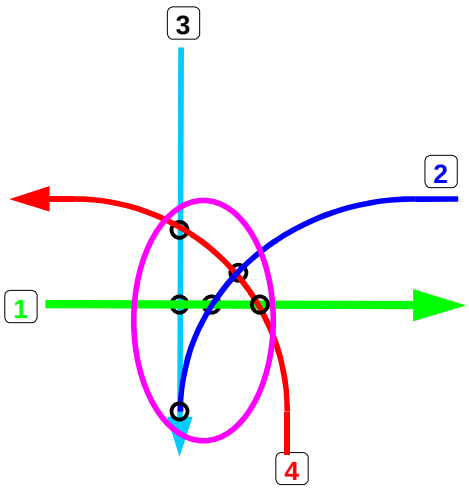


Fig. 3: Conflicts between four movements

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

Up to this point the equations are formulated for the case that each movement i has its own average service time $t_{B,i}$. This basic assumption for the model would, however, imply that after the whole formulation of the model a calibration process will be needed to estimate useful values for the whole variety of t_B-values. This task in reality can, however, not been fulfilled since too many sets of data from comparable situations would be needed. Thus also a simplified set of model assumptions might be useful. A significant simplification can be achieved if - with sufficient degree of precision - it could be assumed that the $t_{B,i}$-values are identical for all movements i. Then we come to the following set of equations:

$$C_2 = \frac{3600}{t_B} - Q_1$$

$$C_3 = \frac{3600}{t_B} - (Q_1 + Q_2) = C_2 - Q_2 \qquad \text{[veh/h]} \quad (5)$$

$$C_4 = \frac{3600}{t_B} - (Q_1 + Q_2 + Q_3) = C_3 - Q_3$$

(For a negative result of the equations the corresponding capacity is always = 0).

Also an intermediate degree of simplification of equations 1 to 4 might be useful; i.e. the assumption that highest ranked through movements (i.e. with absolute priority) have their own - usually lower - t_B-value t_{B1}, whereas all the non-priority and turning movements can be described by a common service time t_{BM}. Then we get as a set of capacity equations:

$$C_2 = \frac{3600 - Q_1 \cdot t_{B1}}{t_{BM}}$$

$$C_3 = C_2 - Q_2 \qquad \text{[veh/h]} \quad (6)$$

$$C_4 = C_3 - Q_3$$

Calibrations will show, however, that these simplifications are not very realistic.

In each of the equations 2 to 6, of course, negative values for capacities C_i are not allowed. In case, that a negative value should occur, the capacity must be set as 0.

2.2 Involvement of one stream into more than one conflict group

At real intersections all movements have to travel through several conflict groups (for examples see fig. 4). For AWSC intersections the capacity for one subject stream is the smallest capacity that can be achieved in each of the conflict groups (cf. Wu 2000a). The reason is the departure discipline according to the traffic rules: The vehicles depart in the sequence, in which they arrive at their respective stop lines (first in first out, FIFO). Thus, with queues on all entrances, vehicles from all the conflicting movements will wait and give way if (according to FIFO) it is the term for a subject stream vehicle to depart. On the other hand, under such saturated conditions, two vehicles from non-conflicting movements will depart simultaneously after they have stopped, if they arrive rather at the same time .

At a TWSC-intersection we have different traffic rules. Priority movements operate independently from each other. Vehicles from priority movements are not stopped. They occupy the conflict area as soon as they arrive. The arrival process itself has properties of randomness. A minor stream vehicle, however, can only depart in the case that all conflict groups, which they need to cross, are free (i.e. not occupied by other vehicles) at the same moment. The probability that both conflict areas are free simultaneously, is the product of the individual p_i-values. With that in mind we find for the cases from fig. 4:

$$C_x = C_{\max,x} \cdot p_{0,A} \cdot p_{0,B}$$

For more than two conflict groups , which have to be passed within a hierarchical system of priorities we get:

$$C_i = C_{\max,i} \cdot \prod_{k=1}^{n_i} p_{0,k,i} \qquad (7)$$

where

i	=	index for a movement	[-]
C_i	=	capacity of movement i	[veh/h]
C_{max}	=	capacity of movement i for the case that all other movements have no traffic	[veh/h]
k	=	index for a conflict group	[-]
$p_{0,k,i}$	=	probability that conflict group k is free for movement i	[-]
n_i	=	number of conflict groups which a vehicle from movement i has to pass	[-]

Of course, mathematically speaking, eq. 7 is only valid, if all conflict groups would operate independently from each other, which is not necessarily the case for $n_i > 2$. Thus, for simplicity stochastic interdependencies between succeeding conflict groups are neglected when using eq. 7 for $n_i > 2$.

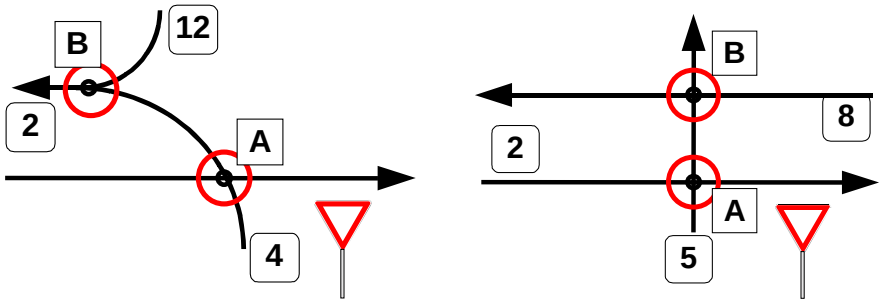


Fig. 4: One movement passing through two subsequent conflict groups

3 Conflict groups at an intersection

3.1 Motorized vehicle movements

We now look on 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 eq. 2 - 4 the hierarchical system of priorities according to traffic rules is represented.

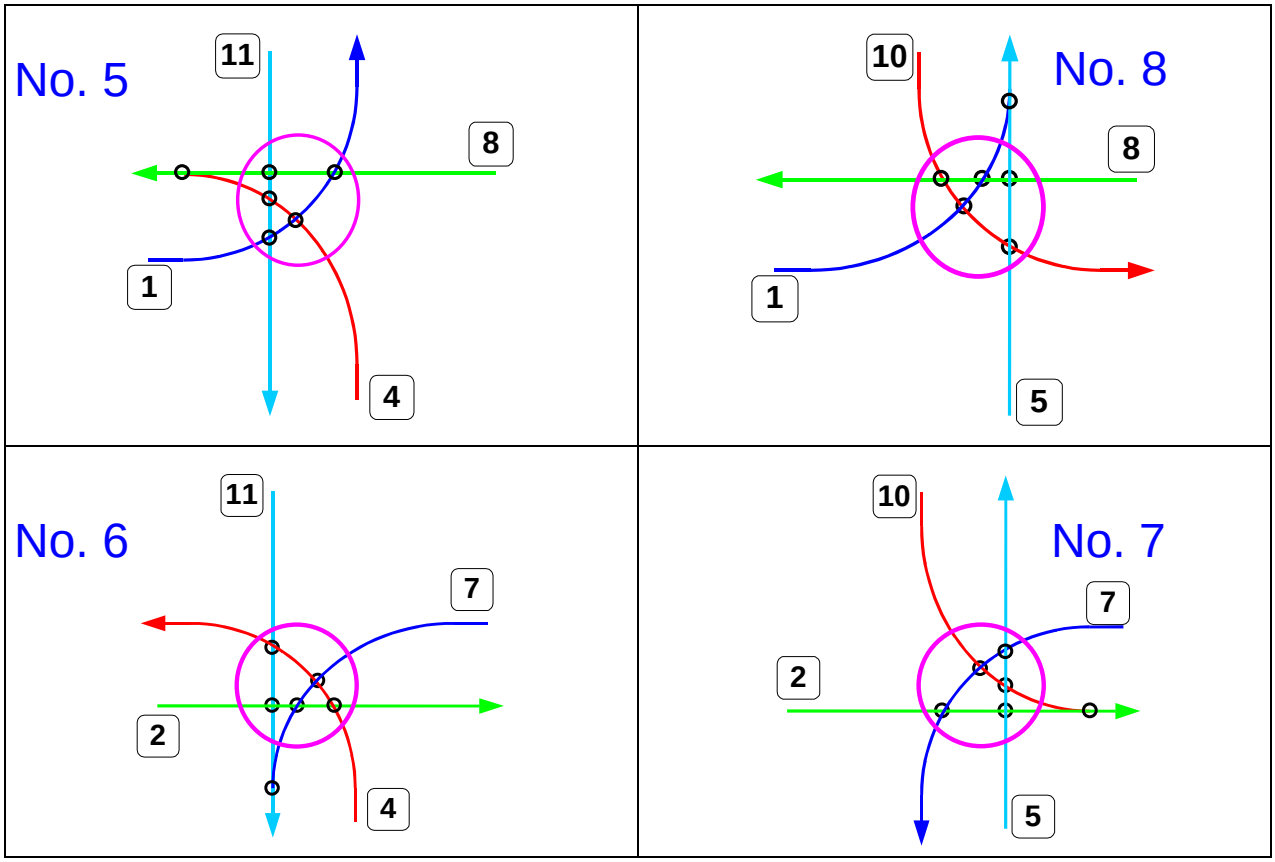


Fig. 5: Four typical conflict groups at an intersection

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. eq. 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 tested against different alternative definitions. This definition, however, represents the traffic rules and the hierarchy of priorities in the most accurate way.

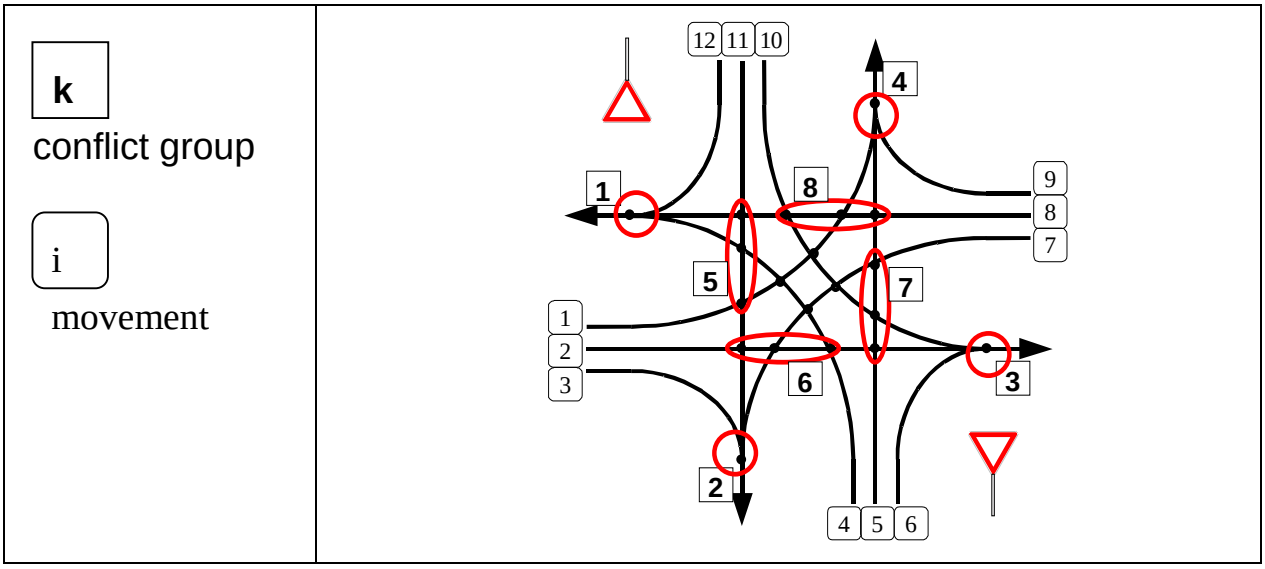


Fig. 6: Arrangement of conflict groups at a simple cross intersection (for conflict groups 5 - 8 : see fig. 5)

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

$$C_1 = C_{max,1} \cdot (1 - B_8) \cdot (1 - B_9) \quad \text{[veh/h]} \quad (8)$$

$$C_2 = C_{max,2} \quad \text{[veh/h]} \quad (9)$$

$$C_3 = C_{max,3} \quad \text{[veh/h]} \quad (10)$$

$$C_4 = C_{max,4} \cdot [1 - (B_2 + B_7 + B_{11})] \cdot [1 - (B_8 + B_1 + B_{11})] \cdot [1 - (B_8 + B_{12})] \quad \text{[veh/h]} \quad (11)$$

$$C_5 = C_{max,5} \cdot [1 - (B_2 + B_7)] \cdot [1 - (B_8 + B_1)] \cdot [1 - (B_9 + B_1)] \quad \text{[veh/h]} \quad (12)$$

$$C_6 = C_{max,6} \cdot [1 - B_2] \quad \text{[veh/h]} \quad (13)$$

$$C_7 = C_{max,7} \cdot [1 - B_2] \cdot [1 - B_3] \quad \text{[veh/h]} \quad (14)$$

$$C_8 = C_{max,8} \quad \text{[veh/h]} \quad (15)$$

$$C_9 = C_{max,9} \quad \text{[veh/h]} \quad (16)$$

$$C_{10} = C_{max,10} \cdot [1 - (B_8 + B_1 + B_5)] \cdot [1 - (B_2 + B_7 + B_5)] \cdot [1 - (B_2 + B_6)] \quad \text{[veh/h]} \quad (17)$$

$$C_{11} = C_{max,11} \cdot [1 - (B_8 + B_1)] \cdot [1 - (B_2 + B_7)] \cdot [1 - (B_3 + B_7)] \quad \text{[veh/h]} \quad (18)$$

$$C_{12} = C_{max,12} \cdot [1 - B_8] \quad \text{[veh/h]} \quad (19)$$

Subject movement No.	rank	Conflict group	conflicting movements higher priority ranking rank : 1	2	3	lower rank	
i	**r**	**k**	**a**	**b**	**c**		
1	2	5	8			4	11
		8	8			5	10
		4	9			5	
2	1	priority					
3	1	2				7	11
4	4	6	2	7	11		
		5	8	1	11		
		1	8	12			
5	3	7	2	7		10	
		8	8	1		10	
		4	9	1			
6	2	3	2			10	
7	2	7	2			5	10
		6	2			4	11
		2	3			11	
8	1	priority					
9	1	4				1	5
10	4	8	8	1	5		
		7	2	7	5		
		3	2	6			
11	3	5	8	1		4	
		6	2	7		4	
		2	3	7			
12	2	1	8			4	
i	**r**	**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 equations 8 - 19 in a more general way :

$$C_i = C_{\max,\,i} \cdot \prod_{each\ k} \left[1 - \left(B_a + B_b + B_c\right)\right] \qquad \text{[veh/h]} \qquad (20)$$

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 = 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.

3.2 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).

The question is to which degree these pedestrians have priority over the car traffic. The answer may differ from country to country according to their specific traffic rules. The rules from the German highway code (StVO, 1998) are expressed in table 2. They mean:

- In each conflict where pedestrians are crossing the path of vehicles driving straight ahead, the vehicle has the right of way.
- At entrances to an intersection - both at the minor and the major street - the vehicles have priority over pedestrians.
- The pedestrians, however, have priority at the exits over all turning vehicles.
- Only at a zebra-crossing the pedestrians have absolute priority over all vehicle movements.

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.

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, 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, 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.

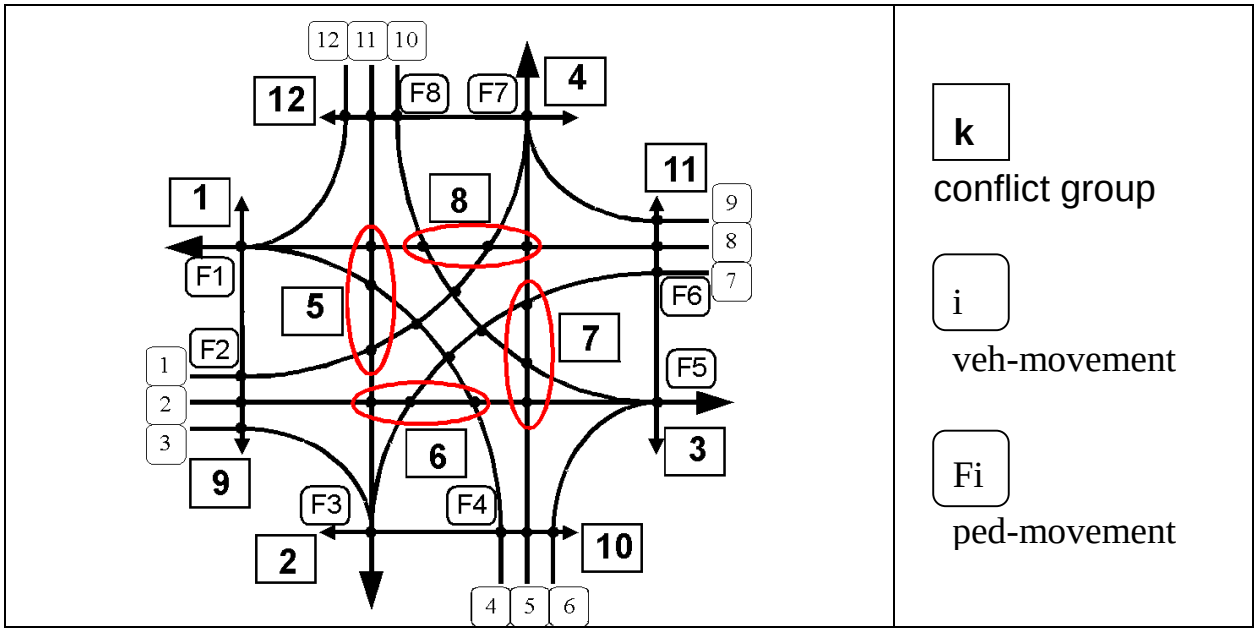


Fig. 7: Arrangement of conflict groups at a simple cross intersection including pedestrians

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**

Subject movement		Con-flict group	conflicting movements of higher priority ranking rank r					lower rank			
i	**r**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**m**
No.	**rank**		**1**	**2**	**3**	**4**	**5**				
1	3	9 5 8 4	 8 8	 9			 F7	F2	 4 5 5	 11 10	
2	1	9 6 7 3						F2 F5	4 5 6	 7 7 10	 11 10
3	2	9 2	 F3					F2	 7	 11	
4	5	10 6 5 1	 2 8 8	 F1	 7 1 12	 11 11		F4			
5	4	10 7 8 4	 2 8	 9	 7 1 1			F4 F7	 10 10		
6	3	10 3	 2	 F5				F4	 10		
7	3	11 7 6 2	 2 2	 3			 F3	F6	 5 4 11	 10 11	
8	1	11 8 5 1						F6 F1	 1 1	 5 4	 10 11
9	2	11 4	 F7					F6	 1	 5	
10	5	12 8 7 3	 8 2 2	 F5	 1 7 6	 5 5		F8			
11	4	12 5 6 2	 8 2	 3	 1 7 7			F8 F3	 4 4		
12	3	12 1	 8	 F1				F8	 4		
i	**r**	**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.

Subject movement		Con-flict group	conflicting movements of higher priority ranking rank r					lower rank			
i	**r**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**m**
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**	**k**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**m**

Table 3 (continued): Conflict groups and conflicting movements for each traffic stream at the intersection including pedestrians.

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.

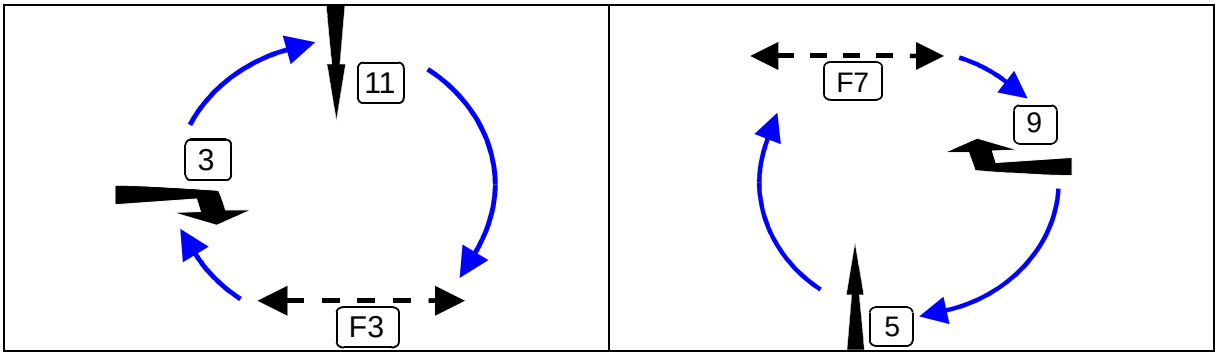


Fig. 8: Cycle of priorities: the round arrows are a symbol for "has priority over".

Regardless of this problem, in the new theory table 3 together with eq. 20 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:

$$C_{i,p} = C_{\max,\,i,\,p} \cdot \prod_{each\ k} \left[1 - \sum_{j=a}^{f} \left(\frac{A_j}{100} \cdot B_{k,j} \right) \right] \qquad \text{[veh/h]} \qquad (21)$$

where

$C_{i,p}$	=	capacity for movement i including the influence of pedestrians	[veh/h]
A_j	=	100 if j is a vehicle movement (cf. remark "limited priority" below)	
A_j	=	$A_{k,f,i}$, if j 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	[%]
$B_{k,j}$	=	occupancy in conflict group k by movement j	[-]
	=	$Q_j \cdot t_{B,j} / 3600$	[-]
Q_j	=	volume of movement j	[veh/h or ped/h]
	=	0, if the relevant cell in table 3 is empty	
$t_{B,j}$	=	average service time for one vehicle or pedestrian in movement j	[s]
	=	duration of blocked time caused on average by one vehicle or pedestrian	
a, f, k:		see bottom line of table 3	

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, Boer (1999) found from a limited sample of observations in Germany that for a single pedestrian using the crosswalk on average a service time of $t_{B,j}$ = 3.2 s is consumed. 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. 21 would very easily allow to account for the effect of "limited priority" (Troutbeck, 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. 21. 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 4 must be regarded for the sum in eq. 21 .

4 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

$$C_s = \frac{Q_{s,L} + Q_{s,T} + Q_{s,R}}{x_{s,L} + x_{s,T} + x_{s,R}} \quad \text{[veh/h]} \quad (22)$$

where

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

$$C_s = \frac{Q_{s,L} + Q_{s,T} + Q_{s,R}}{\sqrt{(x_{s,L} + x_{s,T})^2 + (x_{s,R})^2}} \quad \text{[veh/h]} \quad (23)$$

Using both equations (eq. 22 and 23) the following restriction has to be observed

$$(Q_{s,L} \cdot t_{B,s,L}) + (Q_{s,T} \cdot t_{B,s,T}) + (Q_{s,R} \cdot t_{B,sR}) + (Q_F \cdot t_{B,F}) \le 3600 \quad \text{[s]} \quad (24)$$

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.

5 Queue length and delay

To calculate the average delay d the classical solutions can be used. For non-stationary traffic conditions (which is usually the case in practice), the formula derived by Akcelik, Troutbeck (1991) which is contained in the HCM (1997, 2000) can be applied for the calculation of average delay d_i for vehicles from movement i :

$$d_i = \frac{3600}{C_i} + 900 \cdot T \cdot \left[x_i - 1 + \sqrt{(x_i - 1)^2 + \frac{\frac{3600}{C_i} \cdot x_i}{450 \cdot T}} \right] \quad \text{[s]} \quad (26)$$

where

T	=	observation period (usually 1 hour)	[h]
C_i	=	capacity of the movement i or for a shared lane	[veh/h]
x_i	=	degree of saturation = Q_i / C_i	[-]
	=	$x_s = \frac{Q_{s,L} + Q_{s,T} + Q_{s,R}}{C_s}$ in case of a shared lane	[-]

The average queue length can be obtained according to Little's rule

$$N_i = Q_i \cdot d_i \quad \text{[veh]}$$

only for the case of stationary conditions. In case of non-stationary (over-saturated) conditions the relationship

$$N_i = \left(d_i - \frac{3600}{C_i} \right) \cdot x_i \quad \text{[veh]}$$

can be applied (cf. Akcelik, 1980). The percentiles of the queue length distribution can be estimated according to Wu (1994). This means, practically speaking, that exhibit 17-19 of HCM(2000) can be applied.

6 A Rough Calibration of the Model

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.

In this sense, to calibrate the model, only the set of 12 t_B-values 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. Moreover, the t_B-value for the two major through movements was estimated as 2.5 s. For the pedestrian t_B-values the estimate of 3.2 s , mentioned above, could be used as a first approach. Thus it is only necessary to calibrate 4 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.

For this calibration process we look at a rather simple intersection of a quite common shape like it is illustrated in fig. 9. Here we assume one left turning lane for each of the major street approaches. In addition we assume, that the minor street has flares on both entries allowing one additional space for one right turning vehicle. 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 8 - 20 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.

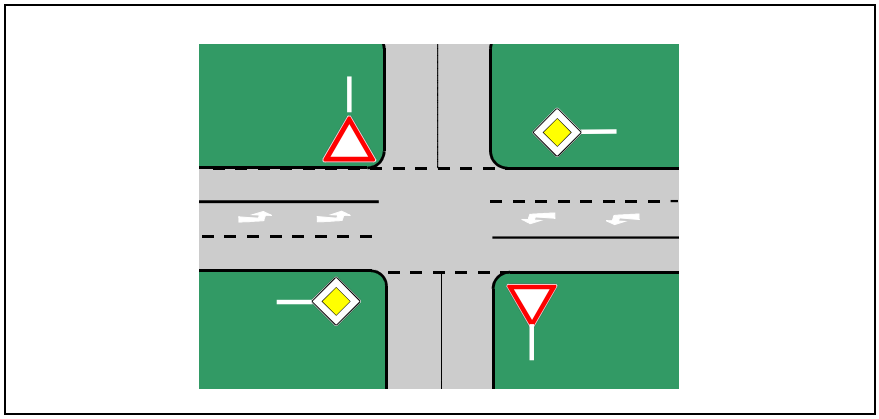


Fig. 9: Type of the intersection for calibration.

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 ACS-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.

move-ment	critical gap t_c	follow-up time t_f	range of volume used for calibration	resulting t_B-values
1	5.5	2.6	0 - 200	2.9
2	-	-	0 - 400	2.5[1)]
3	-	-	0 - 250	2.8[1)]
4	6.6	3.4	0 - 120	6,5
5	6.5	3.5	0 - 150	5,9
6	6.5	3.1	0 - 350	3.8
movements 7 through 12 correspond to movements 1 through 6				
	s	s	veh/h	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) : estimated without calibration

movement	volume	capacity from the new approach	average delay
1	45	920	4
2	220	1337	3
3	67		
4	56	307	41
5	88		
6	78		
7	76	932	4
8	240	1348	3
9	56		
10	45	292	42
11	120		
12	45		
F1 / F2	180	-	-
F3 / F4	230		
F5 / F6	300		
F7 / F8	250		
	veh/h or ped/h	veh/h	s

Table 5: Application of the new technique for an intersection like it is sketched out in fig. 9 (example).

For the application, the whole set of equations has been programmed into another spreadsheet. This enables the calculation of the capacity for each of the non-priority movements at a 2WSC-intersection with a shape like the sketch in fig. 9. Also delays and percentile queue lengths can be calculated by this spreadsheet program if the traffic volumes of the 12 vehicle movements and the pedestrian volumes are given. Thus, also the influence of pedestrian movements on the capacity of the intersection is evaluated. An example of these results is illustrated in table 5. For other intersection layouts the computational procedure still has to be formulated.

7 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. Nevertheless, it ends up in a series of equations which need computer application to get a solution in practice.

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 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. An extended analysis for the potential of the methodology at a series of urban intersections with real world data is currently under investigation in Germany to be finished in 2001.

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