MODELING ADJUSTMENT FACTORS FOR PEDESTRIANS AND BICYCLES ON TURNING VEHICLE MOVEMENTS AT SIGNALIZED INTERSECTIONS

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ABSTRACT

At signalized intersections, the capacity of turning vehicle streams can be affected by conflicting pedestrians and bicycles who share the same signal phase. To analyze this effect, measurements at twelve pedestrian and bicycle crossings at signalized intersections in Germany covering more than 4,300 signal cycles were conducted. The reduction of the capacity can be accounted for by estimating the blockage time of possible turning vehicle departures. In addition to the pedestrian or bicycle volume, the empirical analyses revealed several other parameters influencing the blockage time such as the duration of the green time and the cycle time of signal control as well as the width of the pedestrian crossing. The influencing parameters were further analyzed by microscopic simulation. Since the current quality-of-service assessment procedures in the U.S. Highway Capacity Manual (HCM) and the German Highway Capacity Manual (HBS) do not consider all of these parameters sufficiently, a new model based on the gap acceptance theory was derived. The new model uses the relevant influencing parameters directly as input variables so that a precise calculation of the blockage time was achieved. The new model was derived in a way that it can be incorporated into the existing quality of service assessment procedures to determine the adjustment factors of the saturation flow rate or the capacity for turning movements. For practical applications, also a simplification of the exact model is presented with a good fit of the data.

1. INTRODUCTION

Turning vehicles and conflicting pedestrians and bicycles often share the same signal phase to optimize the efficiency of the signal cycle. In this case, pedestrians or bicyclists have priority over the turning vehicles. On the one hand, this might affect traffic safety particularly in case of high vehicle and pedestrian or bicycle traffic volumes. On the other hand, the saturation flow of the turning vehicle stream gets interrupted because the vehicles must yield the right of way so that the capacity is reduced. Determining this impact is important for the quality-of-service assessment of turning vehicle streams.

Several quality-of-service assessment procedures as given in the U.S. Highway Capacity Manual HCM (*1*), the German Highway Capacity Manual HBS (*2*), or the Canadian Capacity Guide CCG (*3*) consider the influence of conflicting pedestrians and bicycles and provide different calculation methods to determine the corresponding influencing factor. However, these calculation methods are relatively pragmatic and do not consider the wide range of geometric and control conditions at signalized intersections, which directly influence the performance.

In this paper, the effect of conflicting pedestrians and bicycles on the capacity of turning vehicle movements is examined in detail using empirical and simulated data. The main boundary conditions are identified based on traffic flow measurements at twelve pedestrian and bicycle crossings at signalized intersections in Germany. A new model based on the gap-acceptance theory is derived, which can consider these boundary conditions directly as model parameters.

2. LITERATURE REVIEW

In the HCM (*1*) assessment procedure for signalized intersections, the effect of pedestrians and bicycles on right- or left-turning vehicle movements is considered with the pedestrians-bicycle adjustment factors. The adjustment factors of pedestrians and bicycles can be determined with eqs. (31-74) through (31-82) in the HCM. These adjustment factors reduce the base saturation flow rate in case of conflicting pedestrians or bicycles. The pedestrians-bicycle adjustment factors were developed by Milazzo et al. (*4*) with some edits for bicycles from Allen et al. (*5*). Rouphail and Eads (*6*) had shown that the previous HCM model did not describe empirical findings and simulations accurately enough.

Milazzo et al. (*4*) observed the performance effect of pedestrians for 935 signal cycles at nine different intersections with different geometric and traffic conditions. All of the observed movements were left-turns. The occupancy of the conflict zone was defined as a part of the crosswalk with the effective crosswalk width and a lane width along the typical turning vehicle path. It was measured for every cycle as a proportion of the pedestrian service time. Different types of functions and multiple explanatory variables were tested to describe the relationship between the occupancy of the conflict zone and the pedestrian flow rate (sum of both walking directions) during the pedestrian service time. Milazzo et al. (*4*) stated that there are only marginal differences in different turning movements so that this procedure can be applied to right-turning movements as well, as it was implemented in the HCM (*1*). In case that the number of receiving lanes in the crossing street is greater than the number of turning lanes, the turning vehicles can maneuver around the pedestrians and bicycles. Therefore, only 60% of the relevant conflict zone occupancy is considered to calculate the adjustment factors, which was also a result from Milazzo et al. (*4*). Allen et al. (*5*) conducted a similar survey for bicycles and collected occupancy data for conflict zones for 612 signal cycles at four different intersections. The conflict zones of turning vehicles and bicycles were defined with a length of 3.7 m and the width of the cycle path. The observed bicycle volumes varied between 60 and 1,900 bicycles/h with most of the values being below 800 bicycles/h.

The quality-of-service assessment procedure of the HBS (*2*) considers the performance reduction due to conflicting pedestrians and bicycles in the capacity determination. The capacity of right-turn movements C_{RT} is calculated with eq. (1) and is composed of the clearance time in the theoretically unoccupied green time because of the saturated departure of queuing vehicles:

$$c_{RT} = min\begin{cases} \frac{g_{0,pb}}{C}s + n_{RT}n_C \\ \frac{g}{C}s \end{cases} \quad (1)$$

$$g_{0,pb} = g_p + max\begin{cases} g - g_p - b + g_{LPI} - n_{RT}h_s \\ 0 \end{cases} \quad (2)$$

where:	s	=	saturation flow rate of the turning vehicle stream	(veh/h)
	h_s	=	average departure headway of the turning vehicle adjustment factors	
		=	3,600/s	(s/veh)
	C	=	cycle time	(s)
	g	=	effective green time	(s)
	$g_{0,pb}$	=	theoretically unoccupied green time	(s)
	n_{RT}	=	maximum number of queuing right-turning vehicles between the stop line and the subject crossing	(veh)
	n_C	=	number of cycles per hour = 3,600/C	
	g_p	=	additional protected green time without pedestrians or bicycle	(s)
	b	=	blockage time	(s)
	g_{LPI}	=	duration of the leading pedestrian interval	(s)

The theoretically unoccupied green time is calculated with eq. (2) and takes the different sections of the green time of the right-turning vehicles into account. The effect of the pedestrians and bicycles is considered in the blockage time which can be calculated with eq. (3). When the pedestrian crossing and the cycle path is geometrically separated, the blockage time should be determined separately as well and only the higher value should be considered. Eq. (3) was originally derived in the study from Tarko and Gaca (*7*). It was also included in the previous (2001) edition of the HBS, which applied the assessment procedure by Brilon et al. (*8*). Tarko and Gaca (*7*) analyzed the effect of pedestrians in 1,120 signal cycles at 23 crossings in Poland with different geometric and control conditions. They also defined the blockage time as the occupied time of a conflict zone for which the definition of Kraus and Trapp (*9*) was used. The conflict zone had the width of the crossing and the length of one vehicle. The blockage time included an additional time of 1.5 s and 1.0 s before and behind a crossing pedestrian, respectively, since the pedestrians influence the vehicle movement not only on the conflict zone itself. These additional times were derived from the survey of Haeckelmann (*10*). With a regression analysis of the collected data, Tarko and Gaca (*7*) determined eq. (3) as a good relationship between the blockage time and the number of crossing pedestrians per cycle. Since the blockage time was scattered widely, they tried different function types and explanatory variables, which led to slightly better results. Fischer (*11*) evaluated different approaches to describe the effect of pedestrians at signalized intersections in Germany for 243 cycles at two crossings and determined eq. (3) as the best approach. Note that eq. (3) as used in the HBS (2) wasn't derived to evaluate the performance impact of conflicting bicycles. Furthermore eq. (3) does not consider the arrival distribution of the pedestrians sufficiently since it was determined directly from the measured numbers of pedestrians per signal cycle. According to the HBS (*2*), the effect of pedestrians can be neglected for left-turn movements since most pedestrians are crossing during the opposite queue clearance. On one-way streets, the assessment procedures for left-turn and right-turn movements are equivalent.

$$b = \frac{v_C}{0.024 \cdot v_C + 0.48} \tag{3}$$

where: v_{ped} = pedestrian flow rate in the subject crossing (both walking directions) (p/h)
v_{bic} = bicycle flow rate (bicycles/h)
v_C = average number of pedestrians and bicycles per cycle (p+bicycles)
= $\frac{v_{ped}+v_{bic}}{n_C}$

In the CCG (*3*), the effect of pedestrians is also considered as an adjustment factor of the saturation flow rate. In total there are three equations calibrated for three different Canadian cities to calculate the adjustment factor, which were derived in the studies of Richardson (*12*), Poss (*13*), and Teply (*14*). If the pedestrian flow rate during the pedestrian service time is below 200 p/h, the adjustment factor is set to 1.

Further models to determine the effect of pedestrians on the turning capacity were derived by Viney and Pretty (*15*) and Chen et al. (*16*) based on the gap acceptance theory. Chen et al. (*17*) modeled the capacity at the conflict zone with an interacting process calibrated with field data and validated with microscopic traffic simulation. Vortisch et al. (*18*) analyzed the blockage time of pedestrians and bicycles in Germany and noted that the HBS model (eq. (3)) was underestimating the measured blockage times. In the study of Grigoropoulos et al (*19*), a new turning capacity adjustment factor for the consideration of bicycles was retrieved from microscopic simulation.

3. EMPIRICAL ANALYSIS

Data Basis and Methodology

Under real-world traffic conditions, the impact of pedestrians and bicycles on the capacity of turning vehicle streams can hardly be measured because oversaturated traffic conditions with high pedestrian and bicycle volumes are required for a longer time period. Therefore, many studies observed the occupied time of the conflict zone and determined a theoretical adjustment factor on this basis. To obtain comparable results to the formula used in the HBS (*2*), the blockage time was measured for pedestrian and bicycle conflict zones for right-turn movements from recorded videos with a duration of 6 to 10 hours per crossing. In total, twelve crossings at signalized intersections in Germany with different geometric parameters L_1 (width of the first part of the crosswalk), L_{RI} (width of the refuge island, if any), and L_2 (width of the second part of the crosswalk) for the crossings were observed. The lengths L_1, L_{RI} and L_2 of the crossings are shown in FIGURE 1. The parameter L_1 varies from 6.5 m to 12.4 m, L_2 from 6.0 m to 14.0 m, and L_{RI} from 0 (no RI) to 4.2 m. The control included either simultaneous signalization or progressive signalization of the pedestrian movement in the case that the crosswalk is separated by a refuge island (RI). A simultaneous signalization has identical green times for both walking directions and both crossings, so pedestrians that cross at the end of green might have to wait on the refuge island for the next cycle. A progressive signalization ensured that no pedestrian have to wait on the refuge island, so this is nearly the same scenario like a crossing without a refuge island. For the determination of the blockage time, several time stamps (entering and leaving the crossing and the conflict zone) were recorded for every pedestrian and bicycle.

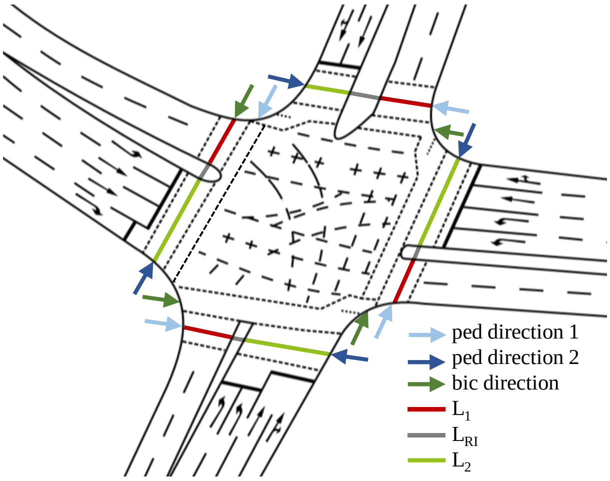


FIGURE 1: Designation of the crossing geometry and crossing directions

The definition of the conflict zone was done similar to Kraus and Trapp (*9*) and is depicted in FIGURE 2 for a pedestrian crossing. The width of the conflict zone corresponds to the width of the crosswalk or the cycle path. The length is composed of the width of a conflicting vehicle B_k placed on the typical turning path which was assumed with 2 m safety distances before (A_v) and after (A_n) a crossing pedestrian or bicycle. First observations showed that the exclusive consideration of B_K as the conflict zone clearly underestimates the impact of pedestrians and bicycles since the saturation flow is interrupted well before a conflicting pedestrian or bicycle enters this area. Therefore, the safety distances were added and measured from traffic observations. For crossing pedestrians in walking direction 1, A_v = 2.5 m and A_n = 2.7 m were determined. Crossing pedestrians in walking direction 2 were considered with A_v = 3.0 m and A_n = 1.9 m. Slow bicycles at the beginning of green time (< 10 km/h) were taken into account with A_v = 5.0 m and A_n = 3.1 m, all other situations were considered with A_v = 10.0 m and A_n = 4.1 m.

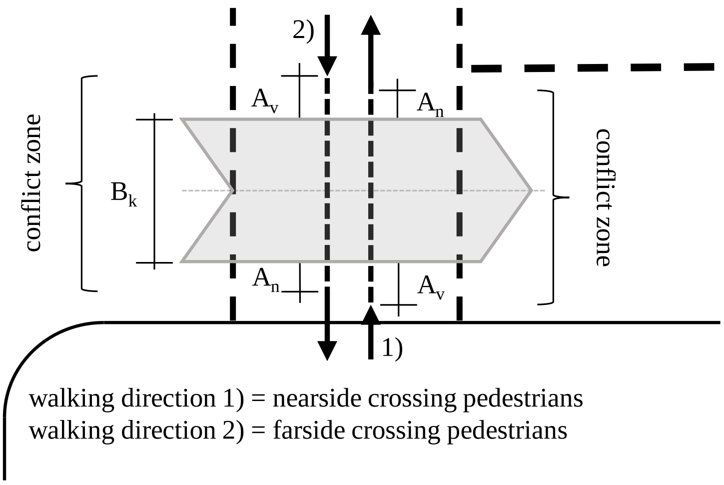


FIGURE 2: Definition of the conflict zone for a pedestrian crossing at a right turn situation

For every cycle, the total time in which at least one pedestrian or bicycle was present on the defined conflict zone was measured as the blockage time. Thereby all crossing pedestrians and bicycles entering the crossing during the respective green time were considered.

Empirical Results

In total, more than 4,300 signal cycles with 12,700 pedestrians and 13,174 bicycles were observed at the twelve crossings. FIGURE 3 shows the measured blockage times *b* of an example crossing. The average blockage time was calculated for all pedestrian and bicycle traffic volumes which were observed at least ten times. The measured blockage times show the characteristic profile with highly scattered data as was also found in other studies. Furthermore, it can be seen that the measured average blockage times are greater than the times calculated with eq. (3) used in the HBS (*2*). The blockage time for cycles with just one pedestrian was measured as 4.3 s (3.5 s for bicycles) at this crossing. Other investigations (e.g. *18*) delivered comparable results. Eq. (3) yields a value of 2.0 s. The huge differences between the values presumably result from different safety distances of the conflict zone A_v and A_n assumed in the studies. As expected, the blockage times of bicycles were slightly smaller than the blockage times of pedestrians because of the higher speeds. However, the difference is rather small since bicycles already affect the turning vehicle traffic at a greater distance. Similar results were obtained at other crossings.

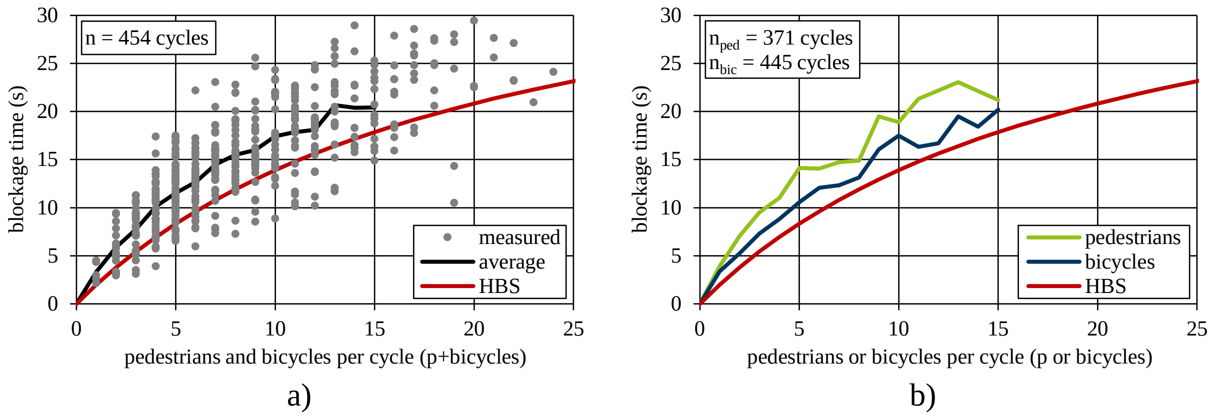


FIGURE 3: Empirically measured blockage times b at the example crossing as a) the total blockage time and b) the separately measured blockage time of pedestrians and bicycles

The analysis of all measured crossings revealed considerable differences of the blockage times, which could not be explained by stochastic variations. Hence, it can be assumed that other parameters than the pedestrian and bicycle traffic volume, which is the only parameter used in eq. (3), influence the blockage time per cycle. First of all, the pedestrian or bicycle green time is obviously a relevant parameter as it limits the possible crossing time. In the HBS (*2*) procedure, this impact is considered in eq. (2) by the limitation of $g_{0,pb}$. However, it is reasonable to take the green time into account when calculating the blockage time since studies (e.g. (*4*)) found that the function profile differs for different green times. Furthermore, the cycle time or the proportion of green could have an influence. This parameter defines how many pedestrians or bicycles arrive during the red interval and cross within one group in the next green time. This leads to smaller blockage times compared with an even arrival within the green time because single blockage times are overlapping. Also, the form of the signalization of the crossing might show an effect because crossing pedestrians in walking direction 2 at the end of green would have to stop on the refuge island in case of a simultaneous signalization.

The intersection geometry or especially the lengths L_1, L_{RI} and L_2 also influence the flow processes at the crossing. The combination of these three distances affects the overlapping of the blockage times of the two or – in case of a simultaneous signalization – three crossing platoons at the beginning of green. A wider crossing leads to less overlapping of the platoons and thus to higher total blockage times. Besides that, the first platoon in walking direction 2 may dissolve in a certain way over a longer distance (L_2 + L_{RI}) due to different walking speeds within the platoon, which can further increase the total blockage times. The average walking speed of all observed 12,700 pedestrians was measured as 1.48 m/s with a standard deviation of 0.35 m/s. Different speeds for the two walking directions or crossing pedestrians at the beginning or end of the green time could not be determined.

4. MICROSCOPIC SIMULATION

Data Basis, Methodology and Calibration

The empirical analysis suggested that there are several more possible influencing parameters in addition to the pedestrian or bicycle traffic volume. Although comprehensive measurements were conducted, the range of the overserved geometric and control parameters wasn't sufficient to cover all possible influencing parameters in detail. Thus, microscopic simulations with PTV Vissim (version 21) were carried out to extend the data. The measurement of the blockage time was done analogously to the empirical study with the same definition of the conflict zone. The simulation was calibrated against the empirical findings such as the pedestrian crossing speed, platooning behavior or reaction times. An interaction-free behavior between pedestrians was implemented, since the empirical analysis showed that at typical pedestrian volumes the crossings were wide enough so that every pedestrian can cross without major conflicts. The parameter combinations given in TABLE 1 were applied for the simulation study. The designation of the intersection geometry and the crossing directions can be seen in FIGURE 1. For a progressive signalization, the green time refers to the green time of the first crossing in the walking direction. The green time of the second crossing in walking direction was assumed being well-coordinated so that every pedestrian can walk the whole crossing. Since a progressive signalization is in principle the same as a crossing without a refuge island, these were not considered separately. For each scenario, 10 simulation runs with different random seeds and a simulated time of 4 hours were carried out with a continuous increase of the pedestrian and bicycle traffic volume. For both crossing directions, the hourly pedestrian volume was set identical. Only one-way cycle paths were considered with a width of 2 m in the simulation. Since the blockage time was measured for an exact number of crossing pedestrians or bicycles, the maximum blockage time was determined with the assumption of Poisson distributed arrivals. In the following, only blockage times determined that way are considered.

TABLE 1: Range of the control and geometric parameters of the simulation

Parameter	Symbol	Unit	Range
Cycle time	C	(s)	60, 75, and 90
Pedestrian or bicycle green time	g	(s)	5, 15, 25, and 35
Length of the crossings	L	(m)	$L_1 = 4$, $L_{RI} + L_2 = 0$ $L_1 = 4$, $L_{RI} + L_2 = 4$ $L_1 = 4$, $L_{RI} + L_2 = 8$ $L_1 = 8$, $L_{RI} + L_2 = 8$ $L_1 = 8$, $L_{RI} + L_2 = 12$ $L_1 = 8$, $L_{RI} + L_2 = 16$
Distance between the bicycle stop line and the crossing	L_{bic}	(m)	0, 2, 4, 6, 8, and 10
Type of crossing signalization			• simultaneous • (progressive) • without refuge island

Extensive calibration wasn't necessary, since no further adjustments had to be made due to the interaction-free walking behavior and the analogous measurement of the blockage times to the empirical analysis. In FIGURE 4, as an example, the empirical and simulated blockage times are illustrated for pedestrians and bicycles. As it can be expected, there are just marginal differences so that an RMSPE of just 4.8% and 4.5% could be determined.

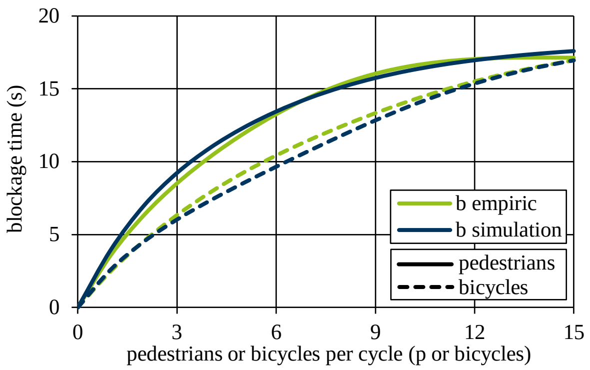


FIGURE 4: Empiric and simulated average blockage times of pedestrians and bicycles at the example crossing

Results of the Simulation Study

The results of the simulation supported the assumption that more factors influencing the blockage time exist. In FIGURE 5, the simulated blockage times of the different pedestrian scenarios are illustrated. For bicycles, a similar pattern was obtained. The wide range of the blockage time can clearly be seen. Furthermore, there are huge differences to the HBS (*2*) with eq. (3) or a blockage time derived from the approach of the HCM (*1*) with the pedestrian occupancy combined with the green time. It has to be noted, that the HCM already considers the influence of the green time in the blockage time, which is done in the HBS in a separate step. The differences to the simulation mostly result from a shorter definition of the conflict zone, which can be seen by the values of the blockage time for cycles with just one pedestrian. These values of the HCM and HBS procedures do not seem to be realistic. Other reasons may be the neglection of relevant influencing factors which are analyzed in the following in detail.

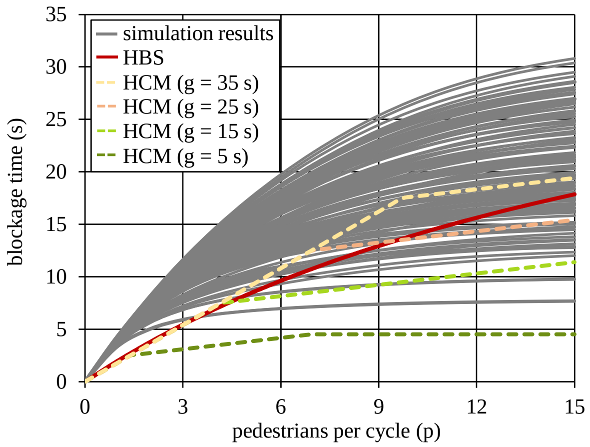


FIGURE 5: Simulated blockage times of all pedestrian scenarios

First, the impact of the type of signalization of the pedestrian crossing is evaluated. With a simultaneous signalization, crossing pedestrians in walking direction 2 who begin their crossing at the end of green have to wait on the refuge island until the next cycle. In the next cycle they start from the refuge island and most of their blockage time overlaps with the first crossing platoon in walking direction 1. That leads to about 10% less total blockage time in comparison with a progressive signalization or a crossing without a refuge island under the same boundary conditions. This can directly be seen in FIGURE 6. The resulting difference is rather small but increases with increasing blockage time or number of crossing pedestrians due to the higher likelihood that some pedestrians clear at the end of green. In the following, only the progressive signalization, which is equivalent to a crossing without a refuge island, is considered for the analysis of other influencing parameters.

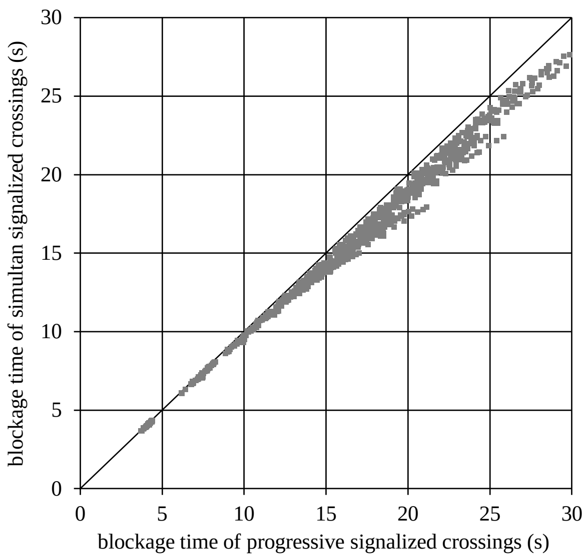


FIGURE 6: Comparison of the pedestrian blockage times for a simultaneous and progressive signalization with otherwise same boundary conditions

A lower proportion of green with the same number of crossing pedestrians or bicycles per cycle leads to a smaller hourly flow rate but un unchanged flow rate during the pedestrian service time. This involves a higher probability that pedestrians or bicycles arrive during the red time and thus cross in one platoon at the beginning of green. Then the single blockings overlap each other and the total blockage time is reduced. This can be seen in FIGURE 7: as an example. Anyway, this correlation has just a minor effect on the blockage time.

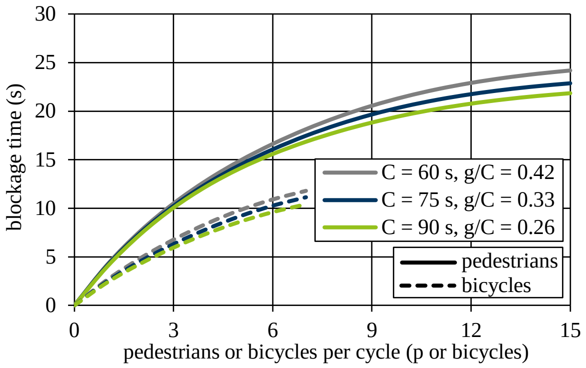


FIGURE 7: Influence of the proportion of green (g = 25 s, L_1 = 8 m, L_{RI} + L_2 = 8 m)

The green time has a major influence on the blockage time. Pedestrians or bicycles can only begin their crossing within the green time so that longer green times obviously result in a possible longer maximum blockage of the crossing. FIGURE 8 shows the simulated blockage times for different green times with the same cycle time and geometry for one example. It can be seen that the blockage times increase with increasing green time for the same number of crossing pedestrians or bicycles per cycle, which leads to smaller flow rates during the pedestrian service time but an unchanged hourly flow rate. This effect interferes with the already mentioned influence of the different proportions of green. Obviously, the green time is not the exact limit of the blockage time. A crossing can be blocked far longer than the green time because of the offset of the crossing pedestrians in walking direction 2 at the end of green who have to walk several seconds after green ends and thus block the crossing when the pedestrian signal already shows red. For simultaneous signalized crossings, this effect is a little less distinct since the crossing pedestrians at the end of green have to wait on the refuge island.

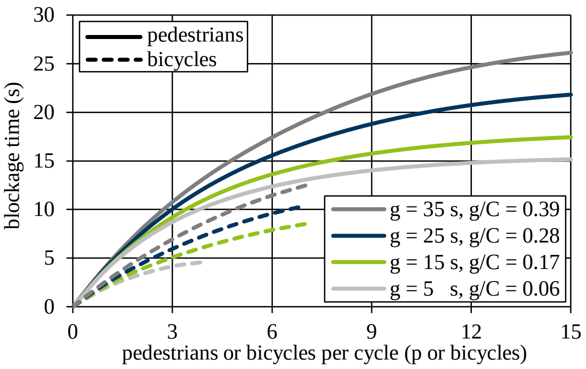


FIGURE 8: Influence of the green time (C = 90 s, L_1 = 8 m, L_{RI} + L_2 = 8 m)

Another major effect on the blockage times of the pedestrians is caused by the geometry of the crossing, particularly its length. The geometry determines the walking time of the crossing pedestrians in walking direction 2 until they reach the conflict zone. With walking speeds of about 1.5 m/s, this walking time can be several seconds depending on the length of the crossing. A longer crossing and thus longer walking time decreases the overlapping of the blocked times by the first platoons of both walking directions, which leads to a longer total blockage time (cf. FIGURE 9). Furthermore, the walking time influences the previously mentioned blocking at the end of green with a longer walking time leading to a possibly longer blocking after the green time ends. Both effects overlap. For bicycles, the geometry was varied with the distance between the bicycle stop line and the crossing since only one-way cycle paths were considered. This parameter had just a minor effect.

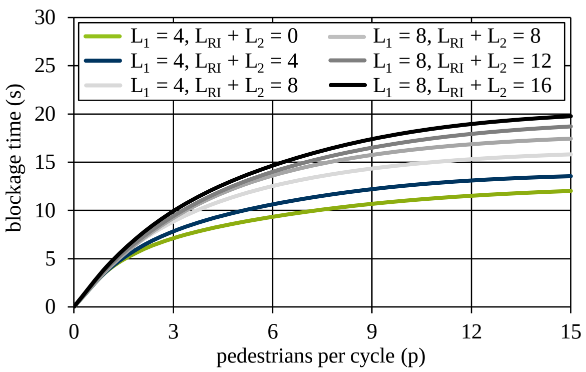


FIGURE 9: Influence of the crossing geometry (*C* = 90 s, *g* = 15 s)

5. MODEL DERIVATION AND CALIBRATION

Since the empirical analyses and the simulations revealed several influencing factors of the blockage time which are not considered in the quality-of-service assessment procedures (e.g. *1*, *2*, *3*), a new model was derived, which takes these parameters directly into account.

At first, only one crossing direction is considered. The blockage time can be calculated separately for the waiting pedestrians at the beginning of green and the pedestrians who arrive during the green time. The first platoon of pedestrians blocks the turning vehicles for the duration b_P^*. If the speed distribution is known, it can be considered. A pedestrian arriving during green blocks the crossing for the duration b_g in the time $(g_{ped} - b_P^*)$ where multiple blockings can overlap. This can exactly be modeled with the well-known gap acceptance theory. The time gaps within the pedestrian stream are assumed to follow a negative exponential distribution. Note, on average, one pedestrian can block the crossing $b_g/2$ longer than the end of green time because it needs this time to leave the conflict zone. If the pedestrian movement has an offset time Δt to reach the conflict zone due to the walking distance or the signalization, the blockage time increases by this time. The combined total blockage time of one pedestrian movement results in:

$$b_{ped} = P_R \cdot \left(b_P^* + P_b \cdot \left(g_{ped} + \frac{b_g}{2} - b_P^* + \Delta t\right)\right) + (1 - P_R) \cdot P_b \cdot \left(g_{ped} + \frac{b_g}{2} + \Delta t\right) \quad (4)$$

$$= \bar{b}_P^* \cdot (1 - P_b) + P_b \cdot \left(g_{ped} + \frac{b_g}{2} + \Delta t\right)$$

where: p_{ped} = total blockage time due crossing pedestrians (s)
P_R = probability that at least one pedestrian arrives during red time R
= $P(t \leq R) = 1 - e^{-v_{ped,d} \cdot R_{ped}}$
$v_{ped,d}$ = pedestrian flow rate in the subject direction = $v_{C,ped,d}/C$ (p/s)
$v_{C,ped,d}$ = average number of pedestrian per cycle in the subject direction = $v_{C,ped}/2$ (p)
R_{ped} = red time duration of the pedestrian signal (s)
b_g = blockage time of one pedestrian arriving during green (s)
P_b = probability of time gaps shorter than b_g
= $P(t \leq b_g) = 1 - e^{-v_{ped,d} \cdot b_g}$
b_P^* = blockage time of the first pedestrian platoon (s)
= $b_{P,N_P} + k \cdot \Delta t$
$\bar{b}_P^*$ = average blockage time of the first pedestrian platoon over all pedestrians (s)
= $b_P^* \cdot P_R$
k = proportion of the blocked offset time
Δt = offset time (usually walking time) of the pedestrians to reach the conflict zone
= $\begin{cases} 0 & direction\ 1 \\ min\left(\frac{L_{crossing}-6}{1.5}\right) & direction\ 2 \end{cases}$ (s)
$L_{crossing}$ = length of the whole crossing (m)
= $L_1 + L_{RI} + L_2$

The first term of eq. (4) represents the mean value of the blockage time by the first platoon of pedestrians who arrived in the red time. The second term represents the mean value of the blockage time by pedestrians who are arriving during the time after the platoon has departed. The duration of the blockage time of the first pedestrian platoon is affected by the number of pedestrians within the first crossing platoon. Pedestrians have got slightly different walking speeds and reaction times so that a larger platoon increases the probability of higher variation in these parameters and thus leads to higher blockage times. This time can be estimated based on measurements or simulations. This duration can be calculated as:

$$b_{P,N_P} = b_P \cdot N_P^{\left(\frac{1}{4.4}\right)} \tag{5}$$

where: N_P = number of pedestrians within the first platoon
= $\frac{v_{ped,d}}{3{,}600} \cdot R_{ped}$

Similarly, the blockage time of two opposing pedestrian movements can be derived. Here it is assumed that:

a) both directions have identical green times
b) the crossing has a progressive signalization or no refuge island
c) direction 1 has no offset time and direction 2 has an offset time Δt
d) $v_{ped,d,1} = v_{ped,d,2}$, $b_{g1} = b_{g2}$ and $b_{P1} = b_{P2}$

For this case an exact formulation can be derived. Since the blockage times of the first platoons of both directions overlap each other, k can be set to zero as an approximation, i.e., $b_P^* = b_{P,N_P}$. The blockage time results in:

$$b_{ped} = \bar{b}_P + P_{b12} \cdot \left(g_{ped} + \frac{b_g}{2} - \bar{b}_P\right) + P_{b2} \cdot \Delta t \tag{6}$$

where: $\bar{b}_P$ = average blockage time of the two first pedestrian platoons (s)
= $2 \cdot b_{P,N_P} \cdot (1 - P_R) \cdot P_R + min(2 \cdot b_{P,N_P}; b_{P,N_P} + \Delta t) \cdot {P_R}^2$
P_{b12} = probability of time gaps shorter than b_g in both pedestrian streams
= $1 - e^{-2 \cdot v_{ped,d} \cdot b_g}$
P_{b2} = probability of time gaps shorter than b_g in direction 2
= $1 - e^{-v_{ped,d} \cdot b_g}$

The parameters b_g and b_P are difficult to measure directly and therefore have to be calibrated with measured or simulated blockage times. From the simulations in this study, b_P = 5.45 s and b_g = 4.20 s were obtained as results of the calibration. Even if the assumption of identical parameters is a simplification of real traffic conditions, the calculated blockage times well match the simulated values which can be seen in FIGURE 10. If a signal-related offset time like an earlier or later start of green of one direction is provided in addition to the geometric offset time of the direction 2, this has to be considered within Δt. Furthermore, the simulation and thus the derived model parameters do not consider socially conditioned pedestrian groups. That is why it is recommended to reduce counted pedestrian volumes from field measurements with a group-factor which may differ between different locations. This allows to describe the local conditions more precisely than using an equation derived from regression of empirical data and therefore considers only proportions of groups within the underlying measurement.

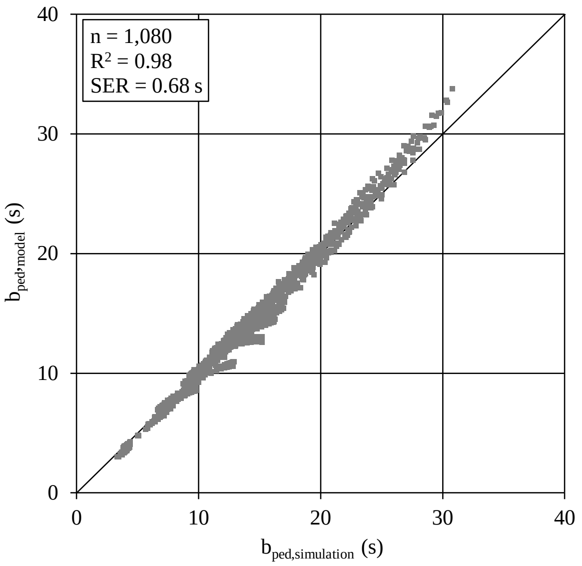


FIGURE 10: Comparison of the simulated and the calculated blockage times from eq. (6) with b_P = 5.45 s and b_g = 4.20 s for $v_{C,ped}$ = 1 to 15 p

In case of a simultaneous signalization, the blockage time is slightly reduced (cf. FIGURE 6). The resulting difference can be calculated with:

$$\Delta b = -\alpha \cdot P_{b12} \cdot \Delta t_2 \qquad (7)$$

where: Δt_2 = walking time of pedestrians in direction 2 until crossing 1 is reached (s)
= $\frac{L_2 + L_{RI}}{1.5}$
α = calibration parameter

With the simulated blockage times, the parameter α was calibrated as 0.75 with a good fit of the data (FIGURE 11).

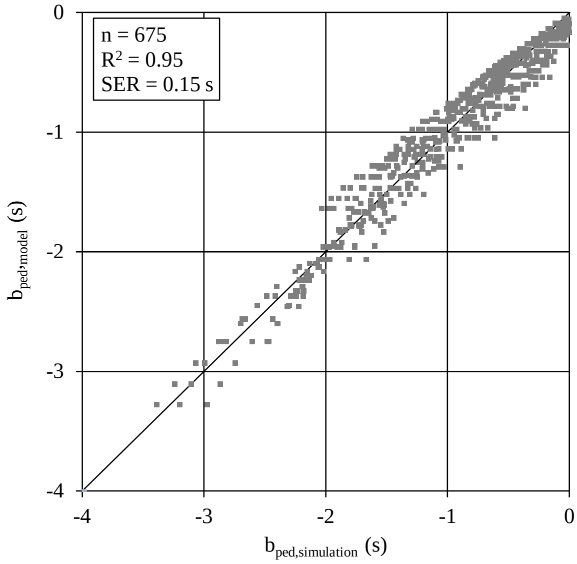


FIGURE 11: Comparison of the simulated and the calculated blockage time differences of a simultaneous signalization with equation (7) and α = 0.75 for $v_{C,ped}$ = 1 to 15 p

Since an additional modeling of a bicycle stream is very complex, the blockage time of bicycles is calculated separately. For this, the corresponding parameters of the bicycle movement need to be applied. Then the blockage time reads:

$$b_{bic} = \bar{b}_{P,bic} + P_{b,bic} \cdot \left(g_{bic} + \frac{b_{g,bic}}{2} - \bar{b}_{P,bic} \right) \quad (8)$$

$$\bar{b}_{P,bic} = b_{P,bic} \cdot N_{P,bic} + k \cdot \Delta t_{bic} \quad (9)$$

where: Δt_{bic} = offset time (usually driving time) of the bicycles to reach the end of the conflict zone (s)

= $\frac{7.2+L_{bic}}{4.2}$

L_{bic} = distance between the bicycle stop line and the crossing (m)

With the simulation-based calibration, $b_{P,bic}$ = 0.557 s, b_g = 3.497 s and k = 0.887 were obtained. In FIGURE 12, the calculated blockage times are compared with the simulation results. Only minor deviations can be seen.

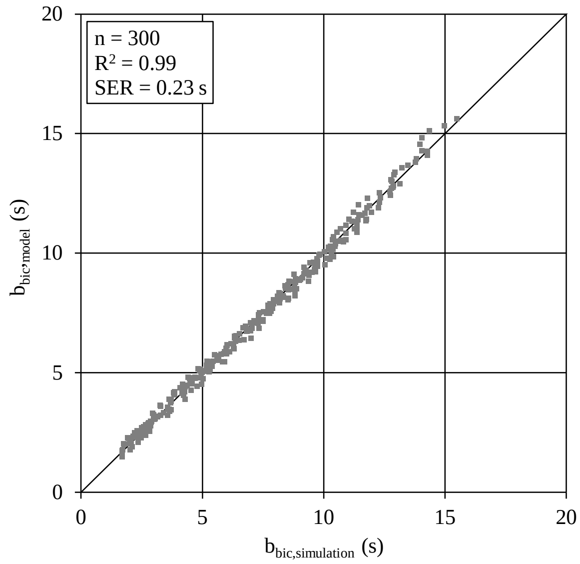


FIGURE 12: Comparison of the simulated and the calculated blockage times with equation (8) and $b_{P,bic}$ = 0.557 s, b_g = 3.497 s and k = 0.887 for $v_{C,bic}$ = 1 to 7 bicycles

Since the exact modeling of the blockage times requires some effort which may be too complicated for an assessment procedure, some simplifications were derived. Instead of eqs. (6) and (8), eqs. (10) and (11) can be used with the specified calibration parameters. All other variables were mentioned and defined above. The simplified equations also describe the simulated data very well, which can be seen in FIGURE 13.

The simplified formulation for the blockage time of a pedestrian movement (progressive signalization or crossing without a refuge island) reads:

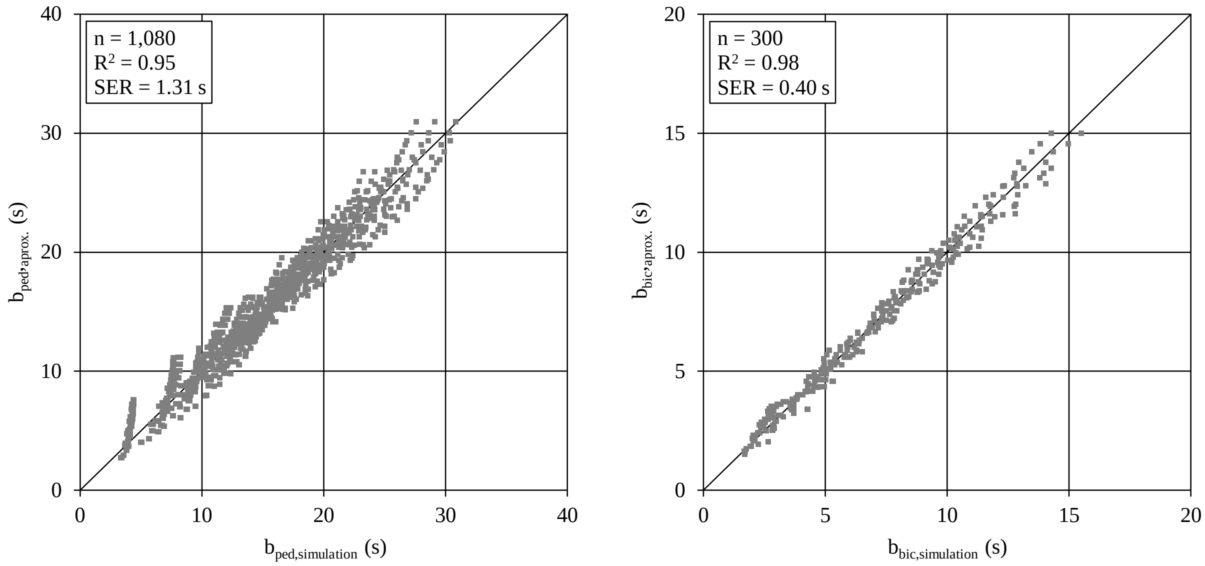
$$b_{ped} = \left(1 - e^{-a \cdot v_{C,ped}{}^{b}}\right) \cdot \left(g_{ped} + c \cdot b_g + d \cdot \Delta t\right) \tag{10}$$

where: b_g = blockage time of one pedestrian arriving during green = 4.2 s (s)
a = calibration parameter = 0.109
b = calibration parameter = 0.595
c = calibration parameter = 1.430
d = calibration parameter = 5.103

The simplified formulation for the blockage time of a bicycle movement reads:

$$b_{bic} = \left(1 - e^{-a \cdot v_{C,bic}{}^{b}}\right) \cdot \left(g_{bic} + c \cdot b_{g,bic} + d \cdot \Delta t_{bic}\right) \tag{11}$$

where: $b_{g,bic}$ = blockage time of one bicycle arriving during green = 3.5 s (s)
a = calibration parameter = 0.058
b = calibration parameter = 0.766
c = calibration parameter = 4.412
d = calibration parameter = 3.922



a) b)

FIGURE 13: Comparison of the simulated and the calculated blockage times with (a) from eq. (10) and (b) from eq. (11) for $v_{C,ped}$ = 1 to 15 p or $v_{C,bic}$ = 1 to 7 bicycles

The proportion of the blocked green time of the turning movement corresponds to the occupancy in the HCM (*1*). In some cases, e.g. at long crossings, the blockage time can be longer than the duration of the green time of turning vehicles so that the proportion of the blocked green time has to limited to 1. The proportion of the blocked green time can then be calculated as:

$$B_{ped} = \frac{b_{ped} - g_{\mathrm{LPI}}}{g} \leq 1 \tag{12}$$

$$B_{bic} = \frac{b_{bic} - g_{\mathrm{LBI}}}{g} \leq 1 \tag{13}$$

where: B_{ped} = proportion of turning movement green time (without additional protected green time) blocked by pedestrians

B_{bic} = proportion of turning movement green time (without additional protected green time) blocked by bicycles

g = effective green time of the turning movement (s)

g_{LPI} = duration of the leading pedestrian interval (s)

g_{LBI} = duration of the leading bicycle interval (s)

The combination of the pedestrian and bicycle blockings or thus the total blockage time or the total proportion of the green time of the turning movement can then be calculated analogous to the HCM model as:

$$B_{ped+bic} = 1 - \left(1 - B_{ped}\right) \cdot (1 - B_{bic}) = B_{ped} \cdot (1 - B_{bic}) + B_{bic} \tag{14}$$

$$b_{ped+bic} = g \cdot B_{ped+bic} \tag{15}$$

where: $B_{ped+bic}$ = proportion of turning movement green time (without additional protected green time) blocked by pedestrians and bicycles

$b_{ped+bic}$ = turning movement green time (without additional protected green time) blocked by pedestrians and bicycles (s)

The saturation flow rate or capacity adjustment factor for right-turn movements results as:

$$f_{Rpb} = 1 - B_{ped+bic} \qquad (16)$$

where: f_{Rpb} = pedestrian–bicycle adjustment factor for right-turn movements

Since the output of the proposed model ($B_{ped+bic}$) is consistent with the HCM method, the model can be easily incorporated into the HCM assessment procedure to calculate the adjustment factors. The model is based on right-turn movements but can also be applied for left-turn movements since the differences are considered to be negligible (*4*). In this case, the clearance of the opposing queue has to be considered as well.

6. CONCLUSIONS

In this paper the impedance of conflicting pedestrians and bicycles on the capacity of turning vehicle movements at signalized intersections was analyzed by empirical field observations and comprehensive microscopic traffic simulations with PTV Vissim. For considering the influence of pedestrians and bicycles, the blockage time, a time while the relevant conflict area is blocked by at least one pedestrian or bicycle, is used similar to the method in the HCM (*1*).

The results reveal that the blockage time is influenced by several geometric and control parameters and many boundary conditions in addition to the pedestrian or bicycle traffic volume. These parameters are the green time, the cycle time, the type of signalization, and the length of the crossing. With the results, a new calculation model was derived based on the gap acceptance theory. The model considers the identified influencing parameters directly as input variables and thus describes the average blockage times more realistically. Since the model is based on simulated data, it is independent of the local influences like the socially conditioned grouping of pedestrians, which might be observed in field measurements. Furthermore, the random arrival of the pedestrians and bicycles is considered within the model.

The model can easily be incorporated into the existing quality-of-service assessment procedures like the HCM (*1*) or the HBS (*2*) to determine appropriate adjustment factors of the saturation flow rate or the turning capacity. For practical applications, a simplification of the exact model was given which also showed a good fit of the data.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: J. Schmitz, N. Wu, J. Geistefeldt; data collection: J. Schmitz; analysis and interpretation of results: J. Schmitz,

N. Wu; draft manuscript preparation: J. Schmitz, N. Wu, J. Geistefeldt. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. TRB. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Transportation Research Board, Washington, D.C., 2022.
2. FGSV. *Handbuch fuer die Bemessung von Strassenverkehrsanlagen (German Highway Capacity Manual)*. German Road and Transportation Research Association (FGSV), Cologne, 2015.
3. CITE. *Canadian Capacity Guide for Signalized Intersections.* Canadian Institute of Transportation Engineers (CITE), Ottawa, 2008.
4. Milazzo II, J.S., Rouphail, N.M., Hummer, J.E. and Allen, D.P. Effect of Pedestrians on Capacity of Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1998. No. 1646: pp. 37-46.
5. Allen, D.P., Hummer, J.E., Rouphail, N.M. and Milazzo II, J.S. Effect of Bicycles on Capacity of Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1998. No. 1646: pp. 87-95.
6. Rouphail, N.M. and Eads, B.S. Pedestrian Impedance of Turning-Movement Saturation Flow Rates - Comparison of Simulation, Analytical, and Field. *Transportation Research Record: Journal of the Transportation Research Board*, 1997. No. 1578: pp. 56-63.
7. Tarko, A. and Gaca, S. Pedestrians at signalized intersections. *Highway Capacity and Level of Service (Brannolte, U. ed.),* International Symposium on Highway Capacity, Karlsruhe, 1991. pp. 367-376.
8. Brilon, W., Grossmann, M. and Blanke, H. Verfahren für die Berechnung der Leistungsfaehigkeit und Qualität des Verkehrsablaufs auf Straßen (Procedure for calculating the efficiency and quality of the flow of traffic on roads). *Forschung Straßenbau und Straßenverkehrstechnik*, No. 669, Kirschbaum-Verlag, Bonn, 1994.
9. Kraus, B. and Trapp, K.-H. Untersuchung über die Beeinflussung des Verkehrsablaufs an städtischen Knotenpunkten mit Lichtsignalanlagen durch Fußgänger und Radfahrer (Investigation of the influence exerted by pedestrians on the traffic flow at urban road junctions with light-signal control). *Forschung Straßenbau und Straßenverkehrstechnik*, No. 464, Kirschbaum-Verlag, Bonn, 1986.
10. Haeckelmann, P. Steuerung des Fußgängerverkehrs an Knotenpunkten mit Lichtsignalanlagen (Management of pedestrians at signalized intersections). *Dissertation at the department for water and traffic*, TH Darmstadt, 1976.
11. Fischer, A. Leistungsfähigkeit für rechtsabbiegende Kfz an LSA mit gleichzeitig freigegebenen bedingt verträglichen Fußgängern (Performance of right turning vehicles at signalized intersections with conflicting pedestrians). *Study project at the Institute for Traffic Engineering and Management*, Ruhr-University Bochum, 1993.
12. Richardson, D.B. Intersection Capacity Guide, Fourth Edition. *Municipality of Metropolitan Toronto*, Roads and Traffic Department, Traffic Control Centre, Toronto, 1982.
13. Poss, M. Saturation Flow Adjustment Factors for Right Turning Traffic at Signalized Intersections. Master’s thesis, Department of Civil Engineering, University of Alberta, 1989.

14 Teply, S. Combined Effect of Radius and Pedestrians on Right-Turn Saturation Flow at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1990. No. 1287: pp. 82-95.
15 Viney, N.D. and Pretty, R.L. Saturation Flow of a Movement Subject to a Pedestrian Stream at Traffic Signals. *Proceedings of the Eleventh Australian Road Research Board Conference*, Melbourne, 1982. Vol. 11: pp. 157–166.
16 Chen, P., Qi, H. and Sun, J. Investigation of Saturation Flow on Shared Right-Turn Lane at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2014. No. 2461: pp. 66-75.
17 Chen, X-M, Shao, C. and Yue, H. Influence of Pedestrian Traffic on Capacity of Right-Turning Movements at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2008. No. 2073: pp. 114-124.
18 Vortisch, P., Buck, S., Leyn, U., Baier, M.M., Schuckliess, W., Schimpf, M. and Schmotz, M. Konzept zur Bewertung des Verkehrsablaufs an Knotenpunkten mit und ohne LSA (Level of service assessment of signalized and unsignalized intersections). *Reports of the German Federal Highway Research Institute (BASt)*, No. V 324, Bergisch Gladbach, 2020.
19 Grigoropoulos, G., Leonhardt, A., Kaths, H., Junghans, M., Baier, M.M. and Busch, F. Traffic flow at signalized intersections with large volumes of bicycle traffic. *Transportation Research Part A*, 2022. Vol. 155: pp. 464-483.