TOTAL APPROACH CAPACITY AT SIGNALIZED INTERSECTIONS WITH SHARED-SHORT LANES – A GENERALIZED MODEL BASED ON SIMULATION STUDY

Ning Wu, Ph.D.

Institute for Traffic Engineering, Ruhr-University Bochum, 44780 Bochum, Germany

phone: +49 234 3226557, fax: +49 234 3214151

e-mail: ning.wu@rub.de, http://homepage.rub.de/ning.wu

Paper presented at the
Transportation Research Board 86th Annual Meeting
January 21-25, 2007, Washington, D.C.

Preprint 07-0138

Words:	4200
Tables:	1
Figures:	12
Total words:	7450

TOTAL APPROACH CAPACITY AT SIGNALIZED INTERSECTIONS WITH SHARED-SHORT LANES – A GENERALIZED MODEL BASED ON SIMULATION STUDY

Ning Wu, Ph.D.
Institute for Traffic Engineering, Ruhr-University Bochum, 44780 Bochum, Germany
phone: +49 234 3226557, fax: +49 234 3214151
e-mail: ning.wu@rub.de, http://homepage.rub.de/ning.wu

ABSTRACT

This paper presents a theoretical-empirical model for estimating the total approach capacity at signalized intersections with of shared-short lanes. This model extends the theoretical capacity formula for shared-short lanes at unsignalized intersection, which was introduced by the author earlier, to signalized intersections. The model takes into account the stochastic nature of traffic flow and the effect of queue blockage to the short turn lanes. Using the simulation package VISSIM, a comprehensive database was generated for calibrating the model under different lane and signal control conditions. The proposed model can be used for arbitrary lane and signal timing configurations. For signalized intersections with simple shared-short lane configurations, explicit equations are given. Detailed monographs are prepared for practical applications.

keywords: Signalized intersection, Short lane, Shared lane, Approach Capacity, Simulation

INTRODUCTION

At signalized intersections, there are normally turning lanes for left-turn or right-turn flows, which have only a limited length (see Figure 1). But in the approach the traffic streams, e. g. the left-turn stream and the through stream, often share a single lane upstream of turn pocket. The calculation procedures in almost all of the current highway capacity manuals (e.g. American HCM (*1*) or German HBS (*2*)) do not exactly treat those shared-short lanes at signalized intersections. The capacities of individual streams (left-turn, through, and right-turn) are calculated separately. The turning lanes are treated as exclusive lanes. Such a treatment neglects the effect of queue blockage to or from the short turning lanes. However, when traffic demand does cause queue blockages to or from the short-lane section, a reduced total capacity of the approach is expected. On the other side, in case that the traffic streams share a common traffic lane without short turn pockets, the current highway capacity manuals estimate the capacity of the shared lane with an extra formula. This implies that the lengths of the left-turn or right-turn lanes, e.g., in case of a left-turn pocket or a right-turn pocket, can be only considered either as infinite or zero. The exact lengths of the separate short turning lanes (lengths the turn pockets) cannot be taken into account. Therefore, the capacity estimated from the current highway capacity manuals is either overestimated or underestimated. The lack of an appropriate procedure for approach capacity estimation under situation with short turning lanes often leads to a longer than necessary and thus more costly turn pocket.

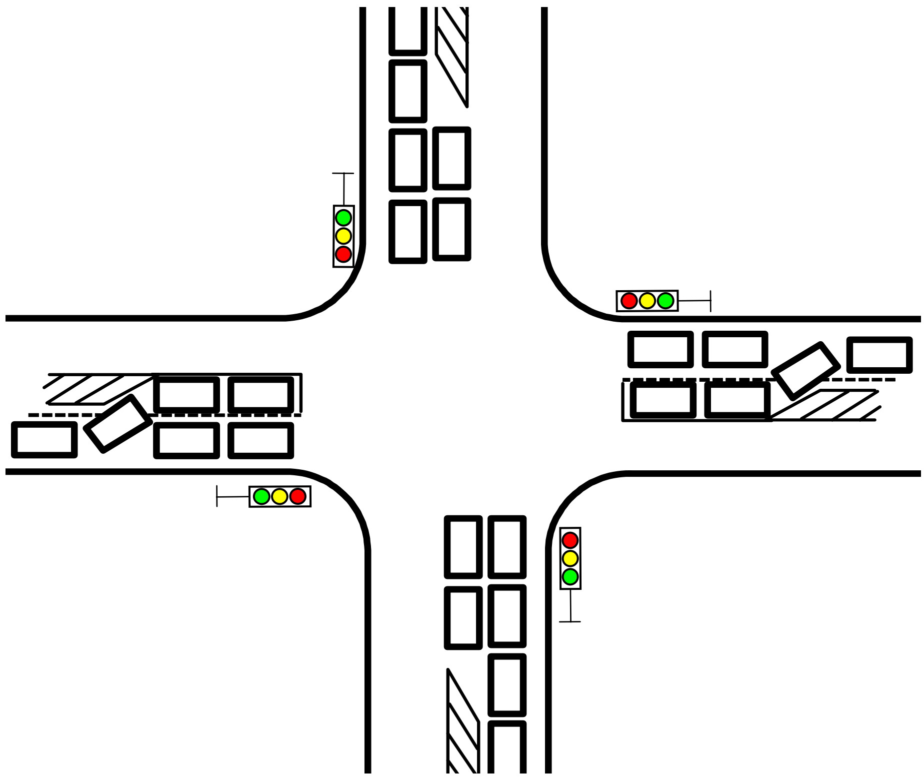


Figure 1 – Approaches at signalized intersections with short and shared lanes

Unfortunately, there exists very limited research on this topic. The well-known documents where the short-lane issue has been addressed are that incorporated in the German Highway Capacity Manual (*3*, *2*) and that in the SIDRA (*4*) software package. The models used in both documents are deterministic models. The stochastic nature of blockage to or from the short lanes has not been taken into account. In this paper, a theoretical-empirical model for estimating the total approach capacity with this combination of shared and short lanes is introduced. This model extends the theoretical capacity formula for shared-short lanes at unsignalized intersection, introduced by the author earlier (*5*), to signalized intersections. The model takes into account the short-lane effect, specifically the stochastic nature of queue blockage. The model is calibrated and verified using the VISSIM (*6*) microscopic simulation package. In the simulation study, the standard parameters in VISSIM are used.

The proposed model provides considerable enhancements to the methodology used in the current highway capacity manuals, where the short-lane issue is not properly addressed. It has been found that the approach capacity with short left-turn or right-turn lanes is specifically related to the length of the short lane, the ratio between the through and turning vehicles and the green times both for through and turning vehicles. It has been also found, like by computing capacities at signalized intersections in general, that the cycle length is not an explicit parameter affecting the total capacity of the approach with shared-short lanes if the capacities are calculated as number of vehicles per cycle time.

According to the case studies presented in this paper, the capacity enhancement for an additional short turning lane lies up to 30 percent compared to the shared-lane situation without additional short lanes. This enhancement depends strongly on the green times and the length of the short lanes. From the result of these studies, a generalized formulation for estimating the total approach capacity with shared-short lanes at signalized intersections can be introduced. This formulation includes an explicit expression that can be easily incorporated into the highway capacity manuals such as HCM 2000 and HBS 2001.

SIMULATION STUDY WITH THE SOFTWARE PACKAGE VISSIM

In the conducted simulation study, the program package "VISSIM 3.70" from the PTV AG (*6*) is used for determining the total approach capacity at signalized intersection with short turn lanes.

In this study, each simulation run has a 3-h runtime and only personal cars are considered in the traffic volume. The parameters for the driver behavior are initialized according to the program's default values. The desired speed is set to 45-60 km/h for standard urban streets. As a model configuration an approach at a signalized intersection with a through and a left-turn lane is used for the simulation study. On the diverge point of the two traffic lanes a permanent queuing saturation is produced for high traffic volume. Thus, the approach capacity can be obtained by simply counting the flow output behind the stop line (cf. Figure 2).

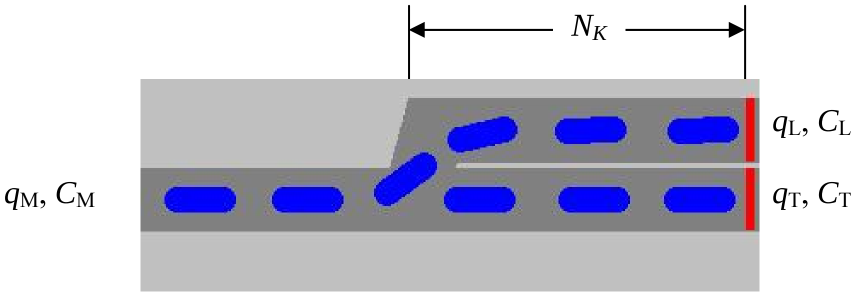


Figure 2 – Permanent queue before the diverge point, screenshot from VISSIM

Denote the traffic flow and the capacity for the let-turn lane *L* and the through lane *T* with q_L, C_L and q_T, C_T and denote the total flow and capacity for the approach with q_M and C_M. We are looking for a model for which the following necessary boundary conditions must be held (Table 1).

Table 1 - Necessary boundary conditions for the capacity of an approach at signalized intersections with short-shared lanes

No.	boundary condition	note
1	$C_L \leq f_L \cdot q_{s,L}$	a)
2	$C_T \leq f_T \cdot q_{s,T}$	a)
3	$C_M = f_L \cdot q_{s,L}$ for $q_T = 0$	b)
4	$C_M = f_T \cdot q_{s,T}$ for $q_L = 0$	b)
5	$C_M = \min(f_L \cdot q_{s.L} \cdot (q_L+q_T)/q_L, f_T \cdot q_{s,T} \cdot (q_L+q_T)/q_T)$ for $N_K \to \infty$	c)
6	$C_M = C_{shared}$ for $N_K = 0$	d)

a) The capacity of a short lane is always smaller than the capacity of an exclusive lane

b) The capacity of the approach is equal to the capacity of an exclusive lane if the flow rate of one of both lanes is zero

c) The ratio between the flow rates of both lanes remains constant for $N_K \to \infty$

d) The capacity of the approach is equal to the capacity of a shared lane for N_K=0

Here q_s is the saturation flow rate, N_K is the length of the short lane area (measured in number of vehicles), and f is the green time ratio of the traffic lanes under consideration.

In the simulation, the short-lane configuration illustrated in Figure 3 is selected. Here q_L is the flow rate of the left turn lane and q_T is the flow rate of the combined through and right turn lane. The through and right turn stream are treated together as a combined single stream because they diverse from each other not before the stop line. Because of the symmetry of the configuration, the simulation results apply also to the configuration of a through lane and a short right-turn lane.

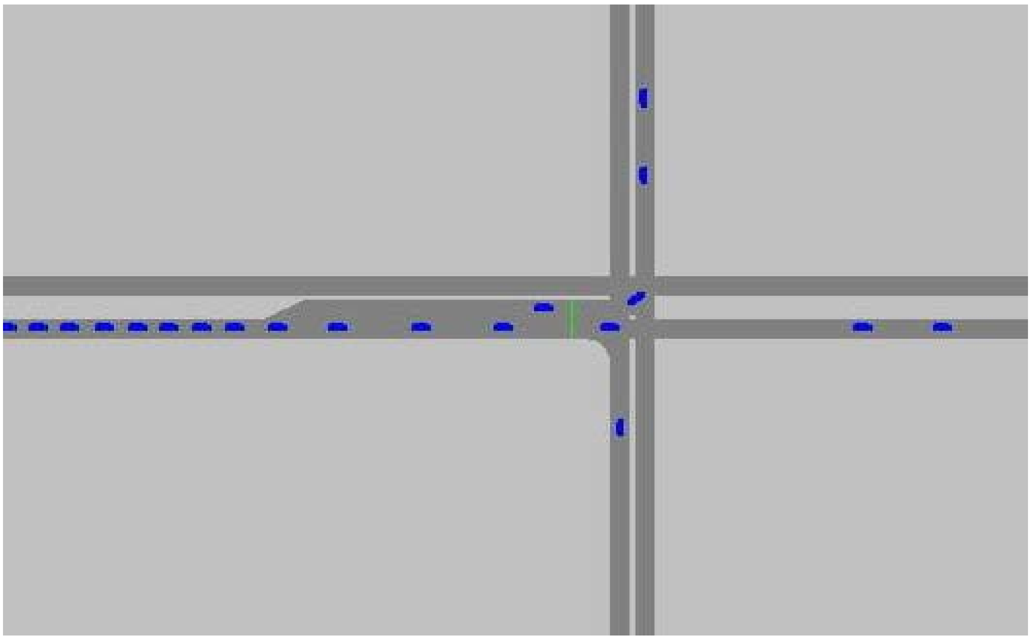


Figure 3 – Simulated short-lane configuration

For this configuration, there are generally three possible basic constellations of signal controls:

1. The green times of both lanes (L, T) fully overlap (e.g. both lanes have the same green time, Figure 4a).
2. The green times of both lanes (L, T) exclude each other (e.g. the green times of both lanes are turned on one after another, Figure 4c).
3. The green times of both lanes (L, T) are intercepted (Figure 4b).

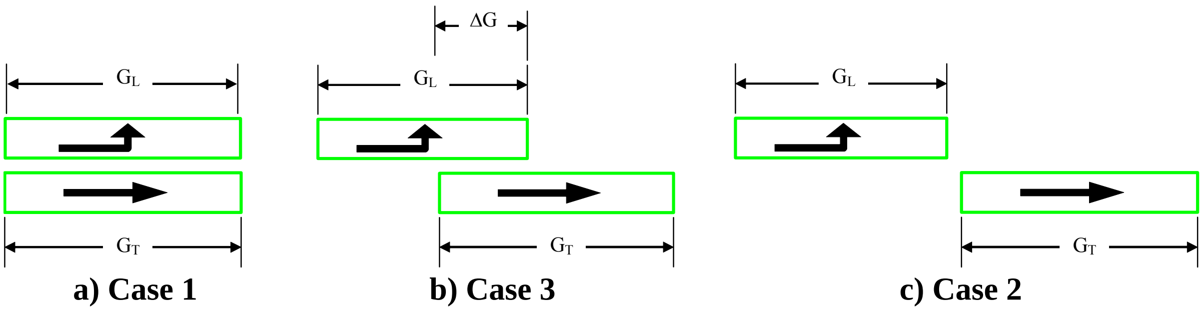


Figure 4 – Possible basic constellations of green times: a) Case 1: green times fully overlap, b) Case 3: green times intercepted, c) Case 2: green times exclude each other

In case 1 that the green times of both lanes (L, T) fully overlap, following input parameters are used for the simulation:

- cycle time, C
- green time, G
- ratio of left-turn flow, $a_L=q_L/(q_L+q_T)$
- number of possible stop places in the short lane area, N_K

The cycle time C is varied form 60s to 90s with a step of 10s. The green time G is varied from 10s to 40s with a step of 10s. The applied ratios of left-turn flow a_L are 50%, 20% and 0%. The number of stop places in the short lane area N_K is chosen to 0, 3, 6, and 9 veh. For each parameter combination, a simulation for 3 h is conducted.

In case 2 that the green times of both lanes (L, T) exclude each other, the parameter combinations are modified slightly. The variation of the cycle time C, ratio of the left turn flow a_L, and the number of possible stop places in the short lane area N_K remains unchanged. In addition, the green time for the through lane G_T is varied from 10s to 40s with a step of 10s. The green time for the left turn lane G_L is varied from 5s to 20s with a step of 5s. The green time for the left turn lane begins 1s after the green time for the through lane is terminated. Again, 3 h simulation is conducted for each parameter combination.

In case 3 that the green times of both lanes (L, T) are intercepted, the intercepted length of green time ΔG is taken into account additionally for interpolation.

In the following sections, the three cases are treated separately.

EVALUATION OF THE SIMULATION RESULTS

In order to obtain the saturation flow rate q_s the simulation is conducted for an exclusive though lane at first. The saturation flow rate q_s is obtained by measuring the discharge flow rate during the green time. In Figure 5, the simulated results are compared with the saturation flow values in HCM 2000 and HBS 2001 in dependence on the green time G. It can be recognized that the simulation results from VISSIM confirm neither the values in HCM 2000 nor those in HBS 2001. Since in VISSIM the saturation flow rate q_s cannot simply be changed by a user, it is not easy to calibrate VISSIM to fit the values in HCM 2000 or HBS 2001. In order to establish a general conclusion based on the simulation results, the capacity within a cycle time, $n_c=q_s \cdot G$, is evaluated in the simulation study. This capacity is then neither dependent on the saturation flow rate q_s nor on the cycle time C.

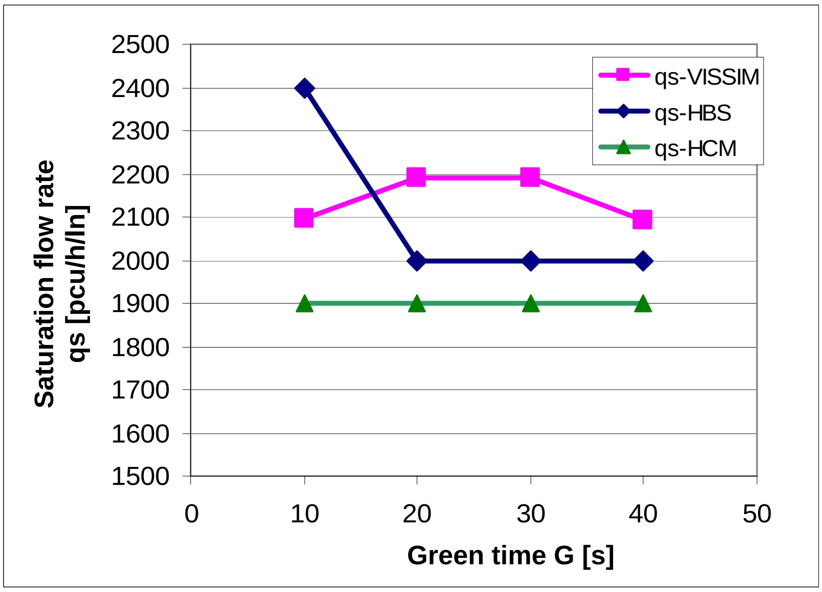


Figure 5 – Saturation flow rates of an exclusive though lane from HCM 2000, HBS 2001 and VISSIM

It turns out, that the capacity of an approach per cycle time, $n_{c,M}$, is only dependent on the number of stop places of the short lane area, N_K, the capacities of the separate traffic lanes $n_{c,L}$ and $n_{c,T}$, and the ratio of left turn flow a_L. Since the capacity per cycle time, $n_{c,M}$, is not more dependent on the cycle time C, the simulation results for different cycle times can be aggregated together. Therefore, the parameter combinations can be simplified by eliminating the cycle time (totally 4 values). For the remaining parameter combinations, the simulation period is now 3 h * 4 = 12 h each. The results of the following sections are based on the mean values of these 12 h simulations.

Total capacity of the approach for case 1: The green times of both lanes (L, T) fully overlap

In Figure 6, the simulated total capacity of the approach for the case 1 that the green times of both lanes (L, T) fully overlap is illustrated. Obviously, the capacity is at lowest if there are no left turn vehicles at all (a_L= 0.0). The approach capacity increases with increasing ratio a_L of left turn flow. Because of the symmetry between both lanes (L, T), the approach capacity has its maximum value at a_L= 0.5. The approach capacity also increases with increasing number of stop places N_K in the short lane area. It can be recognized that there is an upper boundary of capacity because the capacity curve shows an asymptotic shape towards the number of stop places N_K (cf. also Table 1, Boundary condition 5).

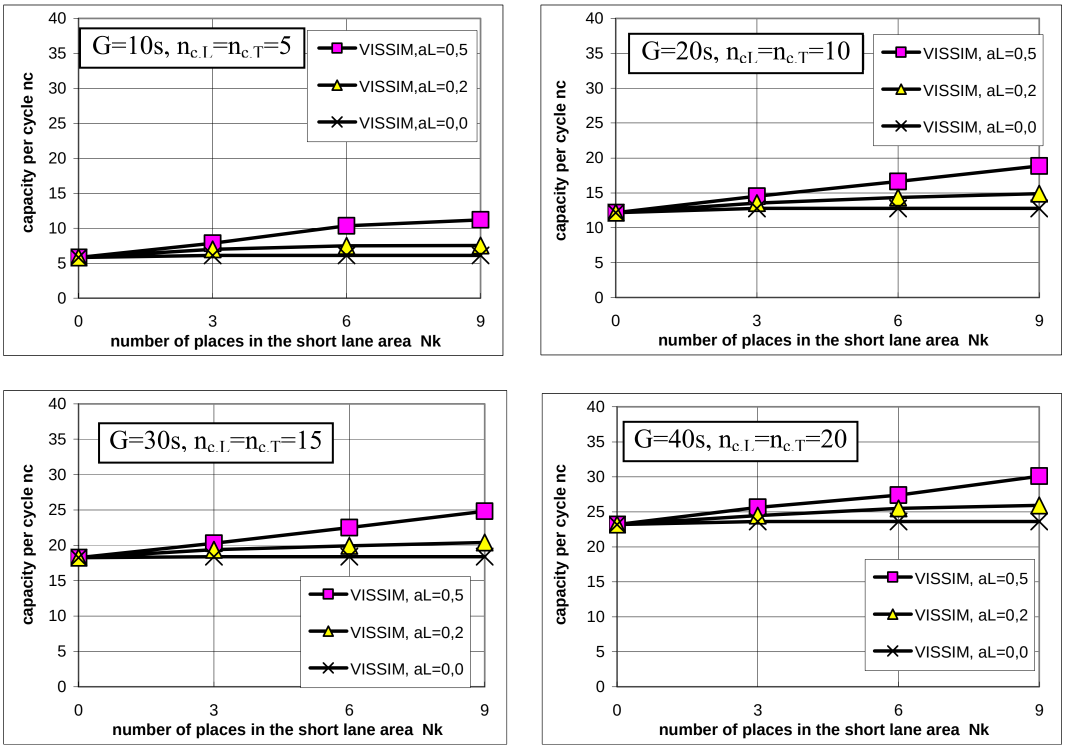


Figure 6 – Simulated total capacity of an approach with a short lane area, case 1: The green times of both lanes (L, T) fully overlap, $n_{c,L}$ = capacity of the left turn lane (L) pro cycle, $n_{c,T}$ = capacity of the through lane (T) per cycle

Total capacity of the approach for case 2: The green times of both lanes (L, T) exclude each other

In Figure 7, the simulated total capacity of the approach for the case 2 that the green times of both lanes (L, T) exclude each other is illustrated. Again, the total capacity is a function of the number of stop places in short lane area N_K and the capacities of both lanes $n_{c,L}$ and $n_{c,T}$. It can be seen that the ratio of the left turn flow does not have an unequivocal influence on the total capacity of the approach. Depending on the number of stop places in the short lane area, the influence can be positive or negative. As in the case 1, the total capacity of the approach increases with increasing number of stop places in the short lane area. This increase has an again asymptotic shape (cf. also Table 1, Boundary condition 5) towards the number of stop places in the short lane area.

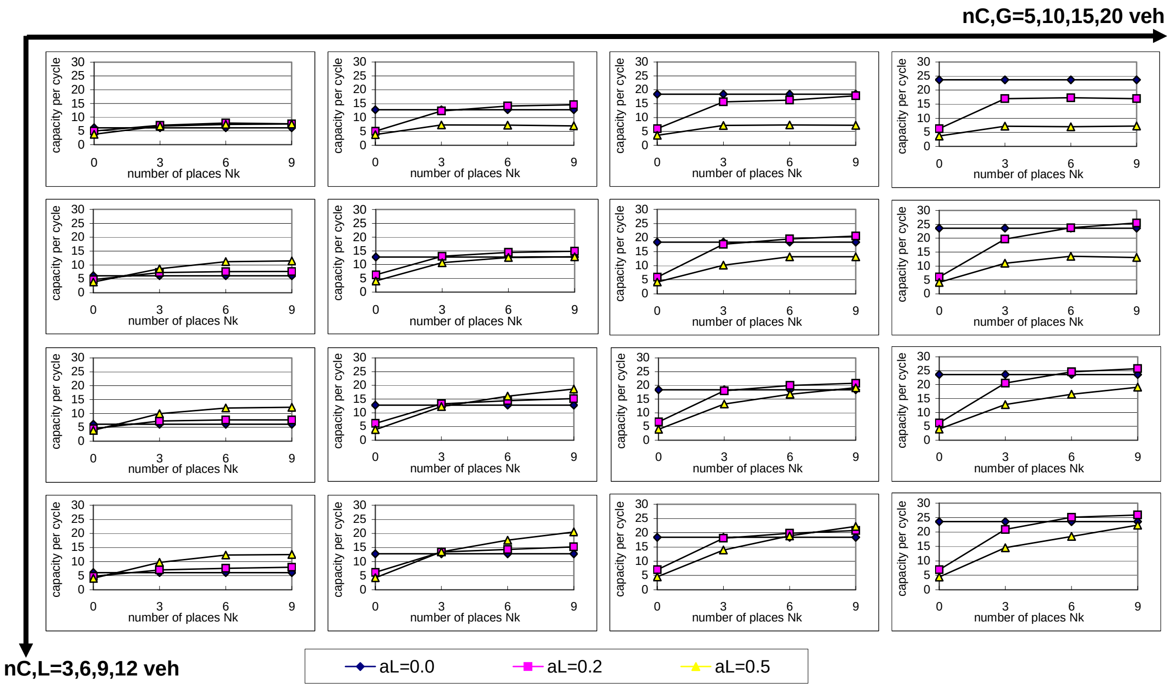


Figure 7 – Simulated total capacity of an approach with a short lane area, case 2: The green times of both lanes (L, T) exclude each other, $n_{c,L}$ = capacity of the left turn lane (L) pro cycle, $n_{c,T}$ = capacity of the through lane (T) per cycle

REGRESSION FUNCTION FOR THE SIMULATION RESULTS

The total capacity of an approach with short lane configurations can be expressed with a universal approximation function (*5*). This function is derived from the point of view of queuing and probability theory. It takes into account both the stochastic property of the traffic flow and the probability of the lane blockage on the brink point. This is valid both for unsignalized and signalized intersections. However, the model parameters of the function must be calibrated according to the configurations under consideration. Die derivation of the universal approximation function is presented below.

Firstly, a generalized system with m sub-streams, which all develop at one point from a shared lane (cf. Figure 8, point A) is considered. The sub-stream i is described by the parameters q_i (traffic flow), C_i (capacity) and x_i (saturation degree). The capacity C_i and the saturation degree $x_i = q_i/C_i$ are considered under the assumption that there are infinitely many queue places for the subject stream i. Accordingly, the shared lane has the parameters q_M, C_M and x_M.

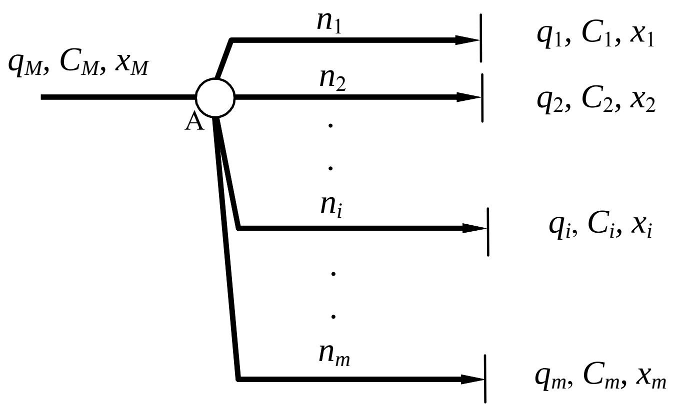


Figure 8 - Relationship between a shared lane and its sub - streams

For the point *A* the following fundamental state condition holds: *The point A is equally occupied from left (shared lane) and from right (all sub-streams) by waiting streams.* That is, the probability that the point *A* is occupied on the side of the shared lane is equal to the probability that the point *A* is occupied on the side of the sub-streams. It follows that

$$P_{s,M} = P_{s,1} + P_{s,2} + ... + P_{s,i} + ... + P_{s,m} = \sum_{i=1}^{m} P_{s,i} \quad (1)$$

The probability that the point *A* is occupied by a sub-stream is equal to the probability that the queue length in this sub-stream is larger than the length of the queue space (section from the stop line to point *A*), i.e., for the sub-stream *i*,

$$P_{s,i} = \Pr(N > n_i) \quad (2)$$

The distribution function of queue lengths in a waiting stream can be represented approximately by the following equation:

$$F(n_i) = \Pr(N \le n_i) = 1 - x_i^{1+f(n_i)} \quad (3)$$

with $x_i = q_i / C_i$ and *a*, *b* = model parameters. The function $f(n_i)$ is a monotony ascending function of n_i with $f(n_i = 0) = 0$. Thus,

$$P_{s,i} = \Pr(N > n_i) = 1 - F(n_i) = x_i^{1+f(n_i)} \quad (4)$$

For estimating the capacity of the shared lane, the following definition is introduced: *The capacity of the shared lane is the traffic flow, at which the merge point A on both sides is occupied 100 percent* ($P_{s,M} = x_M = 1$). As a rule, the traffic flows q_i (existing or predicted) do not describe the complete saturation of the shared lane. The capacity of the shared lane lies generally over the sum of q_i (in case of under-saturation by existing q_i). In this case the traffic flows at the subject traffic stream q_M would approach the limit of the capacity, if the q_i-values increase. In general, each q_i-value could have another increase. It is assumed however, that for these fictional increases of existing traffic flows equal increase factor *k* can be applied to each sub-stream. k is thus that factor, by which all traffic flows on the subject approach has to increase, for reaching just the maximal possible traffic flow: the capacity.

Multiplying the saturation degree of all sub-streams by this factor k and postulating

$$P_{s,M} = x_M = \sum_{i=1}^{m} (k \cdot x_i)^{1+f(n_i)} \overset{!}{=} 1 \tag{5}$$

yields the capacity of the subject shared lane:

$$C_M = k \cdot q_M = k \cdot \sum_{i=1}^{m} q_i \tag{6}$$

Accordingly, the real saturation degree of the shared lane becomes

$$x_{M,real} = \frac{q_M}{C_M} = \frac{1}{k} \tag{7}$$

For the special case with $n_1 = n_2 = ... = n_i = ... = n_m = N_K$, i.e., all sub-streams have the same length of queue space is

$$k\,|_{all\,n_i = N_K} = \frac{1}{\sqrt[n+1]{\sum_{i=1}^{m} x_i^{1+f(N_K)}}} \tag{8}$$

and

$$C_M\,|_{all\,n_i = N_K} = \frac{\sum_{i=1}^{m} q_i}{\sqrt[n+1]{\sum_{i=1}^{m} x_i^{1+f(N_K)}}} == \frac{1}{\sqrt[n+1]{\sum_{i=1}^{m} \left(\frac{a_i}{C_i}\right)_i^{1+f(N_K)}}} \tag{9}$$

For a configuration with two streams, a general form of the approximation function can be expressed as:

$$C_M = \frac{1}{\sqrt[1+f(N_K)]{\left(\frac{a_L}{C_L}\right)^{1+f(N_K)} + \left(\frac{a_T}{C_T}\right)^{1+f(N_K)}}} = \frac{1}{\sqrt[1+f(N_K)]{\left(\frac{a_L}{C_L}\right)^{1+f(N_K)} + \left(\frac{1-a_L}{C_T}\right)^{1+f(N_K)}}} \tag{10}$$

In this expression, C can be considered either the capacity (C), or the saturation flow rate (q_s), or the capacity per cycle time (n_c). The function $f(N_K)$ is a monotony ascending function of N_K with $f(N_K = 0) = 0$. The eq. (10) fulfils all boundary conditions given in Table 1. For example, for $N_K = 0$ is

$$C_M \,|_{N_k=0} = \frac{1}{\sqrt[1+0]{\left(\frac{a_L}{C_L}\right)^{1+0} + \left(\frac{1-a_L}{C_T}\right)^{1+0}}} = \frac{1}{\frac{a_L}{C_L} + \frac{1-a_L}{C_T}} = C_{shared} \tag{11}$$

and for $N_K = \infty$ is

$$C_M \,|_{N_K \to \infty} = \lim_{N_K \to \infty} \frac{1}{\sqrt[1+\infty]{\left(\frac{a_L}{C_L}\right)^{1+\infty} + \left(\frac{1-a_L}{C_T}\right)^{1+\infty}}} \quad . \tag{12}$$

This equation can be rewritten as

$$C_M \,|_{N_K \to \infty} = \lim_{N_K \to \infty} \frac{1}{\sqrt[1+\infty]{1 + \left(\frac{a_L}{C_L} \Big/ \frac{a_T}{C_T}\right)^{1+\infty}} \cdot \frac{a_L}{C_L}}$$

For $\frac{a_L}{C_L} \Big/ \frac{a_T}{C_T} < 1$ is then

$$C_M \,|_{N_K \to \infty} = \lim_{N_K \to \infty} \frac{1}{\sqrt[1+\infty]{1 + \left(\frac{a_L}{C_L} \Big/ \frac{a_T}{C_T}\right)^{1+\infty}} \cdot \frac{a_L}{C_L}} = \frac{1}{1 \cdot \frac{a_L}{C_L}} = \frac{C_L}{a_L} < \frac{C_T}{a_T}$$

For $\frac{a_L}{C_L} \Big/ \frac{a_T}{C_T} > 1$ is respectively

$$C_M \,|_{N_K \to \infty} = \lim_{N_K \to \infty} \frac{1}{\sqrt[1+\infty]{1 + \left(\frac{a_T}{C_T} \Big/ \frac{a_L}{C_L}\right)^{1+\infty}} \cdot \frac{a_T}{C_T}} = \frac{1}{1 \cdot \frac{a_T}{C_T}} = \frac{C_T}{a_T} < \frac{C_L}{a_L}$$

In the special case with $\frac{a_L}{C_L} \Big/ \frac{a_T}{C_T} = 1$ is $\frac{C_L}{a_L} = \frac{a_T}{C_T}$ is

$$C_M \,|_{N_K \to \infty} = \lim_{N_K \to \infty} \frac{1}{\sqrt[1+\infty]{1+1} \cdot \frac{a_L}{C_L}} = \frac{1}{1 \cdot \frac{a_L}{C_L}} = \frac{C_L}{a_L} = \frac{C_T}{a_T}$$

Thus, $C_M = \min(C_L/a_L, C_T/a_T)$ for $N_K \to \infty$. That is exact the boundary conditions 5 in Table 1.

In HBS 2001 (*2*), a function $f(N_K) = N_K$ is used for unsignalized intersections. That is, in case of unsignalized intersections HBS 2001 uses

$$C_M = \frac{1}{\sqrt[1+N_k]{\left(\frac{a_L}{C_L}\right)^{1+N_k} + \left(\frac{1-a_L}{C_T}\right)^{1+N_k}}} \tag{13}$$

Using the results of the conducted simulation, eq. (10) is calibrated for both case 1 and 2 of approaches at signalized intersections.

Regression function for case 1: The green times of both lanes (L, T) fully overlap

The calibration of eq. (10) for the case 1 that the green times of both lanes (L, T) fully overlap is carried out with the simulated results represented in Figure 6. The calibration yields:

$$n_{c,M,I} = \frac{1}{\sqrt[1+N_K/m]{\left(\frac{a_L}{n_{c,L}}\right)^{1+N_K/n_{c,M}} + \left(\frac{1-a_L}{n_{c,T}}\right)^{1+N_K/n_{c,M}}}} \tag{14}$$

with $n_{c,M,I}$ = total capacity of the approach per cycle time in case 1 (the green times of both lanes (L, T) fully overlap)

$n_{c,M}$ = $\left(0,32 \cdot \sqrt{n_{c,T} \cdot n_{c,L}}\right)^{1,22}$ = calibrated model parameter

$n_{c,L}$ = capacity per cycle time for the left turn lane

$n_{c,T}$ = capacity per cycle time for the through lane

a_L = ratio of left turn flow

The eq. (14) applies also to the case that the green time does not exactly have the same duration for both the left turn lane and the through lane. The necessary condition for applying the eq. (14) is that the green times are included each other completely. That, is, the green time of one lane has to begin as early and end as late as the green time of the other lane. Since the capacities per cycle time are used as input parameters, eq. (14) is applicable not only for protected but also for permitted left turn streams. In this case the capacity of the permissive left turn stream should be calculated as a function of the opposing volume and the green time. In Figure 9, a comparison between the simulated capacity and the capacity from the regression function (eq. (14)) is illustrated. It shows a very good agreement.

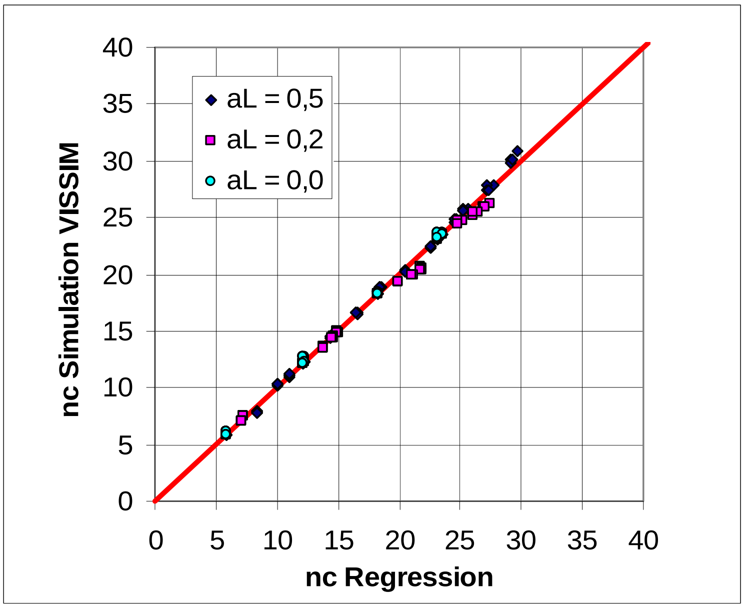


Figure 9 – Comparison between the simulated approach capacity and the approach capacity from the regression (eq.(14)) for the case 1 that the green times of both lanes (L, T) fully overlap (sample size *n*=192, correlation coefficient r^2=0.996, standard deviation *s*=0.44 veh/cycle)

For $N_K = 0$, eq. (14) becomes the well-known shared lane formula:

$$n_{c,M,I}\Big|_{N_K=0} = \frac{1}{\dfrac{a_L}{n_{c,L}} + \dfrac{1-a_L}{n_{c,T}}} \tag{15}$$

For a special case that both lanes are used by only one traffic stream (e.g. the through stream has an exclusive lane and a short lane), eq. (14) becomes:

$$n_{c,M,I}\Big|_{L=T} = \frac{2}{\sqrt[1+N_K/m]{2}} \cdot n_{c,T} \tag{16}$$

In Figure 10, for the case 1 that the green times of both lanes (L, T) fully overlap, the total approach capacity is illustrated as a function of the number of the stop places in the short lane area N_K and the ratio of left turn flow a_L for the parameters $n_{c,T} = 20$ and $n_{c,L} = 10$. For practical applications, further figures ($n_{c,T}$ = 10, 15, 20, 25 and $n_{c,L}$ = 5, 10, 15) as monographs are given by the author (*7*).

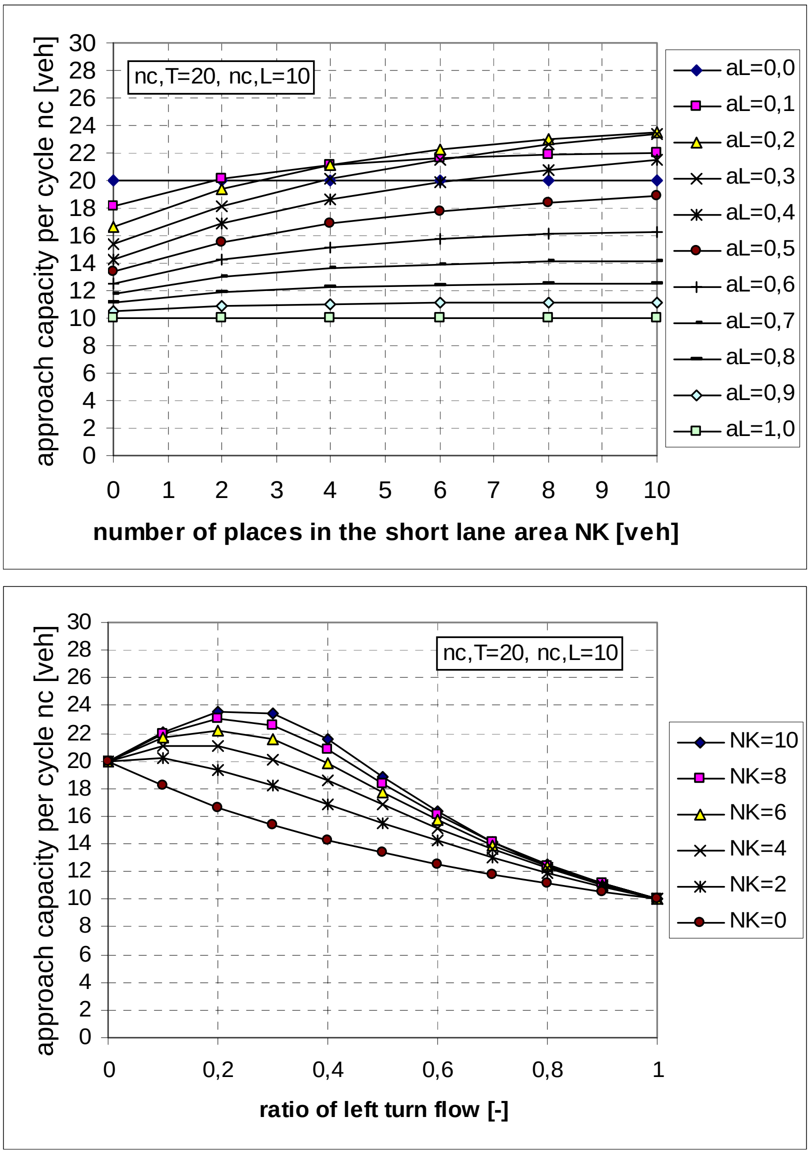


Figure 10 – Total approach capacity from eq. (14) as a function of the number of stop places of the short lane area N_K and the ratio of left turn flow a_L for $n_{c,T}$=20 and $n_{c,L}$=10 (case 1: The green times of both lanes (L, T) fully overlap)

Regression function for case 2: The green times of both lanes (L, T) exclude each other

The calibration of eq. (10) for the case that the green times of both lanes (L, T) exclude each other is carried out with the simulated results represented in Figure 7. The calibration yields:

$$n_{c,M,II} = \frac{1}{\sqrt[1+N_K/m]{\left(\frac{a_L}{n_{c,L}^*}\right)^{1+N_K/m} + \left(\frac{1-a_L}{n_{c,T}^*}\right)^{1+N_K/m}}} \tag{17}$$

with $n_{c,M,II}$ = total capacity of the approach per cycle time in case 2 (the green times of both lanes (L, T) exclude each other)

$n_{c,M}$ = $\left(0{,}13 \cdot \sqrt{n_{c,T} \cdot n_{c,L}}\right)^{2{,}87}$ = calibrated model parameter

$$n_{c,L}^{*} = \left(\frac{a_L(1-a_L)}{2+a_L N_K^{\ 3}} + \frac{1}{n_{c,L}} \right)^{-1}$$

$$n_{c,T}^{*} = \left(\frac{a_L(1-a_L)}{2+(1-a_L) N_K^{\ 3}} + \frac{1}{n_{c,T}} \right)^{-1}$$

$n_{c,L}$ = capacity per cycle time for the left turn lane
$n_{c,T}$ = capacity per cycle time for the through lane
a_L = ratio of left turn flow

Figure 11 shows the comparison between the simulated total approach capacity and that from the regression function (eq. (17)). Again, the agreement is good.

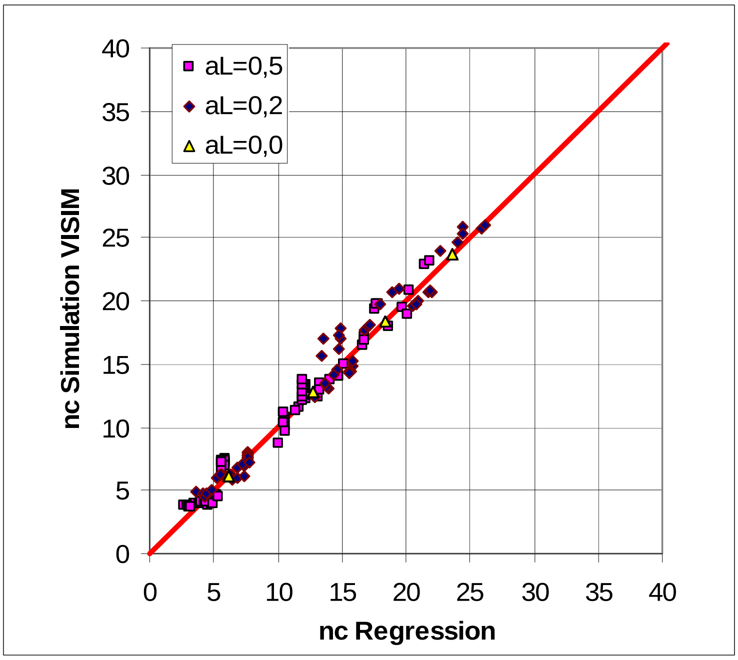
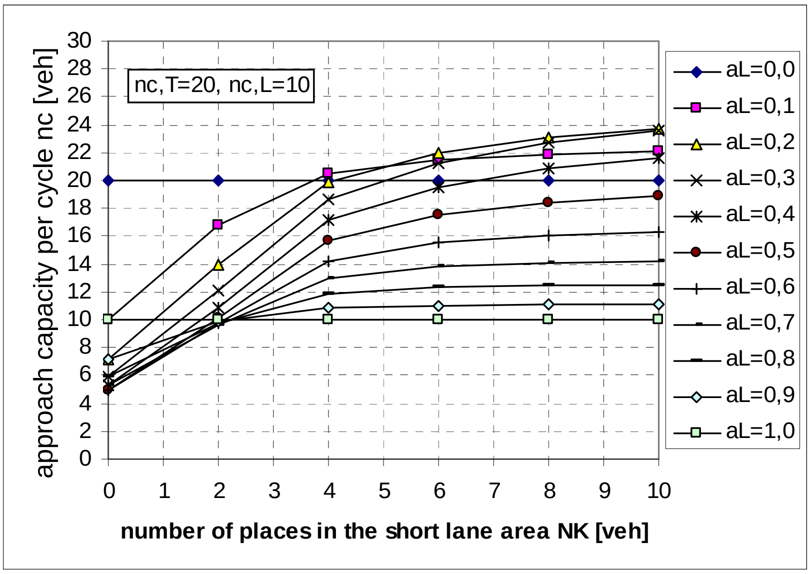


Figure 11 - Comparison between the simulated capacity and the capacity from the regression (eq. (17)) for the case that the green times of both lanes (L, T) exclude each other (sample size *n*=192, correlation coefficient r^2=0.984, standard deviation *s*=0.84 veh/cycle)

In Figure 12, for the case 2 that the green times of both lanes (L, T) exclude each other, the total approach capacity is illustrated as a function of the number of the stop places in the short lane area N_K and the ratio of left turn flow a_L for the parameters $n_{c,T}$ = 20 and $n_{c,L}$ = 10. For practical applications, further figures ($n_{c,T}$ = 10, 15, 20, 25 and $n_{c,L}$ = 5, 10, 15) as monographs are given by the author (*7*).



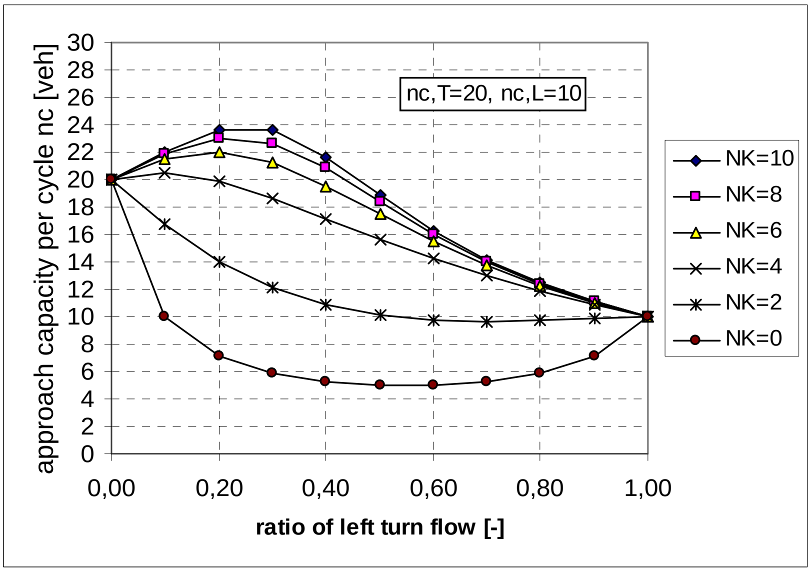


Figure 12 - Total approach capacity from eq. (17) as a function of the number of stop places of the short lane area N_K and the ratio of left turn flow a_L for $n_{c,T}$=20 and $n_{c,L}$=10 (case 2: The green times of both lanes (L, T) exclude each other)

Solution for case 3: The green times of both lanes (L, T) are intercepted: Interpolation between case 1 and 2

For the case 3 that the green time of both lanes (L, T) are intercepted, the total approach capacity can be approximately obtained by interpolating the results of case 1 (green times fully overlap) and case 2 (green times are excluded). The interpolation parameter is the intercepted duration of the green times, ΔG (cf. Figure 4).

The formulation of the interpolation is:

$$n_{c,M,III} = n_{c,M,II} + (n_{c,M,I} - n_{c,M,II}) \cdot \frac{\Delta G}{\min(G_{L,}\ G_T)} \tag{18}$$

with $n_{c,M,III}$ = total capacity of the approach per cycle time in case 3 (the green times of both lanes (L, T) are intercepted)

$n_{c,M,II}$ = total capacity of the approach per cycle time from eq. (17) (the green times of both lanes (L, T) exclude each other)

$n_{c,M,I}$ = total capacity of the approach per cycle time from eq. (14) (the green times of both lanes (L, T) fully overlap)
G_L = green time for the left turn lane
G_T = green time for the through lane
ΔG = duration of the interception

SUMMARY AND CONCLUSIONS

Using the simulation package VISSIM, a comprehensive database was generated for calibrating the approach capacity at signalized intersections under different lane and signal control conditions. This database was used for calibrating a theoretical-empirical model with which the total approach capacity with shared and short lanes can be estimated. This calibrated model can be used for arbitrary lane and signal timing configurations at signalized intersections.

The major contributions of this paper are the eqs. (14), (16), (17), and (18). These equations enable the construction of a complete, theoretical reasonable model for combined through (T) and left turn (L) flows with short lanes. This model is calibrated by simulation studies. Because of the symmetry of the configuration, these equations apply also to the configuration of a through flow (T) and a right turn flow (R) with short lanes. The presented model fills out a gap in the current version of HCM (*1*) and HBS (*2*).

It is shown that the capacity with a short left-turn (or a right-turn lane) is specifically related to the length of the short lane, the ratio of through/turning vehicles and the green times both for through and turning vehicles.

Based on the present studies, the capacity with a short turn lane can be increased up to 30 percent compared to the shared-lane situation without short lanes. This enhancement depends strongly on the green times and the length of the short lanes.

For applications in the practice, monographs based on eqs. (14) and (17) are constructed (cf. Figure 10 and Figure 12) for different traffic conditions. More detailed monographs can be obtained directly from the author.

REFERENCES

1. TRB. *Highway Capacity Manual 2000*. Transportation Research Board, Washington, D.C., 2000.
2. FGSV. *Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS 2001, Germany capacity Manual).* Forschungsgesellschaft für Straßen- und Verkehrswesen (Hrsg.), Nr. 299, FGSV Verlag GmbH, Köln, 2001.
3. Brilon, W., M. Großmann, and H. Blanke. Verfahren für die Berechnung der Leistungsfähigkeit und Qualität des Verkehrsablaufs auf Straßen (Methods for calculation of capacity and quality of traffic operation). *Schriftenreihe "Forschung Straßenbau und Straßenverkehrstechnik"*, Heft 669, Bonn, 1996.
4. Akcelik, R. Lane-by-Lane Modelling of Unequal Lane Use and Flares at Roundabouts and Signalized Intersections: the SIDRA Solution. *Traffic Engineering and Control*, 38 (7/8), 1997, pp. 388-399.
5. Wu, N. Capacity of Shared/Short Lanes at Unsignalised Intersections. *Transportation Research,* A33, Issue: 3-4. Elsevier Science Ltd., New York, Tokyo, Oxford, 1999.
6. PTV. *User Manual VISSIM 3.70*. PTV AG, *Karlsruhe*, Germany, 2003.
7. Wu, N. Kapazität der Zufahrten an signalisierten Knotenpunkten mit kurzen Aufstellfahrstreifen (Capacity of Signalised Intersections with Short Lanes). *Arbeitsblätter der Lehrstuhl für Verkehrswesen (Working papers of the Institute for Traffic Engineering)*, Nr. 23. Ruhr-Universität Bochum, 2003.