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Some New Developments in Two-Way-Stop-Controlled Intersections Procedures and Recommendations for a Future Version of the *Highway Capacity Manual*

Ning Wu[1] and Werner Brilon[1]

Abstract

The estimation of capacities and traffic performance at two-way-stop-controlled (TWSC) intersections has been the subject of investigations conducted by many researchers. The results of these investigations are incorporated in highway capacity manuals like the U.S. *Highway Capacity Manual* (HCM) or the German *Handbuch für die Bemessung von Strassen* (HBS). Although the underlying methodologies are similar, there are two major differences between the current HBS 2015 and HCM6: (a) the procedure for the impedance factor for movements of rank 4 and (b) the procedure for estimating the capacity of shared short lanes for both minor and major movements. In HBS 2015, new developments are accounted for and the accuracy of capacity and traffic quality estimations significantly improved. In HCM6, these two procedures have not been updated. Therefore, the replacement of the two procedures in HCM6 is recommended. In both HCM6 and HBS 2015, the procedures for calculating delays at shared lanes or shared short lanes are inaccurate and they also should be updated. In most cases, the delays are significantly underestimated. Recently, the authors have developed a new methodology dealing with this problem which can be easily incorporated into future versions of HBS and HCM. In this paper, the theoretical backgrounds of the three new methods are presented and major results are summarized. Compared with HCM6, the advantages of the new developments are highlighted. As a recommendation, three corresponding procedures for estimation of capacity and delay are given for potential use in a future version of HCM.

Highway capacity manuals such as the German *Handbuch für die Bemessung von Strassen* (HBS 2015) (*1*) or the U.S. *Highway Capacity Manual* (HCM6) (*2*) offer methodologies for the calculation of capacities and delays at two-way-stop-controlled (TWSC) intersections. These methodologies are the results of a decades-long series of investigations conducted by researchers in Germany, primarily Harders (*3*), Siegloch (*4*), and Grossmann (*5*). Their investigations have delivered the theoretical fundamentals of the current highway capacity manuals. Many other authors have also contributed significant input (*6–10*).

Comparing the current HBS 2015 and HCM6 with each other, however, one can recognize two major differences in the calculation procedures. There are two recent developments in calculation procedures which are already incorporated in HBS 2015 but not in HCM6. The first is the procedure for calculating the impedance factor for movements of rank 4 (*11*) and the second is the procedure for estimating the capacity of shared short lanes (*12*, *13*). There is also a third new development considering the estimation of delay at shared short lanes (*14*), which should be incorporated into future versions of both HBS and HCM.

The first two procedures, considering the impedance factor for movements of rank 4 and the capacity of shared short lanes, are incorporated in HBS 2015 but have not yet been considered in HCM6. These two procedures significantly improve the accuracy of estimations of capacity and traffic quality at TWSC intersections and they are much easier to use than the procedures in the current HCM6. The third is rather new and it should

[1]Institute for Traffic Engineering and Management, Ruhr University Bochum, Bochum, Germany

Corresponding Author:
Ning Wu, ning.wu@rub.de

be incorporated in future highway capacity manuals (e.g., HBS and HCM).

In this paper, the theoretical backgrounds of the three items are presented and the major results are summarized. Compared with the current HCM6, the advantages of the new developments are highlighted. As a recommendation, three corresponding procedures for capacity and delay estimation are formulated for a future version of HCM.

This paper is organized as follows. First, a summary of the three new developments is given to point out the requirements for improvements. Then, based on the results of the approaches, three ready-to-use recommendations in the style of HCM procedures are formulated. Finally, some conclusions are given in the light of the results.

Nomenclature

q = traffic flow rate (vehicles per hour, vph)
c = capacity (vph)
x = degree of saturation = $f(q, c)$ [–]
b = service time = $3600/c$ (s)
w = total delay in the system = $b + d$ (s)
d = delay in the queue (s)
k = number of queue places on a short lane (vehicles, veh)
r = rank of priority for a movement [–]
p_0 = probability of queue-free state [–]

Impedance Factor for Movements of Rank 4 or Higher

First, a major difference between the current HCM6 and HBS 2015 is addressed, that is, the calculation of the impedance factor for movement of rank 4. In HCM6, an adjustment developed by Grossmann (*5*) is applied to address the dependence between the queue-free states in the movements of rank 2 and 3 (Equation 20-52 in HCM6). Unfortunately, this adjustment leads to an overcorrection of the impedance factor and therefore to an overestimation of capacity of rank 4 (cf. *11*). In HBS 2015, a theoretically more reasonable model by Wu (*11*) is utilized. The impedance factor for movements of rank 4 can be directly obtained without an adjustment.

According to Wu (*11*), the queues in higher-ranked movements (cf. Figure 1, higher ranked than the subject rank 4 movement, e.g., rank 2 and rank 3 movements) are considered as one big queue. This means that one imagines that the conflict area can be passed by vehicles in movements of different ranks, one after the other. The order of the departures of the vehicles is not crucial for the consideration. Queuing vehicles thus form one virtual common queue with rank 2 in front and followed by rank

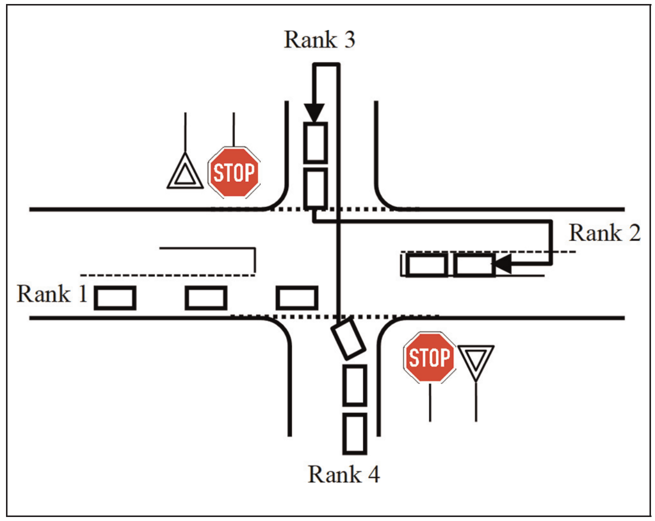

Figure 1. Queues in movements of different ranks and the operation sequence (cf. Wu, 1998 [*11*]).

3. Furthermore, the queues in the movements of different ranks and the big queue are considered as M/M/1 queuing systems. Thus, the total impedance factor for a movement of rank r, that is, the probability of queue-free state in all movements of ranks lower than r, is

$$f^*_{rank\,=\,r} = (p_0)_{r\,=\,2\text{ to }r-1} = \frac{1}{1 + \sum_{i=2}^{r-1} \frac{1-(p_0)_{rank\,=\,i}}{(p_0)_{rank\,=\,i}}} = \frac{1}{1 + \sum_{i=2}^{r-1} \left(\frac{1}{(p_0)_{rank\,=\,i}} - 1\right)} \tag{1}$$

Thus, the impedance factor for the movement of rank 4 (cf. HBS 2015) is

$$f^*_{rank\,=\,4} = (p_0)_{rank\,=\,2\text{ and }3} = \frac{1}{\frac{1}{(p_0)_{rank\,=\,2}} + \frac{1}{(p_0)_{rank\,=\,3}} - 1} \tag{2}$$

In Figure 2, the impedance factor for rank 4 movements from HCM6 and HBS 2015 is compared with simulation results. If the guideline procedure delivered the correct result, the data points should be on the diagonal line. However, the HCM procedure reveals higher values, meaning that HCM overestimates the impedance factor (Figure 2*a*). The overestimation can lead to as much as 20% overestimation of the capacity of rank 4 movements. Equation 2, that is, the procedure in HBS 2015, matches quite well with the diagonal (Figure 2*b*) which underlines the validity of this equation.

Capacities of Shared Short Lanes at TWSC Intersections

At TWSC intersections, there are often lanes for left-turn movements which might be too short to accommodate

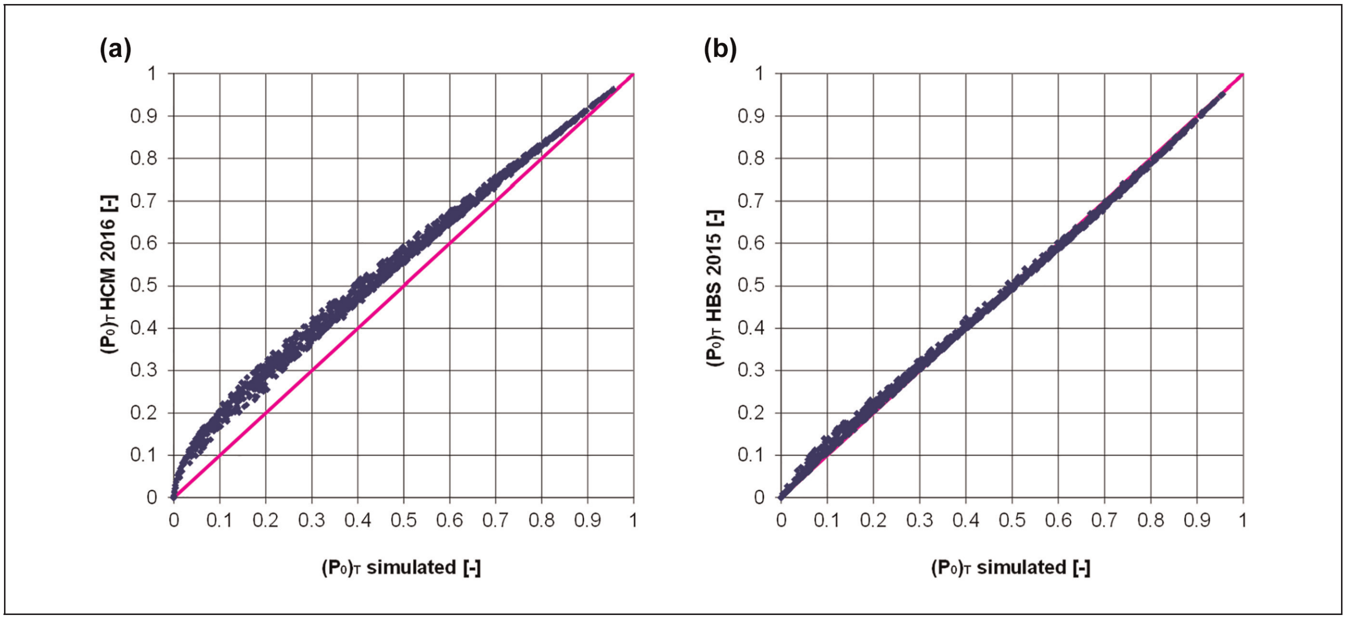

Figure 2. Impedance factor for movements of rank 4 from (*a*) HCM6 and (*b*) HBS 2015 (cf. Wu, 1998 [*11*]).

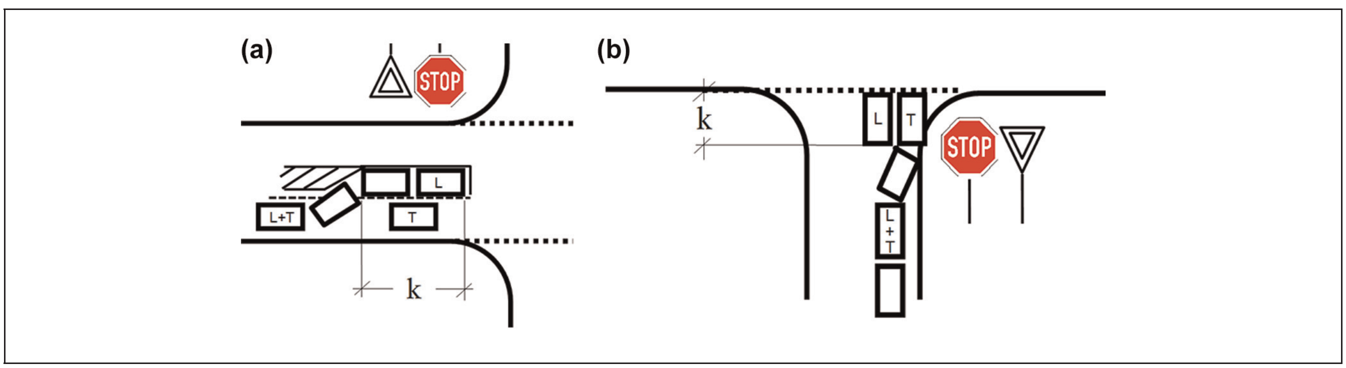

Figure 3. Possible queues and lane configurations at approaches of two-way-stop-controlled intersections: (*a*) major approach, (*b*) minor approach (cf. Wu, 1999 [*12*], Wu and Brilon, 2010 [*13*]).

the queue of turning vehicles. Such short lanes can exist both on the minor and major approaches, as illustrated in Figure 3. The indices L, T, and $L + T$ in Figure 3 refer to the left-turn, through, and shared movement (left + through). The right-turn movement is not explicitly considered here. As an approximation, it can be included into the through movement. There are common situations at TWSC intersections where two traffic movements each use their own short traffic lane near the stop-line but share a common traffic lane upstream from the short lane. This constellation is called shared short lane (SSL). The queues on both lanes L and T can block each other and the resulting total capacity has to be estimated. Wu (*12*) developed a general methodology dealing with the capacity of those configurations. The proposed model can also be used for calculating impedance effects of left turners from the major street (*13*). This model was verified by simulation studies.

In HBS 2015, the model from Wu (*12*) is incorporated for calculating the capacity of the SSL at the diverging point. In this model, there is a generalized system with m sub-movements, all of which develop at point A from one shared lane (cf. Figure 4). The sub-movement i has the parameters q_i, c_i, and x_i. The capacity c_i and the saturation degree $x_i = q_i/c_i$ are calculated for exclusive long lanes of the subject movement i. Accordingly, the shared lane has the parameters q_{SH}, c_{SH} and x_{SH}.

Point A must be equally occupied from left (shared lane) and from right (all sub-movements) by waiting vehicles, that is, the probability $P_{O,SH}$ that Point A is occupied on the side of the shared lane is equal to the probability $P_{O,i}$ that Point A is occupied on the side of the sub-movements. Thus,

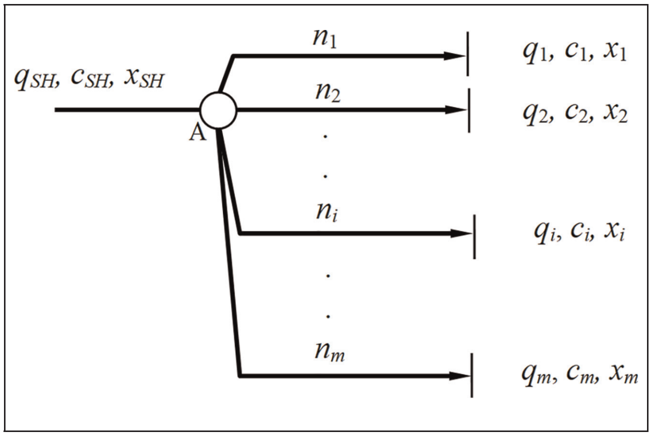

Figure 4. Relationship between a shared lane and its sub-movements (cf. Wu, 1999 [*12*]).

$$P_{O,SH} = P_{O,1} + P_{O,2} + \ldots + P_{O,i} + \ldots + P_{O,m} = \sum_{i=1}^{m} P_{O,i}, \text{ subject to } P_{O,SH} \leq 1 \tag{3}$$

The probability that Point A is occupied (the probability that a sub-movement is at or upstream of Point A) by a sub-movement is equal to the probability that the queue length in this sub-movement is larger than the length of the queue space (section from the stop-line to Point A). The capacity of the shared lane is reached by setting $P_{O,SH} = 1$. Thus, for a SSL with two sub-movements L and T, considering the queuing system in the sub-movements as an M/M/1 queuing system yields

$$c_{L+T,\text{minor}} = \frac{q_{L+T}}{x_{L+T,\text{minor}}} = \frac{q_L + q_T}{x_{L+T,\text{minor}}} \quad (\text{subject to } c_{L+T,\text{minor}} \leq \text{capacity of a single lane}) \tag{4}$$

with the definition

$$x_{L+T,\text{minor}} = \left(x_L{}^{k+1} + x_T{}^{k+1}\right)^{\frac{1}{k+1}} \tag{5}$$

In HCM6, a pragmatic procedure is used for calculating the capacity of minor approaches with SSL (called flared lane in HCM6). The procedure (cf. Equations 20-60 through 20-63 in HCM6) is complex, and the accuracy of the estimated capacity of the flared lane is poor. The capacity can be overestimated or underestimated depending on traffic flow rates of both movements and the length of the short-lane area. The HCM procedure delivers up to 10% of differences in capacity compared with the HBS procedure, which is based on Wu (*12*) and verified by comprehensive simulation studies. In Figure 5, a comparison of calculated SSL capacities c_{SH} from HBS 2015 and HCM6 is depicted for a T-junction with traffic flow rates of $q_2 = 450$ vph, $q_3 = 150$ vph, $q_4 = 100$ vph, and $q_7 = 400$ vph. The proportion of the left-turn flow rate in the minor approach a_L varies from 0.3 to 0.7 with an increase of 0.1.

Note that there is no HCM procedure for determining the capacity of the major approach with SSL. In HBS 2015, the capacity of an SSL at the diverging point in major approaches (Figure 3*a*) is calculated as follows (cf. *13*).

$$c_{L+T,\text{major}} = \frac{q_{L+T}}{x_{L+T,\text{major}}} = \frac{q_L + q_T}{x_{L+T,\text{major}}} \quad (\text{subject to } c_{L+T,\text{major}} \leq \text{capacity of a single lane}) \tag{6}$$

with the definition

$$x_{L+T,\text{major}} = x_L \left(1 + \frac{x_T{}^{k+1}}{1 - x_T}\right)^{\frac{1}{k+1}} \tag{7}$$

Note that the degrees of saturation of the SSL x_{L+T} do not have the same expression for a minor and a major approach (cf. *12*, *13*) because of different queuing

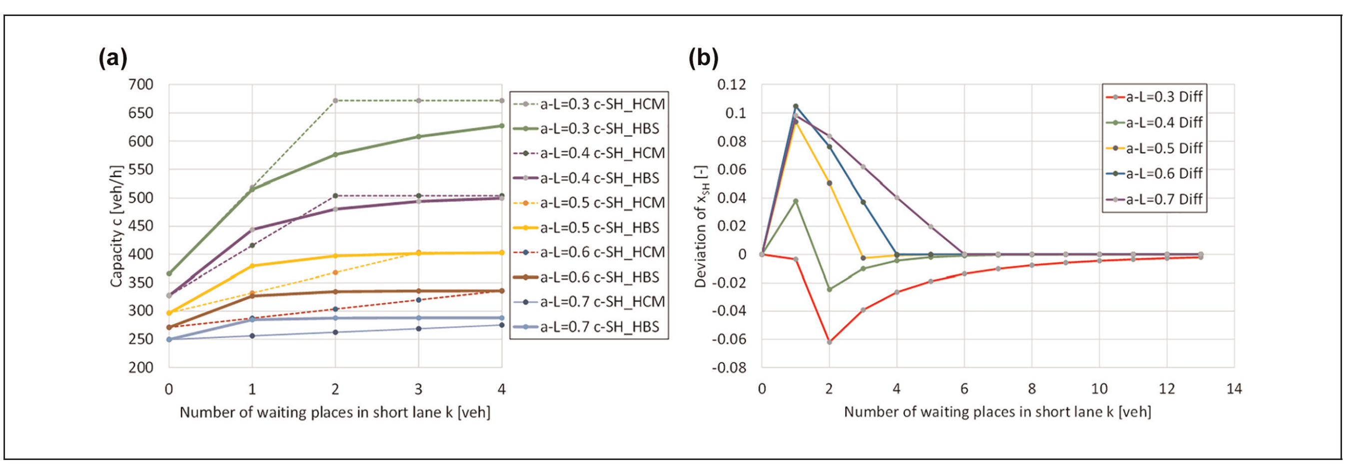

Figure 5. Capacity of shared short lane at a minor approach, according to the HCM6 and HBS 2015 procedures: (*a*) capacity c and (*b*) deviaition of x_{SH}.

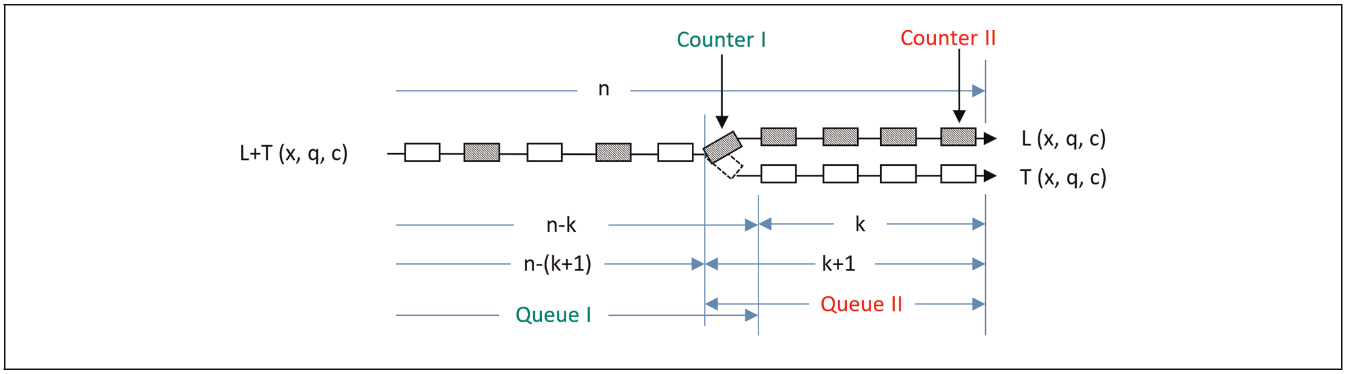

Figure 6. "Two-queue" system at a shared short lane: Queue I: M/G/1, Queue II: M/M/1 (cf. Wu and Brilon, 2019 [*14*]).

processes. Other than a left-turning vehicle, a vehicle in the major-through movement does not have to stop at a "stop" line. The same expression as Equation 7 is also adopted in HCM6 (Equation 20-43) for calculating the queue-free state in the major approach (*2*).

Queuing System in SSL at TWSC Intersections

Once the capacity is given, the performance of traffic flow can be assessed using average delays. Although the capacity manuals (e.g., HBS 2015, HCM6) provide methodologies for calculating capacities and delays for most of the geometric configurations, there are no methods for estimating delays at an SSL at a TWSC intersection. Actually, the queuing system at an SSL is a system consisting of two queues (cf. Figure 6), a short queue II at the stop-line and a queue I upstream from the diverging point of the two sub-movements. In the guidelines (*1*, *2*) the delays can be calculated for the two queuing systems separately—for queue II, however, only under the assumption of two exclusive lanes. There is no model to estimate the total average delays experienced by the two movements when passing through the two subsequent queues I and II. In addition, the service times at the stop-line are not calculated reasonably for these situations. Therefore, the methodology in these guidelines leads to a significant misjudgment of average delays and thus to an incorrect assessment of traffic quality.

The authors have developed a model dealing with this specific problem (*14*). Based on the capacity (Equations 4 and 6), the total delays of SSL can be estimated. The queuing system at an SSL can be considered as a system of two interrelated queues: the shared-lane section upstream of the diverging point (queue I) and the section downstream from the diverging point (queue II) with two parallel short lanes of length k. The two queues are connected at the position $k + 1$. Approximately, the two queues in section II can be treated as independent M/M/1 queues. The queue I upstream from the diverging point is considered as a general queuing system of type M/G/1.

Either at a minor or a major approach the total delay of a left-turn vehicle in the "Two-Queue" system is then

$$w_L = b_L + C_2 d_{\mathrm{MM1},L} + C_1 d_{\mathrm{MG1},L+T}(C_{0,L+T}) \qquad (8)$$

where

$C_2 = 1 - x_L^k$,

$C_1 = 1 - x_{L+T}^k$,

d_{MM1} = delay in the queue for an M/M/1 queue system,

d_{MG1} = delay in the queue for an M/G/1 queue system, and

$C_{0,L+T} = \frac{1}{2}\left(1 + \frac{Var(b_{L+T})}{b_{L+T}^2}\right)$ = parameter accounting for the stochastic properties of the M/G/1 queuing system

The total delay of a through vehicle in the "Two-Queue" system is different for a minor approach and for a major approach. For a minor approach, the total delay of a through vehicle is

$$w_{T,\mathrm{minor}} = b_T + C_2 d_{\mathrm{MM1},T} + C_1 d_{\mathrm{MG1},L+T}(C_{0,L+T}) \qquad (9)$$

For a major-through vehicle, there is no delay in queue II and the service time occurs only by queuing in queue I on the position $k + 1$. The total delay of a major-through vehicle is

$$w_{T,\mathrm{major}} = C_1\left(b_T + d_{\mathrm{MG1},L+T}(C_{0,L+T})\right) \qquad (10)$$

The parameter $C_{0,L+T}$ for the M/G/1 queue in the SSL is (cf. *14*, *15*)

$$C_{0,L+T} = 1 + \frac{c_{L+T}}{c_L}\left(\frac{c_{L+T}}{c_L} - 1\right)a_{L,b} + \frac{c_{L+T}}{c_T}\left(\frac{c_{L+T}}{c_T} - 1\right)a_{T,b} \qquad (11)$$

For a minor approach it is

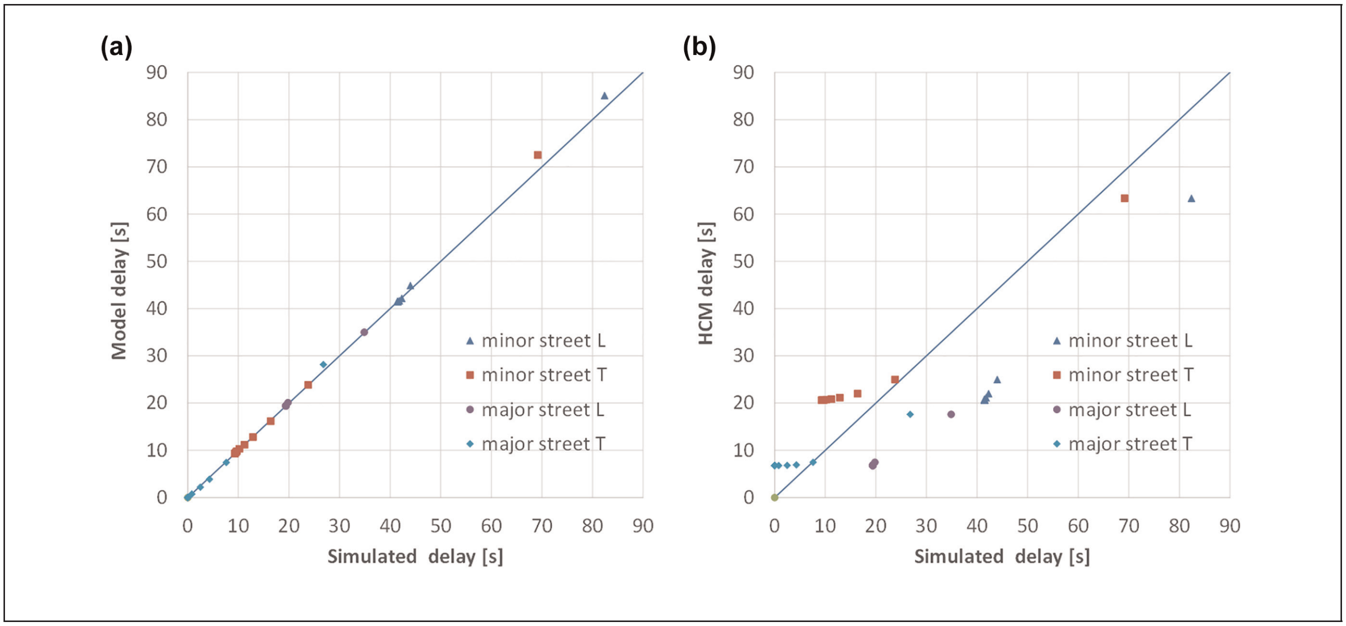

Figure 7. The results from the authors' proposed new model (*a*) and the HCM6 procedure (*b*) compared with simulation results.

$$a_{L,b} = a_L\left(x_L\left(x_L^{k+1} + x_T^{k+1}\right)^{-\frac{1}{k+1}}\right)^k \text{ and}$$
$$a_{T,b} = a_T\left(x_T\left(x_L^{k+1} + x_T^{k+1}\right)^{-\frac{1}{k+1}}\right)^k \quad (12)$$

For a major approach it is

$$a_{L,b} = a_L\left(1 + \frac{x_T^{k+1}}{1 - x_T}\right)^{-\frac{k}{k+1}} \text{ and}$$
$$a_{T,b} = a_T\frac{x_L}{1 - x_T}\left(x_T\left(1 + \frac{x_T^{k+1}}{1 - x_T}\right)^{-\frac{1}{k+1}}\right)^k \quad (13)$$

The parameters $a_{L,b}$ and $a_{T,b}$ can be significantly simplified by setting $k = 0$ as an approximation with a very simple expression. The resulting deviations are very small and they are not significant for practical use (*14*).

In the current HCM6, the total delay in the SSL is calculated using the same formula for both the left-turn and through movements. The delay formulas there are derived based on an M/M/1 queue. That is

$$w_{L,HCM} = w_{T,HCM} = w_{L+T} = b_{L+T} + d_{MM1,L+T} \quad (14)$$

where

$b_{L+T} = \frac{3600}{c_{L+T}} = a_L b_L + a_T b_T$

In HBS 2015, the delays of individual movements (L and T) and the delay of the diverging point ($L + T$) are examined separately. The longer delay is the decisive one to determine the level of service. The procedures in both HCM6 and HBS 2015 lead to inaccurate delay estimations and thus to an improper assessment of traffic quality.

The results from the new, correct model and from the HCM procedure are summarized in Figure 7, compared with simulation results. It shows to what degree the model results represent delays obtained by simulation: delays as estimated by the new model match quite well with simulated results (Figure 7*a*) and the HCM results are rather misleading (Figure 7*b*). It can be seen that the current HCM procedure can deliver an error of up to 20 s in estimated delay.

Correspondingly, using the same model considerations, the percentiles of queue lengths can be estimated as well (*14*).

Recommendations for Procedures to Be Incorporated in a Future Version of HCM

The three new developments mentioned above can be easily incorporated into a future version of HCM. In the following, they are formulated in the style of HCM6 with corresponding numbers of calculation steps, exhibits, and equations.

Recommendations can be made for

- Step 9a: Rank 4 Capacity for One-Stage Movements
- Step 10b: Flared Minor-Street Lane Effects
- Step 10c: Shared Major-Street Lane Effects (an additional step to HCM6)
- Step 11b: Compute Control Delay to Rank 1 Movements (Major-through)

- Step 11c: Compute Control Delay to Major Left-turn Movements
- Step 11d: Compute Control Delay to Minor Movements at Flared Approach
- Step 13: Compute 95th Percentile Queue Lengths Including Shared Lanes and Flared Approaches

Because of a necessary additional calculation step (Step 10c) and a few new equations, the equations numbers in HCM6 cannot be used consequently. Thus, in the following recommendations, there are some supplementary numbers in the enumeration of equations to show the possible positions of the equations in a future HCM.

HCM6 pages 20-26 through 20-27

Step 9a: Rank 4 Capacity for One-Stage Movements. The probability that higher-ranked traffic movements will operate in a queue-free state is central to determining their overall impeding effects on the minor-street left-turn movement. However, not all these probabilities are independent of each other. Specifically, queuing in the major-street left-turning movement affects the probability of a queue-free state in the minor-street crossing movement. Applying the simple product of these two probabilities will likely overestimate the impeding effects on the minor-street left-turning traffic (see Wu, 1998).

The queue-free probability within statistically dependent queues in movements of ranks 2 and 3 is determined from Equation 20-52.

$$\text{Equation } 20-52\, p' = \frac{1}{\frac{1}{p_{0,j}} + \frac{1}{p_{0,k}} - 1}$$

where

p' = adjustment to the major-street left, minor-street through impedance factor,

$p_{0,j}$ = probability of a queue-free state for the conflicting major-street left-turning traffic, and

$p_{0,k}$ = probability of a queue-free state for the conflicting minor-street crossing traffic.

When determining p' for rank 4, movement 7, in Equation 20-52, $p_{0,j} = (p_{0,1})(p_{0,4})$ and $p_{0,k} = (p_{0,11})$. Likewise, when determining p' for rank 4, movement 10, $p_{0,j} = (p_{0,1})(p_{0,4})$ and $p_{0,k} = (p_{0,8})$.

Note:
The new solution is very simple and elegant, and has fewer computational steps. It is theoretically solid (Wu, 1998). It is already incorporated in HBS (2001, 2015).
Equation 20-52 in HCM 6th Edition overestimates the capacity.
Exhibit 20-16 in HCM 6th Edition is no longer necessary because Equation 20-52 is very simple.

HCM6 Pages 20-28 through 20-31

Step 10b: Flared Minor-Street Lane Effects. To estimate the capacity of a flared right-turn lane (such as in Exhibit 20-17), the average queue length for each movement sharing the right lane on the minor-street approach must first be computed. Figure 8.

Where several movements share the same lane, the capacity for this lane results from the capacity of the individual movements. If the shared lane flares out near the entrance to the major street more than one vehicle can stand near the stop-line side by side (as in Exhibit 20-17), which increases the capacity. To estimate the capacity of a flared right-turn lane, Equation 20-60 is used to compute the flared lane capacity (see Wu, 1999):

$$\text{Equation } 20-60\, c_F = \frac{v_R + v_{L+TH}}{\sqrt[(n_R+1)]{\left(\frac{v_R}{c_R}\right)^{(n_R+1)} + \left(\frac{v_{L+TH}}{c_{L+TH}}\right)^{(n_R+1)}}}$$

where

c_F = capacity of the flared lane (veh/h), subject to less than the saturation flow rate of the considered lane (default assumed to be 1,800 veh/h; however, this parameter can be measured in the field),

c_R = capacity of the right-turn movement (veh/h),

c_{L+TH} = capacity of the combined through and left-turn movements (veh/h),

v_R = right-turn volume (veh/h),

v_{L+TH} = combined through and left-turn volume (veh/h), and

n_R = storage places in the flared area (veh, see Exhibit 20-17).

For the special situation of shared lanes without any flaring effects ($n_R = 0$), Equation 20-60 yields Equation 20-59.

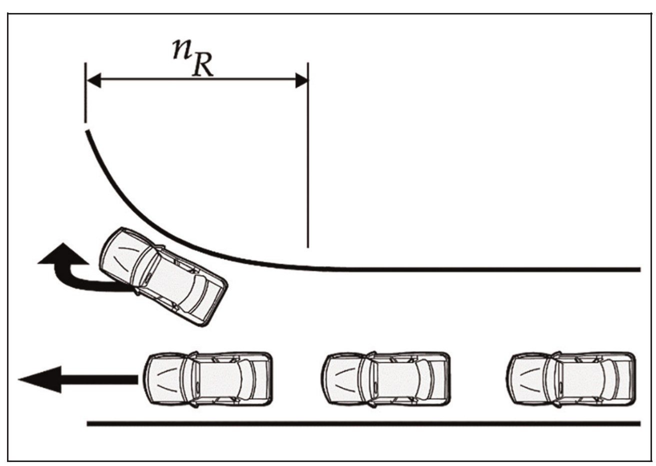

Exhibit 20-17. Capacity of a Flared Lane Approach.

Note:
The new solution is a simple, elegant, one-step solution. It is theoretically solid and all boundary conditions are held automatically (Wu, 1999). It is already incorporated in HBS (2001, 2015).
The current solution in HCM 6th Edition is only a pragmatic solution. It delivers deviations of up to 10% in capacity estimation. Furthermore, the boundary condition must be checked additionally.

HCM6 Page 20-29pp, Additional Step

Step 10c: Shared Major-Street Lane Effects. Where the left-turn lane on the major approach is too short to accommodate the queue of the left-turn movement, the major-through movement can be impeded by the left-turn queue. Equation 20-63(+ 1) is used to compute shared lane capacity (Wu and Brilon, 2010).

$$\text{Equation 20}-63(+1)\; c_{SS} = \frac{v_j + v_{i1} + v_{i2}}{x_j\left[\sqrt[(n_L+1)]{1+\frac{x_{i,1+2}^{(n_L+1)}}{1-x_{i,1+2}}}\right]}, \text{subject to } x_{i,1+2} < 1$$

with

$$\text{Equation 20}-63(+2)\; x_j = \frac{v_j}{c_{m,j}} \text{ and } x_{i,1+2} = \frac{v_{i1}}{s_{i1}} + \frac{v_{i2}}{s_{i2}}$$

where

c_{SS} = capacity of the shared short lane on the major street, subject to $< s_{i1}$,

$j = 1 + 1U$ and $4 + 4U$ (major-street left-turning vehicular movements),

$i1 = 2$ and 5 (major-street through vehicular movements),

$i2 = 3$ and 6 (major-street right-turning vehicular movements),

(When $j = 1 + 1U$, $i1 = 2$, and $i2 = 3$; when $j = 4 + 4U$, $i1 = 5$, and $i2 = 6$.)

x_j = degree of saturation for the major-street left-turn movements

$x_{i,1+2}$ = combined degree of saturation for the major-street through and right-turn movements,

$c_{m,j}$ = movement capacity of the left-turn movement (veh/h),

s_{i1} = saturation flow rate for the major-street through movements (default assumed to be 1,800 veh/h; however, this parameter can be measured in the field),

s_{i2} = saturation flow rate for the major-street right-turn movements (default assumed to be 1,500 veh/h; however, this parameter can be measured in the field),

v_j = major-street left-turn movement flow rate (veh/h),

v_{i1} = major-street through-movement flow rate (veh/h),

v_{i2} = major-street right-turn flow rate (veh/h) (0 if an exclusive right-turn lane is provided), and

n_L = number of vehicles that can be stored in the left-turn pocket (see Exhibit 20-15).

For the special situation of shared lanes ($n_L = 0$), Equation 20-63(+ 1) becomes Equation 20-63(+ 3) as follows.

$$\text{Equation 20}-63(+3)\; c_{SS} = \frac{v_j + v_{i1} + v_{i2}}{x_j\left[1+\frac{x_{i,1+2}}{1-x_{i,1+2}}\right]} = \frac{1-x_{i,1+2}}{x_j}\left(v_j + v_{i1} + v_{i2}\right), \text{subject to } x_{i,1+2} < 1$$

where all terms are as previously defined.

Note:
HCM 6th Edition does not offer a procedure for calculating the major approach capacity with shared lanes. This capacity is required for further delay calculation.
The new solution fills this gap (Wu and Brilon, 2010). It is already incorporated in HBS (2001, 2015).

HCM6 Page 20-30pp

Step 11b: Compute Control Delay to Rank 1 Movements (Major-Through). The effect of a shared lane on the major-street approach, where left-turning vehicles may block rank 1 through or right-turning vehicles, can be significant. If no exclusive left-turn pocket is provided on the major street, a delayed left-turning vehicle may block the rank 1 vehicles behind it. This will delay not only rank 1 vehicles but also lower-ranked movements. While the delayed rank 1 vehicles are discharging from the queue formed behind a left-turning vehicle, they impede lower-ranked conflicting movements.

Field observations have shown that such a blockage effect is usually very small, because the major street usually provides enough space for the blocked rank 1 vehicle to bypass the left-turning vehicle on the right. At a minimum, incorporating this effect requires estimating the proportion of rank 1 vehicles being blocked and computing the average delay to the major-street left-turning vehicles that are blocking through vehicles (Wu and Brilon, 2019a).

$$\text{Equation 20}-65\; d_{Rank\,1} = \left(\frac{v_{SS}}{c_{SS}}\right)^{n_L} \left\{\frac{3600}{c_{Rank\,1}} + 900T\left[\frac{v_{SS}}{c_{SS}} - 1 + \sqrt{\left(\frac{v_{SS}}{c_{SS}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{SS}}\right)\left(\frac{v_{SS}}{c_{SS}}\right)}{450T}C_0}\right] + 5\right\}$$

with

$$\text{Equation } 20-65(+1)\; C_0 = 1 + a_j \frac{c_{SS}}{c_j}\left(\frac{c_{SS}}{c_j}-1\right) + a_{i1}\frac{c_{SS}}{s_{i1}}\left(\frac{c_{SS}}{s_{i1}}-1\right) + a_{i2}\frac{c_{SS}}{s_{i2}}\left(\frac{c_{SS}}{s_{i2}}-1\right)$$

where

$$a_j = \frac{v_j}{v_j + v_{i1} + v_{i2}}\left(1 + \frac{x_{i,1+2}{}^{n_L+1}}{1-x_{i,1+2}}\right)^{-\frac{n_L}{n_L+1}},$$

$$\text{subject to } x_{i,1+2} < 1,$$

$$a_{i1} = \frac{v_{i1}}{v_j + v_{i1} + v_{i2}}\frac{x_j}{1-x_{i,1+2}}\left[x_{i,1+2}\left(1 + \frac{x_{i,1+2}{}^{n_L+1}}{1-x_{i,1+2}}\right)^{-\frac{1}{n_L+1}}\right]^{n_L}, \text{subject to } x_{i,1+2} < 1,$$

$$a_{i2} = \frac{v_{i2}}{v_j + v_{i1} + v_{i2}}\frac{x_j}{1-x_{i,1+2}}\left[x_{i,1+2}\left(1 + \frac{x_{i,1+2}{}^{n_L+1}}{1-x_{i,1+2}}\right)^{-\frac{1}{n_L+1}}\right]^{n_L}, \text{subject to } x_{i,1+2} < 1,$$

or as recommended simplifications

$$a_j \approx \frac{v_j}{v_j + v_{i1} + v_{i2}},$$

$$a_{i1} \approx \frac{v_{i1}}{v_j + v_{i1} + v_{i2}}\frac{x_j}{1-x_{i,1+2}}, \text{subject to } x_{i,1+2} < 1,$$

$$a_{i1} \approx \frac{v_{i2}}{v_j + v_{i1} + v_{i2}}\frac{x_j}{1-x_{i,1+2}}, \text{subject to } x_{i,1+2} < 1,$$

c_{SS} = capacity of the shared short lane on major streets from Equation 20-63(+1),

C_0 = parameter accounting for the stochastic characteristics of the queue system (−),

Rank 1 = *i*1 or *i*2

j = 1 + 1U and 4 + 4U (major-street left-turning vehicular movements),

*i*1 = 2 and 5 (major-street through vehicular movements),

*i*2 = 3 and 6 (major-street right-turning vehicular movements),

(when *j* = 1 + 1U, *i*1 = 2 and i2 = 3; when *j* = 4 + 4U, *i*1 = 5 and *i*2 = 6.)

s_{i1} = saturation flow rate for the major-street through movements (default assumed to be 1,800 veh/h; however, this parameter can be measured in the field),

s_{i2} = saturation flow rate for the major-street right-turn movements (default assumed to be 1,500 veh/h; however, this parameter can be measured in the field),

v_j = major-street left-turning movement flow rate (veh/h),

v_{i1} = major-street through-movement flow rate (veh/h),

v_{i2} = major-street right-turn flow rate (veh/h) (0 if an exclusive right-turn lane is provided),

n_L = number of vehicles that can be stored in the left-turn pocket (see Exhibit 20-15), and

x_j, $x_{i,1+2}$ = Equation 20-63(+2).

Note:
With the proposed procedure, delays of rank 1 movements upstream from the diverging point at a major shared short-lane can be estimated. Furthermore, using the parameter C_0, the service time of different movements can be accounted for properly (Wu and Brilon, 2019a).
The procedure in HCM 6th Edition does not consider both effects. The delay is generally underestimated.
With the recommended simplifications, the calculation of C_0 is of sufficient precision.

Step 11c: Compute Control Delay to Major Left-Turn Movements.

$$\text{Equation } 20-65(+2)\; d_j = \frac{3600}{c_j} + d_1 + d_2 + 5$$

where

d_1 = delay downstream of the diverging point

$$= \left(1-\frac{v_j}{c_j}\right)^{n_L} 900T\left[\frac{v_j}{c_j} - 1 + \sqrt{\left(\frac{v_j}{c_j}-1\right)^2 + \frac{\left(\frac{3600}{c_j}\right)\left(\frac{v_j}{c_j}\right)}{450T}}\right]$$

d_2 = delay upstream of the diverging point

$$= \left(\frac{v_{SS}}{c_{SS}}\right)^{n_L} 900T\left[\frac{v_{SS}}{c_{SS}} - 1 + \sqrt{\left(\frac{v_{SS}}{c_{SS}}-1\right)^2 + \frac{\left(\frac{3600}{c_{SS}}\right)\left(\frac{v_{SS}}{c_{SS}}\right)}{450T}C_0}\right]$$

All symbols are previously defined in Equation 20-65.

Note:
With the proposed procedure, delays of major left-turn movements, downstream und upstream from the diverging point at a shared short-lane can be estimated. Using the parameter C_0, the service time of different movements can be accounted for properly (see Wu and Brilon, 2019a).
The procedure in HCM 6th Edition does not consider both effects. The delay is generally underestimated.
With the recommended simplifications, the calculation of C_0 is of sufficient precision.

Step 11d: Compute Control Delay to Minor Movements at Flared Approach. To estimate the delay a flared right-turn lane Equation 20-65(+3) is used to compute the flared lane delay:

$$\text{Equation 20} - 65(+3)\; d_m = \frac{3600}{c_m} + d_I + d_{II} + 5$$

where

d_I = delay downstream of the diverging point

$$= \left(1 - \frac{v_{L+TH}}{c_{L+TH}}\right)^{n_F} 900T \left[\frac{v_{L+TH}}{c_{L+TH}} - 1 + \sqrt{\left(\frac{v_{L+TH}}{c_{L+TH}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{L+TH}}\right)\left(\frac{v_{L+TH}}{c_{L+TH}}\right)}{450T} C_{0,1}}\right],$$

d_{II} = delay upstream of the diverging point

$$= \left(\frac{v_F}{c_F}\right)^{n_F} 900T \left[\frac{v_F}{c_F} - 1 + \sqrt{\left(\frac{v_F}{c_F} - 1\right)^2 + \frac{\left(\frac{3600}{c_F}\right)\left(\frac{v_F}{c_F}\right)}{450T} C_0}\right],$$

$$C_{0,1} = 1 + \frac{v_L}{v_L + v_{TH}} \frac{c_{L+TH}}{c_L}\left(\frac{c_{L+TH}}{c_L} - 1\right) + \frac{v_{TH}}{v_L + v_{TH}} \frac{c_{L+TH}}{c_{TH}}\left(\frac{c_{L+TH}}{c_{TH}} - 1\right),$$

$$C_0 = 1 + a_L \frac{c_F}{c_L}\left(\frac{c_F}{c_L} - 1\right) + a_{TH} \frac{c_F}{c_{TH}}\left(\frac{c_F}{c_{TH}} - 1\right) + a_R \frac{c_F}{c_R}\left(\frac{c_F}{c_R} - 1\right),$$

$$a_L = \frac{v_L}{v_L + v_{TH} + v_R}\left(\frac{v_{L+TH}}{c_{L+TH}} \Big/ \frac{v_F}{c_F}\right)^{n_R},$$

$$a_{TH} = \frac{v_{TH}}{v_L + v_{TH} + v_R}\left(\frac{v_{L+TH}}{c_{L+TH}} \Big/ \frac{v_F}{c_F}\right)^{n_R},$$

$$a_R = \frac{v_R}{v_L + v_{TH} + v_R}\left(\frac{v_R}{c_R} \Big/ \frac{v_F}{c_F}\right)^{n_R},$$

or as recommended simplifications

$$a_L \approx \frac{v_L}{v_L + v_{TH} + v_R},$$

$$a_{TH} \approx \frac{v_{TH}}{v_L + v_{TH} + v_R},$$

$$a_R \approx \frac{v_R}{v_L + v_{TH} + v_R},$$

c_F = capacity of the flared approach on minor streets from Equation 20-60,

$C_{0,1}$, C_0 = parameters accounting for the stochastic characteristics of the queue system (−),

$m = L$, TH or R,

c_{L+TH} = capacity of the combined minor-street left-turn and through movements (veh/h)

$$= c_{L+TH} = \frac{3600(v_L + v_{TH})}{\frac{v_L}{c_L} + \frac{v_{TH}}{c_{TH}}},$$

c_R = capacity of the minor-street right-turn movements (veh/h),

v_L = minor-street left-turning movement flow rate (veh/h),

v_{TH} = minor-street through-movement flow rate (veh/h), and

v_R = minor-street right-turn flow rate (veh/h) (0 if an exclusive right-turn lane is provided), and

n_R = actual storage area for right-turning vehicles as defined in Exhibit 20-17.

Note:
With the proposed procedure, delays of minor movements, down- and upstream from the diverging point at a shared short-lane can be estimated separately. Furthermore, using the parameter C_0, the service time of different movements can be accounted for properly (Wu and Brilon, 2019a).
The procedure in HCM 6th Edition does not consider both effects. The delay is generally underestimated.

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Step 13: Compute 95th Percentile Queue Lengths Including Shared Lanes and Flared Approaches. Queue length is an important consideration at unsignalized intersections. Theoretical studies and empirical observations have demonstrated that the probability distribution of queue lengths for any minor movement at an unsignalized intersection is a function of the capacity of the movement and the volume of traffic being served during the analysis period. In addition, a parameter C_0 accounting for the stochastic characteristics of the queuing system has to be considered. Equation 20-68 can be used to estimate the 95th percentile queue length on a traffic lane for any minor movement at an unsignalized intersection including major shared short-lanes and minor flared approaches during the peak 15 min period on the basis of these three parameters (*10*, Wu and Brilon, 2019b).

$$\text{Equation 20} - 68\; Q_{95} = \left[\frac{v_{m,x}}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_{m,x}}{c_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{m,x}}\right)\left(\frac{v_{m,x}}{c_{m,x}}\right)}{150T} C_0}\right] \frac{c_{m,x} T}{4}$$

where

Q_{95} = 95th percentile queue from the stop-line on the considered traffic lane (either an exclusive lane, or a shared major approach/lane), or a flared minor approach/lane (veh),

v_x = flow rate for the considered traffic lane x (veh/h),

$c_{m,x}$ = capacity of the considered traffic lane x (veh/h),

C_0 = parameter accounting for the stochastic characteristics of the queuing system (for an exclusive lane $C_0 = 1$; use Equation 20-65(+1) for major approaches and 20-65(+5) for minor approaches), and

T = analysis time period (0.25 h for a 15 min period) (h).

Note:
The same procedure can be used for exclusive lanes and shared short-lanes with an additional parameter C_0 (Wu and Brilon, 2019b).
The 95th percentile queue is the 95th percentile queue from the stop-line (Wu and Brilon, 2019b).

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Conclusions

Three new developments in the theory of TWSC intersections account for: (a) the impedance factor for movements of rank 4, (b) the capacity of shared short-lanes, and (c) delays at SSLs. The first and the second issue are already incorporated in HBS 2015 but not in HCM6. According to simulation studies, the procedures in the current HCM6 are not up-to-date and they lead to significant misjudgments in capacity and delay estimations.

The current procedure in HCM6 for calculating the impedance factor of rank 4 movements is a simple regression approach. This procedure underestimates the queuing impedance in movements of higher ranks and thus overestimates the capacity. These overestimations can sometimes be as large as 20% of the expected capacity of a rank 4 movement. The procedure in HCM6 for estimating the capacity of SSLs is a very pragmatic one and it delivers up to 10% of differences in capacity compared with simulation studies. For estimation of SSL delay, the procedures in both HCM6 and HBS 2015 lead to inaccurate delay estimations and thus to an improper assessment of traffic quality. The current HCM procedure can lead to an error of up to 20 s in estimated delay.

To enhance the accuracy of the TWSC procedures, the three new developments are formulated as calculation procedures in the style of the HCM6 for inclusion in a future version of the HCM. The same procedure for estimation of SSL delay can also be incorporated into a future version of HBS.

Author Contributions

Conception and design of the research, analysis and interpretation of results, and manuscript preparation: Ning Wu and Werner Brilon. Both authors have approved the final version of the paper.

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