Capacity at Unsignalized Two-Stage Priority Intersections

by Werner Brilon and Ning Wu

Abstract

The subject of this paper is the capacity of minor-street traffic movements across major divided four-lane roadways (also other roads with two separate carriageways) at unsignalized intersections. The center of the intersection, corresponding to the width of the median, often provides room for drivers who have crossed the first half of the major road to stop before proceeding across the second major traffic stream. This situation, which is common with multilane major streets, is called two-stage priority. Here the capacity for minor-street through traffic is larger than at intersections without such a central storage space. The additional capacity being provided by these wider intersections cannot be evaluated by conventional capacity calculation models. An analytical theory is presented for the estimation of capacity under two-stage priority conditions. It is based on an approach by Harders although major improvements were necessary to match the results with realistic conditions. In addition to analytical theory, simulations were performed that enable an analysis under more realistic conditions. The result is a set of equations that compute the capacity for a minor-street through-traffic movement in the two-stage priority situation.

keywords:

capacity, unsignalized intersection, two-stage priority, median central storage.

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INTRODUCTION

At many unsignalized intersections, there is a room in the center of the major street where several minor-street vehicles can be stored between the two directions of traffic flow on the major street, especially in the case of multilane major-street traffic. This storage space within the intersection enables the minor-street driver to pass each of the major-street streams one at a time, which can contribute to an increased capacity.

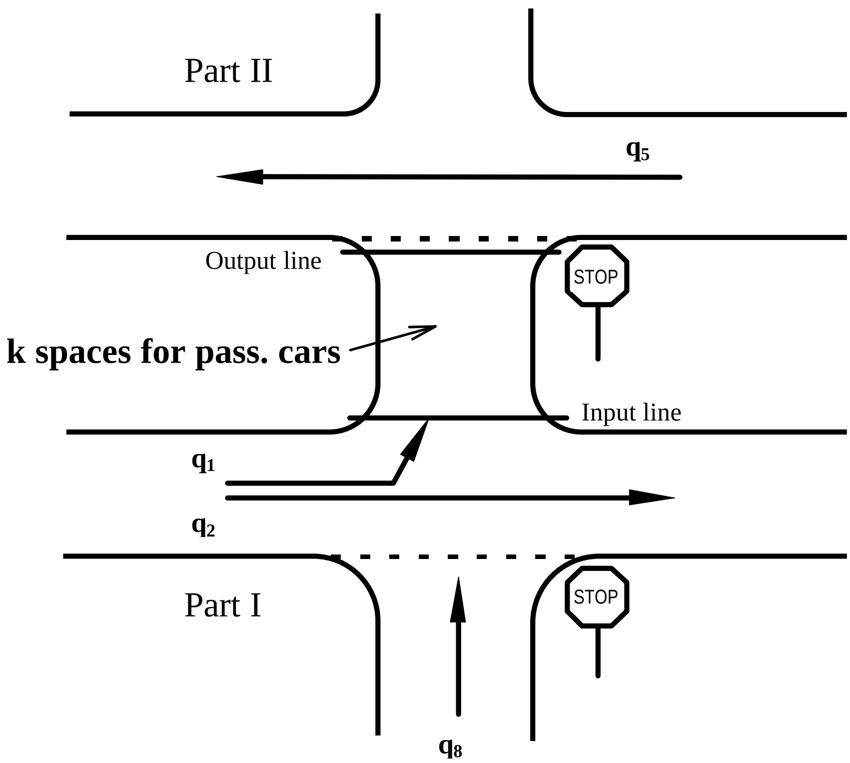

Figure 1: Minor-street through traffic (Movement 8) crossing the major street in 2 phases (the theory discussed here is also available if major street provides more or fewer than two lanes per direction).

A model is needed that can describe this behavior and its implication for intersection capacity. A model of this type has been developed by Harders (*1*). His concept has been used here as the basis; it is described in the following derivations. However, some major amplifications as well as a correction and an adjustment for reality were made to achieve better correspondence with realistic conditions.

For these derivations an intersection consisting of two parts is used (Figure 1). Between the intersection Parts I and II there is a storage space for k vehicles. This area has to be passed vehicles turning left from the major street (Movement 1) and by minor-street through traffic (Movement 8). Also, a minor-street left-turning vehicle (Movement 7, not shown) has to pass through this area. It will be seen that Movement 7 can be treated like Movement 8. Therefore, these derivations concentrate on the minor-street through traffic (Movement 8) crossing both parts of the major street. The enumeration of movements has been chosen in accordance with Chapter 10 of the 1994 *Highway Capacity Manual* (*2*). It is assumed that the usual rules for unsignalized intersections from the highway code are applied by drivers at the intersections. Thus Movements 2 and 5 (major-street through traffic) have priority over all other movements. Movement 1 vehicles have to obey the priority of Movement 5, whereas Movement 8 has to give the right-of-way to each of the movements shown in Figure 1 . In these derivations, Movement 5 stands for all major-street traffic streams in Part II of the intersection. These, depending on the layout of the intersection, could include through traffic (Movement 5), left turning traffic (Movement 4) and right turning traffic (Movement 6).

ANALYTICAL CAPACITY MODEL

To determine the capacity of the whole intersection, a constant queue on the minor-street approach (Movement 8) to Part I is assumed.

Let w_i be the probability for a queue of i vehicles in the central storage space. Then the probabilities w_i for all of the possible queue lengths i must sum up to 1 with $0 \le i \le k$, that is,

$$\sum_{i=0}^{k} w_i = 1 \tag{1}$$

where k is the number of spaces in the central storage area.

The central storage area of the intersection is considered as a closed storage system limited by the input line and output lines (Figure 1). The capacity properties of the storage system are restricted depending on the aspects of maximum input and maximum output. Now different states of the system may be distinguished.

State 1

Part I of the intersection determines the input to the storage area. Under state 1 in situations during which i vehicles in the storage area are less than the maximum possible queue length k, that is, $i < k$, a minor-street vehicle (Movement 8) can enter the storage space if the major-street streams (Movements 1 and 2) provide sufficient gaps. In this case the capacity of Part I (possible input from Movement 8) characterizes the capacity; that is,

$$c_1 = c_{\mathrm{I}} = c(q_1 + q_2) \tag{2}$$

where $c_{\mathrm{I}} = c(q_1 + q_2)$ is the capacity of Part I in case of no obstruction in Part II, which is the capacity of an isolated unsignalized cross intersection for through minor-street traffic with major-street traffic volume $q_1 + q_2$. The probability for this State 1 is $p_1 = 1 - w_k$. Thus, the contribution of State 1 to the capacity of Part I for Movement 8 is

$$c_{\mathrm{I},1} = (1 - w_k) \cdot c_{\mathrm{I}} \tag{3}$$

Of course, during State 1 vehicles from Movement 1 can also enter the storage space.

State 2

For State 2 the storage area is assumed to be occupied; that is, k vehicles are queuing in the storage space. In this case, normally no minor-street vehicle (Movement 8) or vehicles from Movement 1 can enter the storage area. If, however, a sufficient gap for the passage of one minor-street vehicle can be accommodated in both Parts I and II of the intersection simultaneously, a vehicle can also enter the storage area. The capacity for q_8 (possible input from Movement 8) during this stage is

$$c_2 = c_{I+II} = c(q_1 + q_2 + q_5) \tag{4}$$

where $c_{I+II} = c(q_1+q_2+q_5)$ is the capacity of the whole intersection (Part I+II) as an isolated cross intersection for through traffic with major-street traffic volume $q_1 + q_2 + q_5$. Thus, the contribution of State 2 to the capacity of Part I is

$$c_{I,2} = w_k \cdot c_{I+II} \tag{5}$$

where w_k is the probability that k vehicles are in the storage space.

States 1 and 2 exclude each other. The capacity of Part I is the total maximum input to the storage area. Here the volume q_1 of Movement 1 has to be included to the partial capacities mentioned above. Therefore, the total maximum input to the storage area is

$$\begin{aligned} Input &= c_{I,1} + c_{I,2} + q_1 \\ &= (1-w_k) \cdot c_I + w_k \cdot c_{I+II} + q_1 \end{aligned} \tag{6}$$

State 3

The output of the storage area is now considered, concentrating on Part II of the intersection. For $i > 0$ each possibility for a departure from the storage area provided by the major-street stream of volume q_5 can be utilized. The capacity (maximum output of the storage area) of Part II in this case is

$$c_3 = c_{II} = c(q_5) \tag{7}$$

where $c_{II} = c(q_5)$ is the capacity of Part II in case of no obstruction by the upstream Part I, which is the capacity of an isolated unsignalized cross intersection for through minor-street traffic with major traffic volume q_5 .

The probability for this state is $p_3 = 1 - w_0$. Thus the contribution of State 3 to the capacity of Part II is

$$c_{II,3} = (1 - w_0) \cdot c_{II} \tag{8}$$

where w_0 is the probability that no vehicles are in the storage space.

No vehicles from Movement 1 (volume q_1) can directly (i.e., without being impeded by Movement 5) pass through the storage area in this state.

State 4

For $i = 0$ (i.e., an empty storage area) no vehicle can leave the storage area even if the major-street stream of volume q_5 allows a departure. If, however, a sufficient gap is provided in the major-street streams of both parts of the intersection simultaneously, a minor-street vehicle (Movement 8) can pass the whole intersection without being queued somewhere in the storage area. The possible output of the storage area from Movement 8 vehicles during this state is

$$c_4 = c_{I+II} = c(q_1 + q_2 + q_5) \tag{9}$$

Thus, the contribution of State 4 to the capacity of Part II is

$$c_{II,4} = w_0 \cdot c_{I+II} \tag{10}$$

Vehicles from Movement 1 can also pass through the storage area during this state. The number of vehicles from Movement 1 that pass through the storage area during this state is

$$c_{II,4,q1} = w_0 \cdot q_1 \tag{11}$$

Here, $c_{II,4,q1}$ does not mean the capacity for q_1, but the demand on the capacity. The traffic intensity of q_1 should be less than the capacity of the Part II c_{II}; that is, q_1 is subject to the restriction $q_1 < c_{II}$. Otherwise, the intersection is overloaded and due to this nonstationarity no solution can be derived.

States 3 and 4 exclude each other. Therefore, the total maximum output of the storage area is

$$\begin{aligned} output &= c_{\mathrm{II},3} + c_{\mathrm{II},4} + c_{\mathrm{II},4,q1} \\ &= (1-w_0) \cdot c_{\mathrm{II}} + w_0 \cdot c_{\mathrm{I+II}} + w_0 \cdot q_1 \\ &= (1-w_0) \cdot c_{\mathrm{II}} + w_0 \cdot (c_{\mathrm{I+II}} + q_1) \end{aligned} \tag{12}$$

One might argue that the derivations of $c_{\mathrm{I},2}$ and $c_{\mathrm{II},4}$ neglect the travel time of the vehicles from Part I to Part II . This, however, is justified. The probability that a minor-street vehicle will meet a sufficient gap in Part I and II at time t_{I} and time t_{II} (with $t_{\mathrm{II}} = t_{\mathrm{I}} + \Delta t$ and with Δt = travel time between the stop lines of Part I and II) is independent of the travel time Δt if Δt = constant for all vehicles and if the two arrival processes in the major-street streams are independent of each other. Therefore, the result is the same if Δt has a realistic positive value or if Δt is assumed to be 0.

During times when the whole intersection is operating at capacity because of continuity, the maximum input and output of the storage area must be equal. Therefore input = output (cf. Equations 6 and 12); that is,

$$(1-w_k) \cdot c_{\mathrm{II}} + w_k \cdot c_{\mathrm{I+II}} + q_1 = (1-w_0) \cdot c_{\mathrm{II}} + w_0 \cdot [c_{\mathrm{I+II}} + q_1] \tag{13}$$

The total capacity c_T for minor-street through traffic (Movement 8) regarding the whole intersection is identical to both sides of this equation minus q_1 . In addition, since negative traffic volumes are not possible c_T must fulfill the restriction

$$c_T = \max\begin{cases} output - q_1 = c_{\mathrm{II},3} + c_{\mathrm{II},4} + c_{\mathrm{II},4,q1} - q_1 \\ 0 \end{cases} \tag{14}$$

For the easiest case of $k = 1$,

$$w_0 + w_1 = 1 \tag{15}$$

Together with Equation 13 and the subsequent explanation,

$$c_T = \frac{c_{\text{I}} \cdot \left(c_{\text{II}} - q_1\right) - c_{\text{I+II}}{}^2}{c_{\text{I}} + c_{\text{II}} - q_1 - 2 \cdot c_{\text{I+II}}} \qquad \text{for } k = 1 \tag{16}$$

For $k > 1$ some more general derivations are necessary for which the following simplifying conditions are assumed:

- Let q_1, q_2 and q_5 be constant over time. Then $c_{\text{I}} = c(q_1 + q_2)$, $c_{\text{II}} = c(q_5)$, and $c_{\text{I+II}} = c(q_1 + q_2 + q_5)$ are also constant over time.
- Divide the continuous time scale into intervals of duration t_f = follow-up time = average time interval between the departure of two subsequent minor-street vehicles that enter into the same gap of the major-street flow. It is also assumed that the minimum gap between two vehicles of Movement 1 is of the same size as t_f .

- Let a be the probability that a vehicle can enter the central storage area from intersection Part I during a time interval of duration t_f .
- Let b be the probability that a vehicle can pass intersection Part II during a time interval of duration t_f .

The a and b variables are introduced only for the following derivations. They need not to be evaluated later for the application of the theory. Both a and b are used for the fictitious case in which Parts I and II are independent intersections. The follow-up time t_f for Part I and II should be of similar duration for this derivation. Treating the process of the number of vehicles in the storage space as a stochastical process with Markow properties yields

$$w_0(t) = w_0(1-a) + w_0 \cdot a \cdot b + w_1 \cdot b \cdot (1-a) \tag{17}$$

= probability that no vehicle is queuing in the storage area at time t

This is valid because the case of an empty queue at time t can be achieved by the following possibilities:

- No queue at time t - t_f (prob. = w_0) and no arrival (prob. = 1 - a) during t_f; or

- No queue at time t - t_f (prob. = w_0) and one arrival (prob. = a) and one departure (prob. = b) during t_f; or
- One vehicle queued at time t - t_f (prob. = w_1) and no arrival (prob. = 1 - a) and one departure (prob. = b) during t_f .

By similar considerations, the expression for the probability of i vehicles queuing in the storage space at time t is

$$\begin{aligned} w_i(t) \;=\;& w_{i-1} \cdot a \cdot (1 - b) \\ &+ w_i \cdot a \cdot b \\ &+ w_i \cdot (1 - a) \cdot (1 - b) \\ &+ w_{i+1} \cdot (1 - a) \cdot b \end{aligned} \tag{18}$$

Since k is the maximum number of vehicles in the storage space,

$$\begin{aligned} w_k(t) =\;& w_k \cdot (1 - b) \\ &+ w_k \cdot a \cdot b \\ &+ w_{k-1} \cdot a \cdot (1 - b) \end{aligned} \tag{19}$$

Because of the assumed stationarity of the process, w_0, w_i, and w_k do not depend on each other at time t .

Equations 17 through 19 form a system of $k + 1$ equations that can be written as

$$-w_0 \cdot (a - ab) + w_1(b - ab) = 0 \tag{20}$$

$$w_{i-1}(a - ab) - w_i\left[(a - ab) + (b - ab)\right] + w_{i+1}(b - ab) = 0 \tag{21}$$

$$w_{k-1}(a - ab) - w_k(b - ab) = 0 \tag{22}$$

For abbreviation

$$A = a - a \cdot b \tag{23}$$

$$B = b - a \cdot b \tag{24}$$

The system of Equations 20, 21, and 22 is then

$$
\begin{array}{llllllll}
(0) & -A\cdot w_0 & +B\cdot w_1 & & & & = 0 & \\
(1) & A\cdot w_0 & -(A+B)\cdot w_1 & +B\cdot w_2 & & & = 0 & \\
(2) & & A\cdot w_1 & -(A+B)\cdot w_2 & +B\cdot w_3 & & = 0 & \\
\ldots & & & & & & & \\
(i) & & & A\cdot w_{i-1} & -(A+B)\cdot w_i & +B\cdot w_{i+1} & = 0 & (25) \\
\ldots & & & & & & & \\
(k-2) & & A\cdot w_{k-3} & -(A+B)\cdot w_{k-2} & +B\cdot w_{k-1} & & = 0 & \\
(k-1) & & & A\cdot w_{k-2} & -(A+B)\cdot w_{k-1} & +B\cdot w_k & = 0 & \\
(k) & & & & A\cdot w_{k-1} & -B\cdot w_k & = 0 &
\end{array}
$$

From the first Equation,

$$A \cdot w_0 = B \cdot w_1$$

$$w_1 = \frac{A}{B} \cdot w_0 \tag{26}$$

From the last equation,

$$A \cdot w_{k-1} = B \cdot w_k$$

$$w_k = \frac{A}{B} \cdot w_{k-1} \tag{27}$$

Summing all equations (0) through (i),

$$-A \cdot w_i + B \cdot w_{i+1} = 0$$

$$w_{i+1} = \frac{A}{B} \cdot w_i \tag{28}$$

The sequence of the probabilities, therefore, is forming a geometric series in which each subsequent term is resulting from the prior term by a multiplication with the factor $y = A/B$.

$$y = \frac{A}{B} = \frac{a - ab}{b - ab} \tag{29}$$

That is,

$$w_{i+1} = y \cdot w_i \tag{30}$$

or

$$w_i = y^i \cdot w_0 \tag{31}$$

According to Equation 1, w_i (i = 0,...,k) are subject to the restriction

$$\sum_{i=0}^{k} w_i = 1$$

$$\sum_{i=0}^{k} y^i \cdot w_0 = 1$$

$$w_0 \sum_{i=0}^{k} y^i = 1$$

Therefore,

$$w_0 = \frac{1}{1 + y^1 + y^2 + \ldots + y^k} \tag{32}$$

The denominator is the sum of a finite geometric series,

$$\sum_{i=0}^{k} y^i = \frac{y^{k+1} - 1}{y - 1} \tag{33}$$

Thus, and with Equations 30 and 29,

$$w_0 = \frac{y - 1}{y^{k+1} - 1} \tag{34}$$

$$w_k = \frac{y^{k+1} - y^k}{y^{k+1} - 1} \tag{35}$$

Let us now recall Equations 13 and 14 and combine those with Equations 34 and 35:

$$\left(1-\frac{y^{k+1}-y^{k}}{y^{k+1}-1}\right)\cdot\, c_{\mathrm{I}}\, + \frac{y^{k+1}-y^{k}}{y^{k+1}-1}\cdot\, c_{\mathrm{I+II}}\, + q_{1}$$
$$=\left(1-\frac{y-1}{y^{k+1}-1}\right)\cdot c_{\mathrm{II}}\;\; + \frac{y-1}{y^{k+1}-1}\cdot\left(c_{\mathrm{I+II}}\; + q_{1}\right) \qquad (36)$$

Note that in this equation the capacities c_{I}, c_{II} and $c_{\mathrm{I+II}}$ as well as k are treated to be known, whereas the variable y has to be obtained from the equation. As a result,

$$y=\frac{c_{\mathrm{I}}-c_{\mathrm{I+II}}}{c_{\mathrm{II}}-q_{1}-c_{\mathrm{I+II}}} \qquad (37)$$

Using this result for y, the total capacity c_T for the minor-street Movement 8 is calculated using Equation 14 yields

$$c_{T}=\left(1-\frac{y-1}{y^{k+1}-1}\right)\cdot c_{\mathrm{II}}+\frac{y-1}{y^{k+1}-1}\cdot\left(c_{\mathrm{I+II}}+q_{1}\right)-q_{1} \qquad (38a)$$

or

$$c_{T}=\left(1-\frac{y-1}{y^{k+1}-1}\right)\cdot\left(c_{\mathrm{II}}-q_{1}\right)+\frac{y-1}{y^{k+1}-1}\cdot c_{\mathrm{I+II}}$$
$$=\frac{1}{y^{k+1}-1}\left[y\cdot\left(y^{k}-1\right)\cdot\left(c_{\mathrm{II}}-q_{1}\right)+\left(y-1\right)\cdot c_{\mathrm{I+II}}\right] \qquad (38b)$$

It should be noted that for the special case of $k = 1$, the algebraic solution of Equation 16 might give some confirmation for the above derivations.

For $y = 1$ (i.e., $c_{\mathrm{I}} = c_{\mathrm{II}} - q_1$) this expression is not defined. By developing the limiting case for $y \rightarrow 1$,

$$c_{T}=\frac{1}{k+1}\cdot\left[k\cdot\left(c_{\mathrm{II}}-q_{1}\right)+c_{\mathrm{I+II}}\right] \qquad (39)$$

At this point it should be noted that the capacities $c_{\mathrm{I+II}} = c(q_1 + q_2 + q_5)$ and $c_{\mathrm{II}} = c(q_5)$ can be calculated by any useful procedure, for example, by formulas from gap acceptance theory. But solutions from the linear regression method or Kyte's method, described otherwise (*3*), could also be used.

CAPACITY ACCORDING TO GAP ACCEPTANCE THEORY

The simplest formula for the capacity of an unsignalized intersection with one minor-street and one major-street traffic stream is Siegloch's (*4*) formula. Several authors (*3*) have shown that this formula produces also realistic results if the basic assumptions for the formula are not fulfilled. Siegloch's formula is as follows:

$$c(q) = \frac{1}{t_f} \cdot e^{-q \cdot t_0} \tag{40}$$

where

$c(q)$ =capacity for minor-street movement (veh/s),

t_f =follow-up time (s),

=average gap between two successive minor-flow vehicle entering into the same major-stream gap,

t_0 $= t_c$ - t_f / 2 (s),

t_c =critical gap (s),

=average gap between two successive major-flow vehicle that, as a minimum, is accepted by the minor-stream vehicles to cross the intersection.

The different cases of t_c - and t_f - values that must be distinguished are:

- t_c - and t_f - values for Part I of the intersection (State 1 and 2),
- t_c- and t_f - values for Part II of the intersection (State 3 and 4), and
- t_c - and t_f - values for crossing Part I and II of the intersection simultaneously in the case of $k = 0$. It is realistic to assume that a driver who has to cross the whole major street at one time without having a central storage area needs longer t_c - and t_f - values than in the first and second cases.

It is justified to assume that the t_c - and t_f - values in the firs and second cases are of the same magnitude and that especially the t_f - values between both cases are nearly identical. This assumption is important for the following derivations.

Realistic values for the t_c - and t_f - values can be obtained from Table 1. The given critical gaps t_c and follow-up times t_f are of realistic magnitude compared with the measurement results worked out by the NCHRP-project 3-46 (*5*, *6*). Here the critical gap and the follow-up time for the case without central reserve (k = 0) are larger then for the two-stage priority case, which seems to be more realistic.

	$k = 0$ i.e. no central reserve	$k \geq 1$ i.e. a central reserve of variable (with k) width	
	case c)	part I case a)	part II case b)
t_c	7.0 s	6.0 s	6.0 s
t_f	3.8 s	3.8 s	3.8 s

Table 1: Typical t_c - and t_f - Values for Two-Stage Priority Situations Within Multilane Major Streets under US-Conditions

Based on Equation 40 with the assumption that all of the t_f - values are nearly identical,

$$\frac{c_{\mathrm{I+II}}}{c_0} = \frac{c_{\mathrm{I}}}{c_0} \cdot \frac{c_{\mathrm{II}}}{c_0} \tag{41}$$

where $c_0 = 1/t_f$ is the maximal capacity for the case of no cross traffic in the major-street streams in vehicle per second.

This relation makes it possible to standardize all of the capacity terms by c_0 . If c_0 is used in units of vehicle per second, the other capacity terms must use this unit. Of course, the unit vehicle per hour could be used for all of the capacity terms. Then it is useful to standardize c_T in Equations 38 and 39:

$$\hat{c}_T = \frac{c_T}{c_0} \qquad \text{(veh/s)} \qquad (42)$$

Then $\hat{c}_T$ (which has to be obtained from Equations 38 and 39) can be expressed as a function of $c_I / c_0 = c(q_1 + q_2) / c_0$ and $(c_{II} - q_1) / c_0 = (c(q_5) - q_1) / c_0$. Thus it is possible to indicate the results of these derivations using graphs (Figure 2).

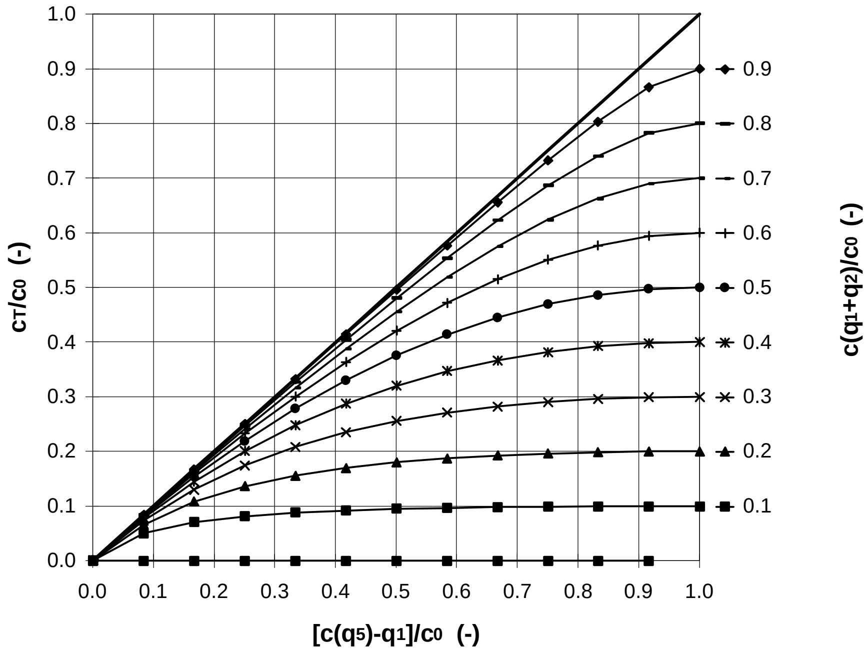

Figure 2: Total capacity $\hat{c}_T = c_T / c_0$ as a result of Equation 42 (in combination with Equation 38) in dependence of $c_I / c_0 = c(q_1 + q_2) / c_0$ and $(c_{II} - q_1) / c_0 = [c(q_5) - q_1] / c_0$ for $k = 1$.

Use of graphs of this type with sufficient approximation is also justified in circumstances that differ from the conditions of gap acceptance theory, for example,

- If capacities c_I and c_{II} are calculated from theories other than gap acceptance or even if they should be measured, or
- If within gap acceptance theory the critical gaps t_c are different for each part of the intersection.

The only necessary condition for the application of these graphs is that the follow-up times t_f be of nearly identical magnitude.

SIMULATION STUDIES

To test the theory leading to Equation 38, the solution has been further investigated using simulations. For this purpose a simulation model was especially developed (*7*). The basic structure of the model is closely related to the ideas of KNOSIMO (*8*). The important features can be characterized as follows:

- The headways in the major-street streams are distributed according to a hyperlang distribution (*8*, *9*).
- The critical gaps and the follow-up times are distributed according to an Erlang distribution with the parameters given by Grossmann (*8*) which are also used in KNOSIMO.

Both these assumptions together relate the model closer to reality than the theoretical derivations mentioned earlier. On the other hand, the following assumptions are a simplification compared with reality.

- No delays due to limited acceleration or deceleration of the vehicles are taken into account.
- The travel time Δt between the two parts of the intersection are not considered, that is, Δt = 0. (see discussion following Equation 12).
- Each minor-street driver has a minimum delay of t_f at the first part of the intersection if no major-street stream vehicle is nearby. This simulates the time which a driver needs to realize the traffic situation on the major-street when he first approaches the intersection. This time margin is also necessary for the driver to decide if he can enter the intersection. Such an orientation time is not applied for vehicles entering the second part of the intersection, where a better visibility is assumed.
- All traffic volumes are kept constant over time.

- The program is organized so that a constant queue in front of the first stop line of Movement 8 is always maintained. Thus, the maximum number of vehicles that can enter the intersection can be evaluated.

This number is the representation of the capacity for Movement 8 . A comprehensive set of simulation runs has been performed for different parameters q_1 , q_2 , and q_5 .

Different attempts were made to find an easy-to-use approximate description of the results, several of these attempts are given elsewhere (*5, 7*) together with a statistical assessment of their precision. A good compromise between easy application and highest precision seemed to be the following solution. Instead of c_T a more realistic solution c_{Tr} is used, which is obtained as a good approximation to the simulation results.

$$c_{Tr} = a \cdot c_T \qquad \text{(veh/s)} \tag{43}$$

where

c_{Tr} = realistic total capacity for Movement 8 (minor-street through traffic),

c_T = result from the theoretical approach obtained from Equation 38 or from Figure 2, and

a = adjustment factor

$$= \begin{cases} 1 & \text{for } k = 0 \\ 1 - 0.32 \cdot \exp(-1.3 \cdot \sqrt{k}) & \text{for } k > 0 \end{cases} \tag{44}$$

These solutions for the total capacity c_{Tr} of Movement 8 approximate the simulated results with a standard deviation s (between results for c_T being simulated and those estimated from Equation 42) according to Table 2. Other solutions with smaller deviations but more complicated formulas for the calculation of realistic c_{Tr} can be obtained from work by Brilon et al.(*5*).

	s		
	q_1 = 50	q_1 = 100	q_1 = 200
a = 1	29	30	32
eq. 44	18	18	19
	veh/h	veh/h	veh/h

Table 2: Standard Deviation s for Computed c_T - Values Compared with Simulated Results

To conclude the steps necessary to estimate the realistic capacity of an unsignalized intersection where the minor-street movements have to cross the major street in two stages (cf. Equations 43, 38b, 39, and 44):

$$c_{Tr} = a \cdot c_T$$

with

$$c_T = \begin{cases} \dfrac{1}{y^{k+1}-1}\left[y \cdot \left(y^k - 1\right) \cdot (c_{\mathrm{II}} - q_1) + (y-1) \cdot c_{\mathrm{I+II}}\right] & \mathit{for}\ y \neq 1 \\ \dfrac{1}{k+1}\left[k \cdot (c_{\mathrm{II}} - q_1) + c_{\mathrm{I+II}}\right] & \mathit{for}\ y = 1 \end{cases}$$

$$\alpha = \begin{cases} 1 & \mathit{for}\ k = 0 \\ 1 - 0.32 \cdot \exp(-1.3 \cdot \sqrt{k}) & \mathit{for}\ k > 0 \end{cases}$$

$$y = \frac{c_{\mathrm{I}} - c_{\mathrm{I+II}}}{c_{\mathrm{II}} - q_1 - c_{\mathrm{I+II}}}$$

where

c_{I} = $c(q_1 + q_2)$

= capacity in Part I ,

c_{II} = $c(q_5)$

= capacity in Part II ,

$c_{\mathrm{I+II}}$ = $c(q_1+q_2+q_5)$

= capacity in a cross intersection for minor-street through traffic with a major-street traffic volume of $q_1+q_2+q_5$ (all capacity terms apply for Movement 8; they are to be calculated by any useful capacity formula, e.g., the Siegloch-formula, Equation 40) ,

q_1 = volume of priority street left turning traffic in Part I ,

q_2 = volume of major-street through traffic coming from the left in Part I , and

q_5 = volume of sum of all major-street flows coming from the right in Part II. [Of course, here the volumes of all priority movements in Part II have to be included. major-street right (6, except if this movement is guided along a triangular island separated from the through traffic), major-street through (5), major-street left (4); numbers of movements according to HCM 1994 (*2*), Chapter 10] .

These equations are only valid for $c_{\mathrm{II}} - q_1 > 0$.

c_{Tr} is the modified total capacity of the intersection for minor-street through traffic. To simplify the calculation procedure, graphs for calculating the capacity c_{Tr} were produced by Brilon et al. (*5*). These graphs enable easy applications of the theory in practice.

CONCLUSION

The two-stage priority situation as it exists at many unsignalized intersections within multilane major streets provides larger capacities compared to intersections without central storage areas. Capacity estimation procedures for this situation have not been available up to now. In this paper, an analytical solution for this problem is provided. In addition, simulation studies lead to a correction of the theoretical results. These procedures are already incorporated in the proposed *Highway Capacity Manual* due 1998.

Nevertheless, an empirical confirmation of this model approaches would be desirable. Also the question of the validity of the model for larger *k*-values should be discussed. It is questionable whether the theory also applies for a grid of one-way street networks. Also if these questions are addressed in the future, the theory presented here is recommended for use at unsignalized intersection in practice.

Delay estimations for the two-stage priority situation can be performed using the concept of reserve capacities (*10*) or the general delay formula by Kimber and Hollis (*11*).

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