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Impedance Effects for Streams of Higher Ranks at Unsignalized Intersections

by Ning Wu

Abstract

In current procedures in the Highway Capacity Manual (HCM) for calculating capacities at unsignalized intersections, the impedance effect for estimating the capacity of high-ranked streams is considered. Normally, the simple product of queue-free probabilities in single major streams is used for obtaining the total queue-free probability in all major streams. For minor streams of higher (>3) ranks, the queue-free probabilities in major streams are not independent of each other. The simple product of the single probabilities underestimates the total queue-free probability, and thus overestimates the total impeding effect. To overcome this problem, HCM uses an adjustment function based on empirical work in Germany. Unfortunately, for some marginal condition, the adjustment function delivers unrealistic results. In general, the procedure in HCM overestimate the total queue-free probability and therefore also the capacity of minor streams of rank 4.

A new approach for estimating the queue-free probability in higher-ranked streams is introduced. The approach is derived from probability theory and is verified by simulations. This approach is much more accurate than the current HCM procedure and it can be extended to streams of arbitrarily high ranks.

Key-words:

Unsignalized intersections, Capacity, Queue-free probability, Higher-ranked stream

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1 INTRODUCTION

In current procedures for calculating capacities at unsignalised intersections (HCM 1994; Kyte et al. 1995; HCM 1997), the impedance effect is considered for estimating the capacity of high-ranked streams. For example, the impedance in streams of rank 2 must be estimated for calculating the capacity of streams of rank 3. In general, the probability of queue-free state in higher-ranked major streams is used for taking the impedance effect into account. Normally, the product of queue-free probabilities in single higher-ranked major streams is used to obtain the total queue-free probability in all higher-ranked major streams for the case that the individual higher-ranked major streams are independent of each other.

For minor streams of high (>3) ranks, the queue-free probabilities in higher-ranked major streams are not independent of each other. The simple product of the single probabilities underestimates the total queue-free probability and therefore overestimates the total impeding effect. To overcome this problem, an adjustment function based on empirical work conducted in Germany (Grossmann 1991; Harders 1968; cf. eq.(10-6) and fig.10-6 in HCM 1994) is used for streams of rank 4. For streams of higher ranks than 4, there is no solution until now. The accuracy of the adjustment function in HCM (1994; 1997) is sufficient for the most cases in the practice. For some marginal conditions, unfortunately, the adjustment function delivers unrealistic results. In general, eq. (10-6) in 1994 HCM overestimate the total queue-free probability.

In this paper, a new approach for estimating the queue-free probability for higher-ranked streams is presented. It is derived from probability theory and is verified by simulations. Under the assumption that the queuing systems for all streams at unsignalised intersections are queuing systems with equal randomness (e.g., all systems are M/M/1-queueing systems), a very simple formula for the total queue-free probability in higher-ranked streams is obtained. Because of the theoretical background, this approach can be extended to streams of arbitrarily high ranks. Therefore, one can use this approach to deal with more complex stream combinations, for example, intersections with priority pedestrian streams.

The present approach has already been incorporated into the forthcoming new version of the German Highway Capacity Manual (D-HCM 1994; D-HCM 1997).

2 IMPEDANCE FACTOR AT TWO-WAY-STOP-CONTROLLED INTERSECTIONS

2.1 Minor Stream with One Higher-ranked Major Stream

In general, the impedance effect can be considered by determining the probability of the state of queuing in the higher-ranked major streams. Normally, at unsignalized intersections, the probability of the state of queuing in a single higher-ranked major stream *i* is set equal to the degree of saturation, that is,

$$p_{imp,i} = x_i \tag{1}$$

Accordingly, the probability $p_{0,i}$ of the queue-free state is equal to

$$p_{0,i} = 1 - p_{imp,i} = 1 - x_i \tag{2}$$

Thus, the probability of the queue-free state in a stream *i* of rank 2 is

$$\left(p_{0,i}\right)_{rank=2} = 1 - \left(p_{imp,i}\right)_{rank=2} = 1 - \left(x_i\right)_{rank=2} \tag{3}$$

which is the impedance factor for the minor stream of rank 3, so that the impedance factor for the stream of rank 3 is,

$$f_{rank=3} = \left(p_{0,i}\right)_{rank=2} \tag{4}$$

This is the impedance factor with which the basic capacity C_{basic} of the stream of rank 3 should be multiplied for obtaining the real capacity. In the derivation, it is assumed that in streams of rank 1 no queue should occur.

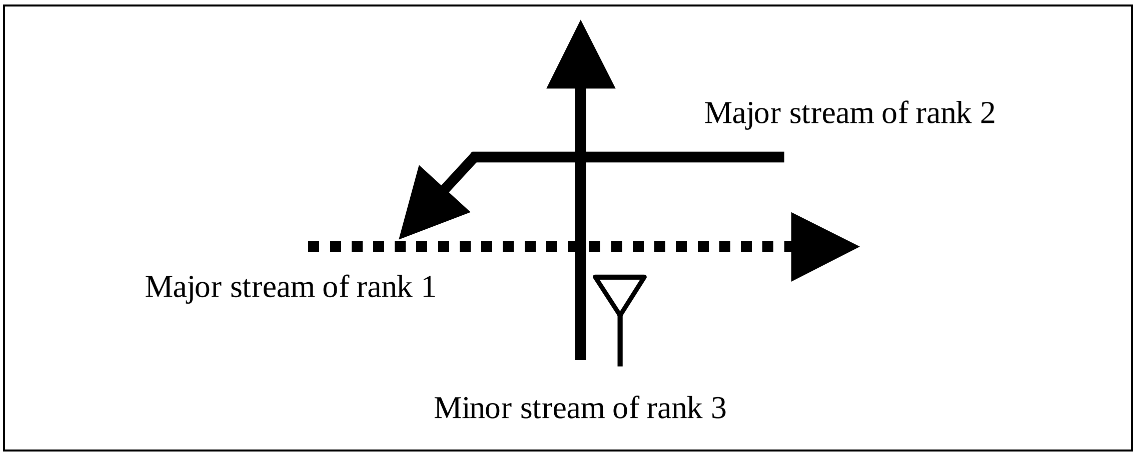


Figure 1 - Basic conciliation of impedance for minor stream of rank 3

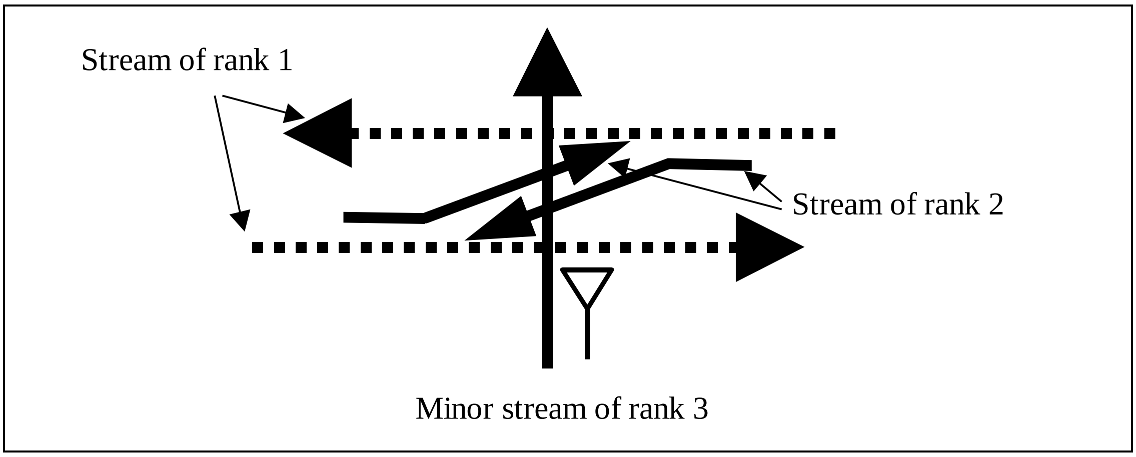


Figure 2 - Impedance for minor stream of rank 3 with two major streams of rank 2

2.2 Minor Stream with More than One Major Stream of Same Rank in a Parallel Group

If there are two higher-ranked major streams of rank 2 (see Figure 2), the probabilities of the queue-free state in the single higher-ranked streams should be logically combined for determining the total queue-free state in both streams of rank 2. Since the queue-free states in streams of the same rank (here rank 2) are independent of each other, one can use the arithmetic product for calculating the logical product of the probabilities. Thus, the probability of queue-free state in both streams of rank 2 yields

$$(p_0)_{rank=2} = \prod_{i=1}^{2} (p_{0,i})_{rank=2} = (p_{0,1})_{rank=2} \cdot (p_{0,2})_{rank=2} \tag{5}$$

The impedance factor for the minor stream of rank 3 becomes

$$f_{rank=3} = (p_0)_{rank=2} = (p_{0,1})_{rank=2} \cdot (p_{0,2})_{rank=2} \tag{6}$$

Generally, the probability that in n higher-ranked streams of the same rank r no impedance occurs is

$$(p_0)_{rank=r} = \prod_{i=1}^{n} (p_{0,i})_{rank=r} \tag{7}$$

The impedance factor for the minor stream of rank r+1 yields

$$f_{rank=r+1} = (p_0)_{rank=r} = \prod_{i=1}^{n} (p_{0,i})_{rank=r} \tag{8}$$

2.3 Minor Stream with More than One Higher-ranked Major Streams of Different Ranks in a Serial Sequence

The queue-free states in higher-ranked streams of different ranks are not independent of each other. For example, the queue-free state in stream of rank 3 is normally a function of the queue-free state in stream 2 (see Figure 3). Thus, it is not possible to use the simple product of probabilities that represent the queue-free states in streams of different ranks for determining the total probability of queue-free state in all streams. That is, for stream of rank 4 the factor

$$f_{rank=4} = (p_0)_{rank=2} \cdot (p_0)_{rank=3} \tag{9}$$

does not represent the impedance effect correctly.

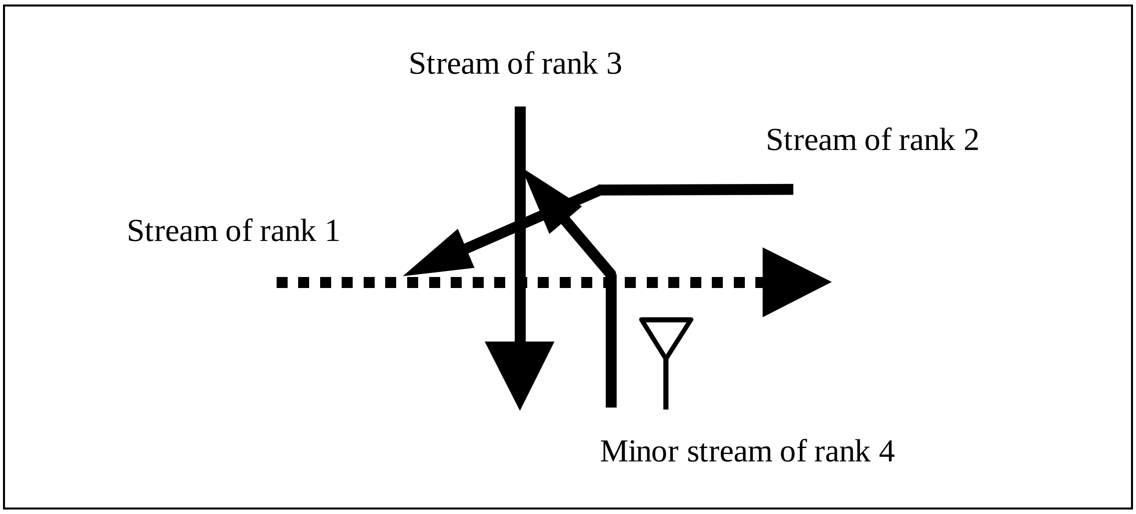


Figure 3 - Impedance for minor stream of rank 4 with two major streams of rank 2 and 3

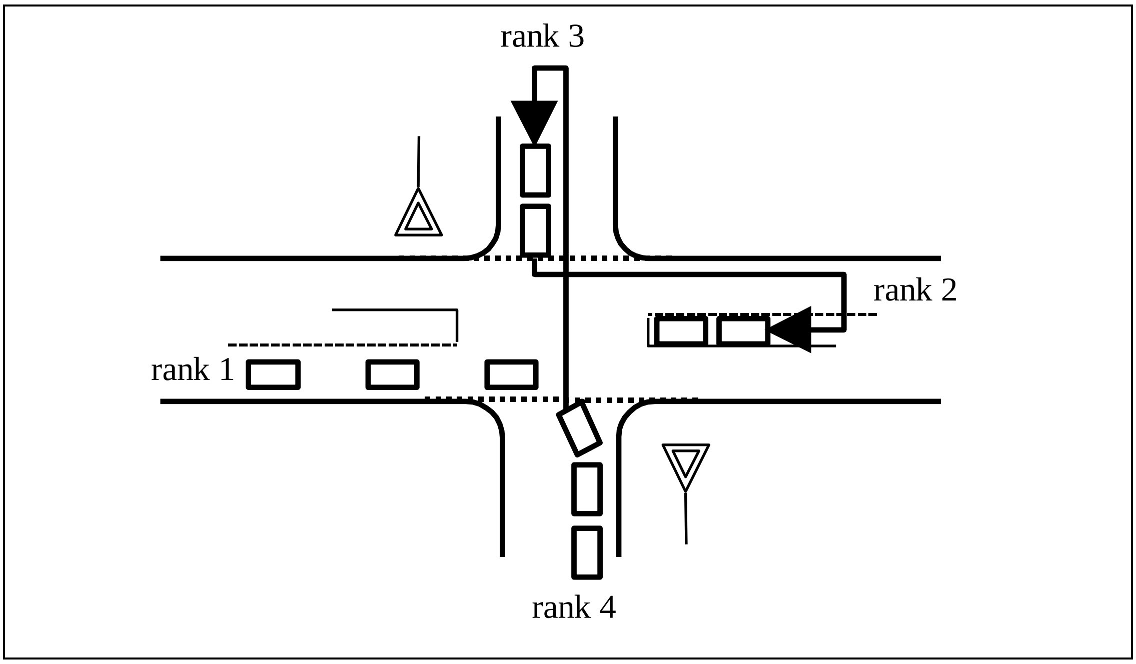


Figure 4: Queues in steams of different ranks and their sequence of operation

To handle this problem, a new model is introduced here. In this model the queues in higher-ranked streams (higher ranked than the subject stream, here rank 2 and 3) are considered as **one** big queue (Figure 4). That means, one imagines that the conflict area can be passed by vehicles in steams of different ranks, one after the other. The order of the departures of the vehicles is not important for the derivation. Queuing vehicles thus form one common queue with rank 2 in front and followed by rank 3. Furthermore, the queues in the streams of different ranks and the big queue are considered as M/G/1-

queueing systems with sufficient approximation. Thus, one obtains for the stream of rank r the average queue length $N_{rank=r}$

$$N_{rank=r} = \frac{C_{rank=r} \cdot x_{rank=r}}{1 - x_{rank=r}} = \frac{C_{rank=r} \cdot \left(1 - (p_0)_{rank=r}\right)}{(p_0)_{rank=r}} \tag{10}$$

where $C_{rank=r}$ is the factor of randomness of the queuing system (e.g., $C = 1$: completely random $\rightarrow$ M/M/1 system; $C = 0.5$: partly random $\rightarrow$ M/D/1 system, see also Kimber and Hollis 1979). Accordingly, one obtains for the big queue with k-1 streams of different ranks the average total queue length N_T

$$N_T = \frac{C_T \cdot \left(1 - (p_0)_T\right)}{(p_0)_T} = \sum_{i=2}^{k-1} N_{rank=i} = \sum_{i=2}^{k-1} \frac{C_{rank=i} \cdot \left(1 - (p_0)_{rank=i}\right)}{(p_0)_{rank=i}} \tag{11}$$

Solving this equation for $(p_0)_T$ yields the probability that in all streams of rank < k no queue occurs,

$$(p_0)_T = \frac{1}{1 + \frac{1}{C_T} \sum_{i=2}^{k-1} \frac{C_{rank=i} \cdot \left(1 - (p_0)_{rank=i}\right)}{(p_0)_{rank=i}}} \tag{12}$$

Assuming that all queuing systems have the same constant factor of randomness (e.g., all systems as M/M/1-systems), i.e., setting all $C_{rank=i} = C_T =$ const., yields

$$(p_0)_T = \frac{1}{1 + \sum_{i=2}^{k-1} \frac{1 - (p_0)_{rank=i}}{(p_0)_{rank=i}}} \tag{13}$$

For example, the probability that both in streams of rank 2 and in streams of rank 3 no queue occurs is

$$(p_0)_{rank=2and3} = \frac{1}{1 + \frac{1 - (p_0)_{rank=2}}{(p_0)_{rank=2}} + \frac{1 - (p_0)_{rank=3}}{(p_0)_{rank=3}}} \tag{14}$$

Thus, the impedance factor for the stream of rank 4 is

$$f^*_{rank=4} = (p_0)_{rank=2and3} = \frac{1}{1 + \frac{1 - (p_0)_{rank=2}}{(p_0)_{rank=2}} + \frac{1 - (p_0)_{rank=3}}{(p_0)_{rank=3}}} \tag{15}$$

2.4 Minor Stream with Higher-ranked Major Stream Groups of Different Ranks

To generalize the theory, a system with l higher-ranked stream groups, which consists of n_2 streams of rank 2, n_3 streams of rank 3, ..., and n_l streams of rank l is considered. The probability that in a stream group of rank r no impedance occurs is (see eq.(7))

$$(p_0)_{rank=r} = \prod_{i=1}^{n_r} (p_{0,i})_{rank=r} \tag{16}$$

The probability that in all l stream groups no impedance occurs becomes (see eq.(13))

$$(p_0)_{rank=2\ to\ l} = \frac{1}{1+\sum_{i=2}^{l} \frac{1-(p_0)_{rank=i}}{(p_0)_{rank=i}}} = \frac{1}{1+\sum_{i=2}^{l} \frac{1-\prod_{j=1}^{n_i}(p_{0,j})_{rank=i}}{\prod_{j=1}^{n_i}(p_{0,j})_{rank=i}}} \tag{17}$$

Analogously, for a system with one group of m sequences, which consist of l_1, l_2, ..., and l_n, streams of rank (2, 3, ..., and l_1), (2, 3, ..., and l_2), ..., (2, 3, ..., and l_m), the probability that in a stream sequence with l streams of different ranks is (see eq.(13))

$$(p_0)_{rank=2\ to\ l} = \frac{1}{1+\sum_{i=2}^{l} \frac{1-(p_0)_{rank=i}}{(p_0)_{rank=i}}} \tag{18}$$

The probability that in all n sequences no impedance occurs becomes (see (see eq.(7))

$$(p_0)_{all\,sequences} = \prod_{k=1}^{m} (p_0)_{rank=2\ to\ l_k} = \prod_{k=1}^{m} \frac{1}{1+\sum_{i=2}^{l_k} \frac{1-(p_0)_{rank=i}}{(p_0)_{rank=i}}} \tag{19}$$

In general, for a system with arbitrary stream configuration, the formula for estimating the probability of queue-free state in higher-ranked streams can be represented as

$$(p_0)_{total} = \prod_{k=1}^{m} \frac{1}{1+\sum_{i=2}^{l_k} \frac{1-\prod_{j=1}^{n_i}(p_{0,j})_{rank=i}}{\prod_{j=1}^{n_i}(p_{0,j})_{rank=i}}} \quad .... \tag{20}$$

Theoretically, Equation (20) can have arbitrary many levels of groups and sequences of stream combinations.

3 PROBABILITY OF QUEUE-FREE STATE FOR STREAMS OF RANK 4 IN THE CURRENT HCM

In the existing calculation guidelines the capacity for streams of high ranks (higher than 2) is calculated by using a impedance factor to the basic capacity. This impedance factor f_k is formed from the probabilities p_0 that no vehicle is queuing in streams of higher-ranked priority. For the usual calculation procedures the p_0 in all streams with higher-ranked priority is multiplied together. Therefore, the impedance factor for stream of rank k, $f_{rank=k}$ can be expressed as

$$f_{rank=k} = \prod_{i=2}^{k-1} \left(\prod_{j}^{n_i} (p_{0,j})_{rank=i} \right) = \prod_{i=2}^{k-1} (p_0)_{rank=i} \tag{21}$$

where $(p_{0,j})_i$ is the probability that stream j of rank i is in a queue-free state. Equation (21) can only be carelessly used for streams of low ranks. For streams of rank 4, Equation (21) overestimates the impeding effects, because the probabilities of queue-free state in streams of rank 2 and 3 are not independent of each other. This was found by (Grossmann 1991). To overcome this stochastical dependence between queues in streams of rank 2 and 3, a correction function based on simulations has been proposed. This correction function (used in the 1994 HCM chapter 10 as eq.10-6 or fig.10-6) is given as

$$f_{rank=4}{}^{*} = 0.65 f_{rank=4} - \frac{f_{rank=4}}{f_{rank=4} + 3} + 0.6\sqrt{f_{rank=4}} \tag{22}$$

with

$$f_{rank=4} = (p_0)_{rank=2} \cdot (p_0)_{rank=3} \tag{23}$$

Equation (22) does not fulfill the necessary boundary conditions

$$f_{rank=4}{}^{*}|_{(p_0)_{rank=3}=1} = (p_0)_{rank=2} \quad \text{and} \quad f_{rank=4}{}^{*}|_{(p_0)_{rank=2}=1} = (p_0)_{rank=3} \tag{24}$$

and it overestimates the probability of the queue-free state. Furthermore, in some extreme cases, Equation (22) gives values that are not plausible to the real-world conditions. For example, using two single queue-free probabilities $(p_0)_{rank=2}=0.7$ and $(p_0)_{rank=3}=0.3$, a total queue-free probability $(p_0)_T=(p_0)_{rank=2 \text{ and } 3}=0.346$ would be obtained. That is not plausible, because the total queue-free probability may not be greater than the single queue-free probabilities.

According to the present theory, the probability that both in streams of rank 2 and in streams of rank 3 no queue occurs is equal to (see eqs.(13) and (15))

$$f^{*}_{rank=4} = (p_0)_{rank=2 and 3} = \frac{1}{1 + \frac{1-(p_0)_{rank=2}}{(p_0)_{rank=2}} + \frac{1-(p_0)_{rank=3}}{(p_0)_{rank=3}}} \tag{25}$$

This corresponds, in the same terminology of HCM (1994), to

$$p' = \frac{1}{1 + \frac{1 - p_{0,j}}{p_{0,j}} + \frac{1 - p_{0,k}}{p_{0,k}}} \qquad (26)$$

where p' = adjustment to major street left, minor street through impedance factor;

$p_{0,j}$ = probability of queue-free state for conflicting major street left-turning traffic (product of the p_0 for both directions, rank 2);

$p_{0,k}$ = probability of queue-free state for conflicting minor street through traffic from the opposite direction (rank 3).

Equation (26) instead of eq.10-6 in the 1994 HCM is used in the forthcoming German Highway Capacity Manual (D-HCM 1997).

4 TEST OF THE THEORY THROUGH SIMULATIONS

For testing the derived theory, simulation studies was undertaken. For this purpose a simulation model was especially developed. The basic structure of the model is closely related to the ideas of KNOSIMO (Grossmann 1991). The important features can be characterized as follows:

- The headways in the major-street streams are distributed according to a hyperlang distribution.
- The critical gaps and the follow-up times are distributed according to an Erlang distribution with the parameters given by Grossmann (1991) that are also used in KNOSIMO.

Both these assumptions together relate the model closer to real world condition than the theoretical derivations mentioned earlier.

Altogether, 1348 combinations of different traffic volumes in stream 1 (rank 1), stream 2 (rank 2), and stream 3 (rank 3) were simulated. From the simulation, the probabilities of queue-free state in stream 2 $(p_0)_{rank=2}$, and in stream 3 $(p_0)_{rank=3}$, and the total probability in both streams 2 and 3 $(p_0)_T=(p_0)_{rank=2 \text{ and } 3}$ can be obtained. With the simulated total probability $(p_0)_T$, different procedures for estimating the total probability of queue-free state were tested.

- **Total queue-free probability as simple product of the single queue-free probabilities**

First, the simple product of single queue-free probabilities as a approximation of the total queue-free probability is tested. That is, it is assumed

$$f^*_{rank=4} = f_{rank=4} = (p_0)_T = (p_0)_{rank=2and3} = (p_0)_{rank=2} \cdot (p_0)_{rank=2} \qquad (27)$$

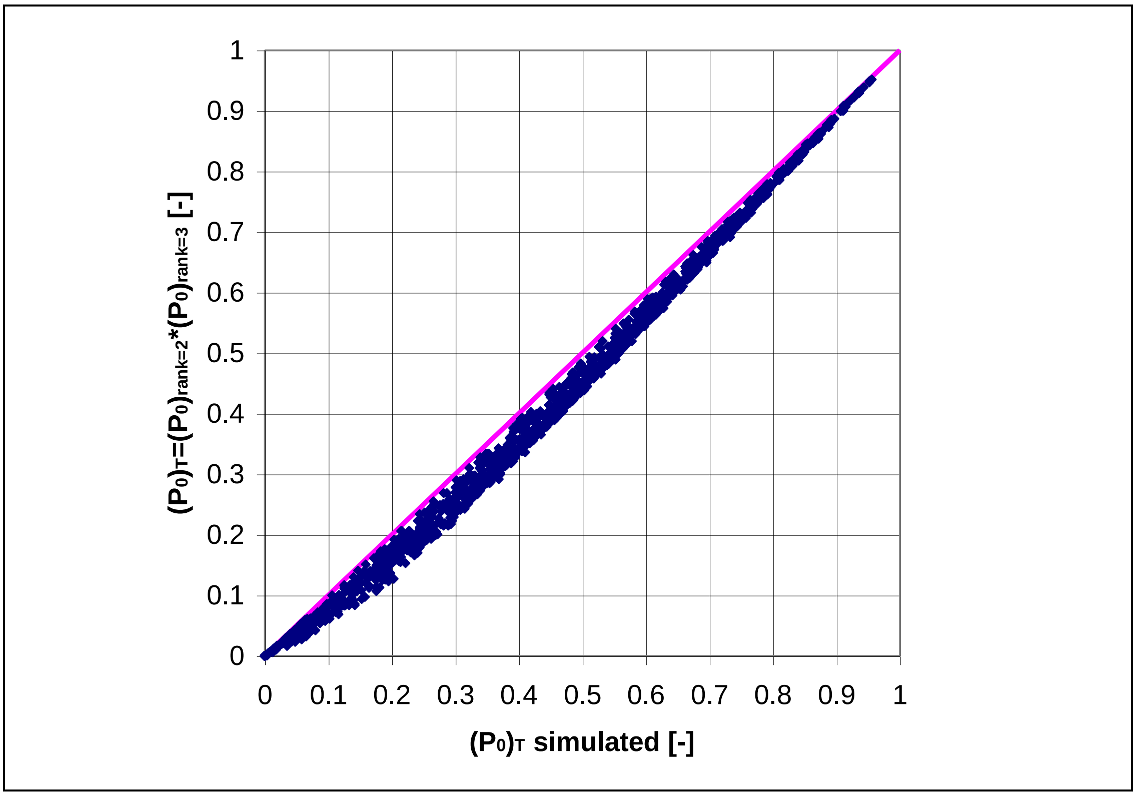


Figure 5 - Comparison between simulations and $(p_0)_T=(p_0)_{rank=2} \cdot (p_0)_{rank=3}$

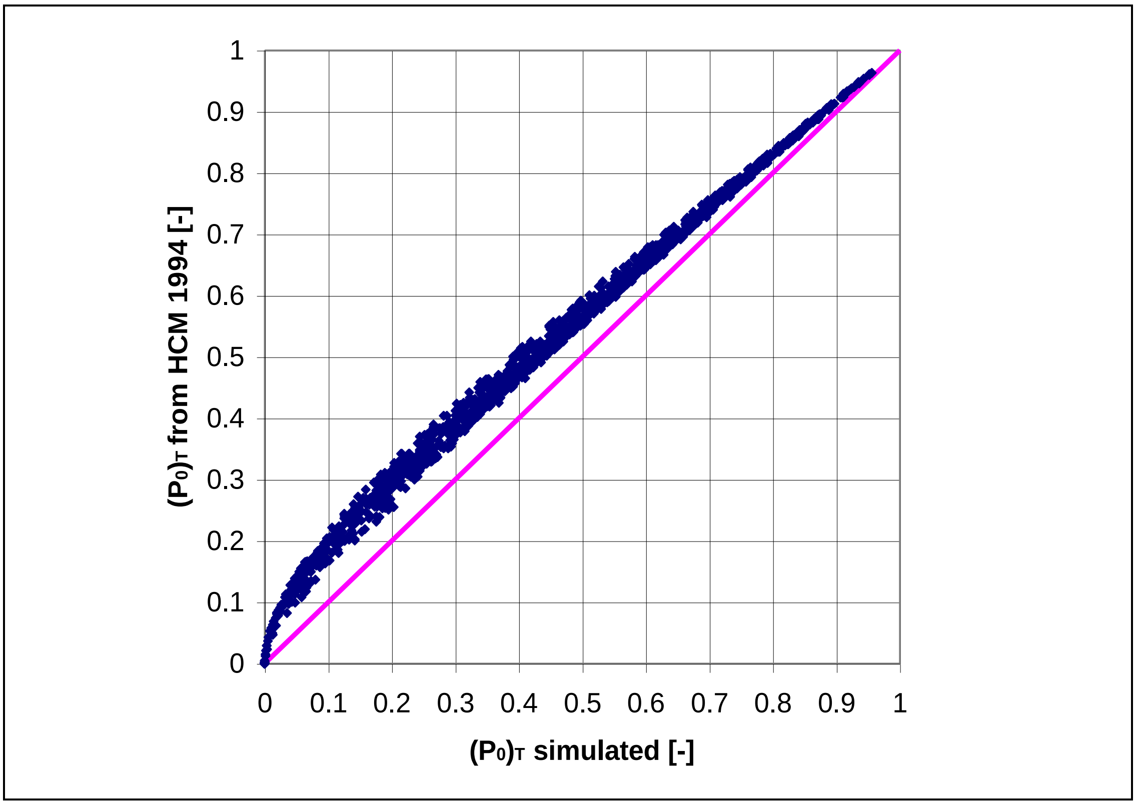


Figure 6 - Comparison between simulations and HCM

In Figure 5, the simulated total queue-free probabilities and the total queue-free probabilities calculated from Equation (27) are compared with each other. It shows systematically lower values from the calculation versus the simulation. That means, Equation (27) underestimates the total queue-free probability or, in other words, it overestimates the total impedance effect.

- **Total queue-free probability from HCM (1994, 1997)**

To overcome the disadvantage of underestimating the queue-free probability by Equation (27), a correction function is introduced in HCM (1994, 1997). This correction function is expressed by Equation (22).

Figure 6 shows the comparison between the simulated total queue-free probabilities and the total queue-free probabilities calculated from Equation (22). It shows now systematically higher values by the calculation versus the simulation. That is, the Equation (22) overcorrects the total queue-free probability or it underestimates the total impedance effect.

- **Total queue-free probability according to the new theory**

Figure 7 shows the comparison between the simulated total queue-free probabilities and the total queue-free probabilities calculated from the derived theory (Equation (25)). It shows now much smaller differences between the calculation and simulation. Figure 8 shows these differences on a larger scale. The new theory delivers a much better estimate than the correction function in HCM (1994, 1997) for calculating the total queue-free probability in higher-ranked streams. This is expected due to the more accurate derivation of the new theory. However, there are still systematically small deviations between the simulated results and the theoretical results (see Figure 8), because the assumption that all queuing systems in streams at unsignalized intersections have the same constant randomness (e.g., as M/M/1-systems) does not agree with the real-world queuing systems at unsignalized intersections. For practical applications, the accuracy of the new theory can be considered as sufficient.

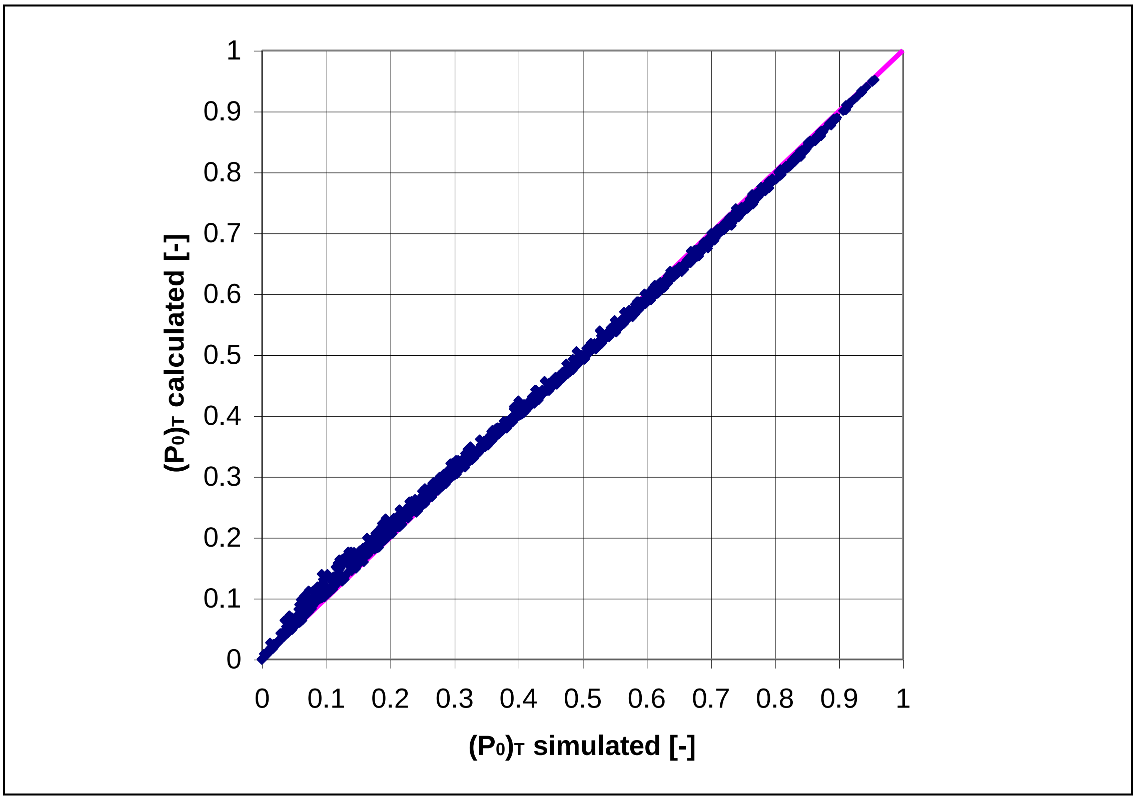


Figure 7 - Comparison between simulations and the new theory

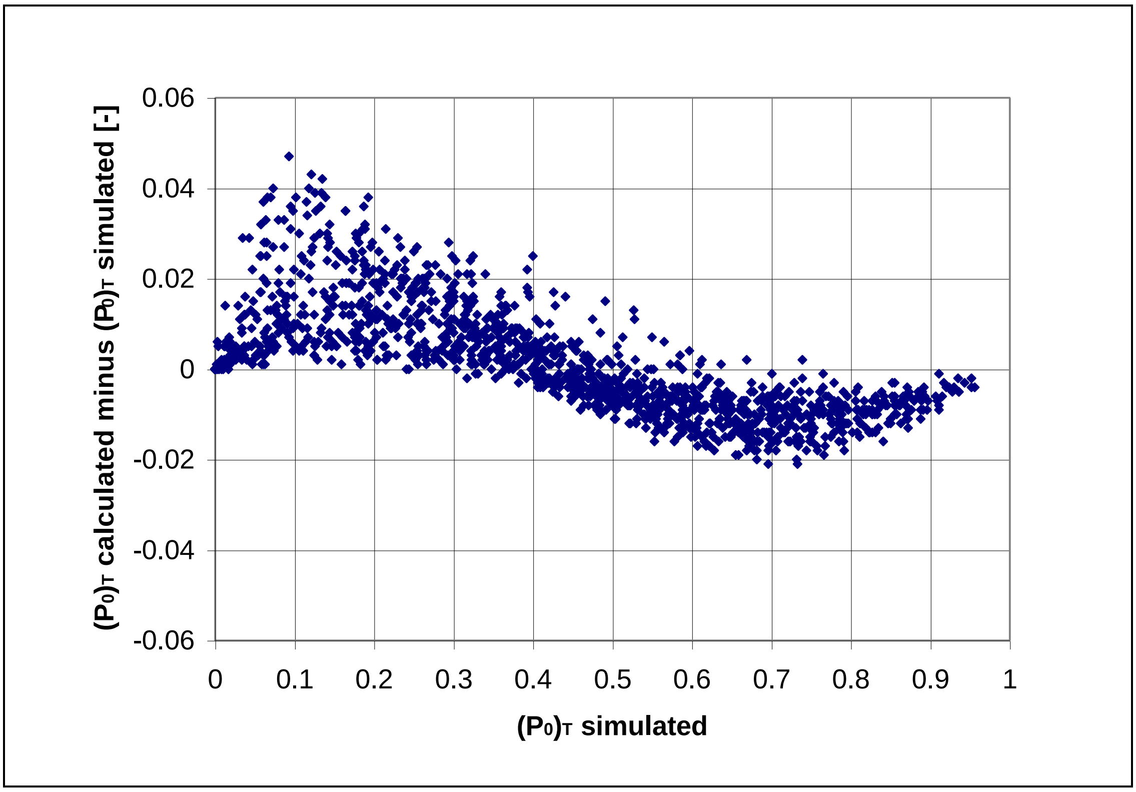


Figure 8 - Comparison between simulations and the new theory on large scale

In Table 1, the statistical key values for the results of all the comparisons are assembled. It shows again that the new theory describes the results of simulation much better than the correction function in the HCM (1994, 1997).

Statistical key values	procedures		
	simple product	HCM (1994, 1997)	new theory
Multiple correlation coefficient [-]	0.9973	0.9969	0.9994
Certainty [-]	0.9946	0.9937	0.9988
Adjusted certainty [-]	0.9946	0.9937	0.9988
Standard errors [-]	0.0180	0.0179	0.0080
maximal absolute deviation [-]	0.0770	0.1270	0.0470
Observations [-]	1348		

Table 1 - Statistical key values for different calculation procedures

5 APPLICATIONS OF THE THEORY

In order to show the applications of the new theory, an ideal unsignalized intersection with 12 streams is considered. For simplicity, it is assumed that every stream has its own exclusive traffic lane (Figure 9). The enumeration of the streams is show in the figure and is used in the following equations.

For the ideal unsignalized intersection (Figure 9), the ranks of the streams and their higher-ranked streams is assembled in Table 2.

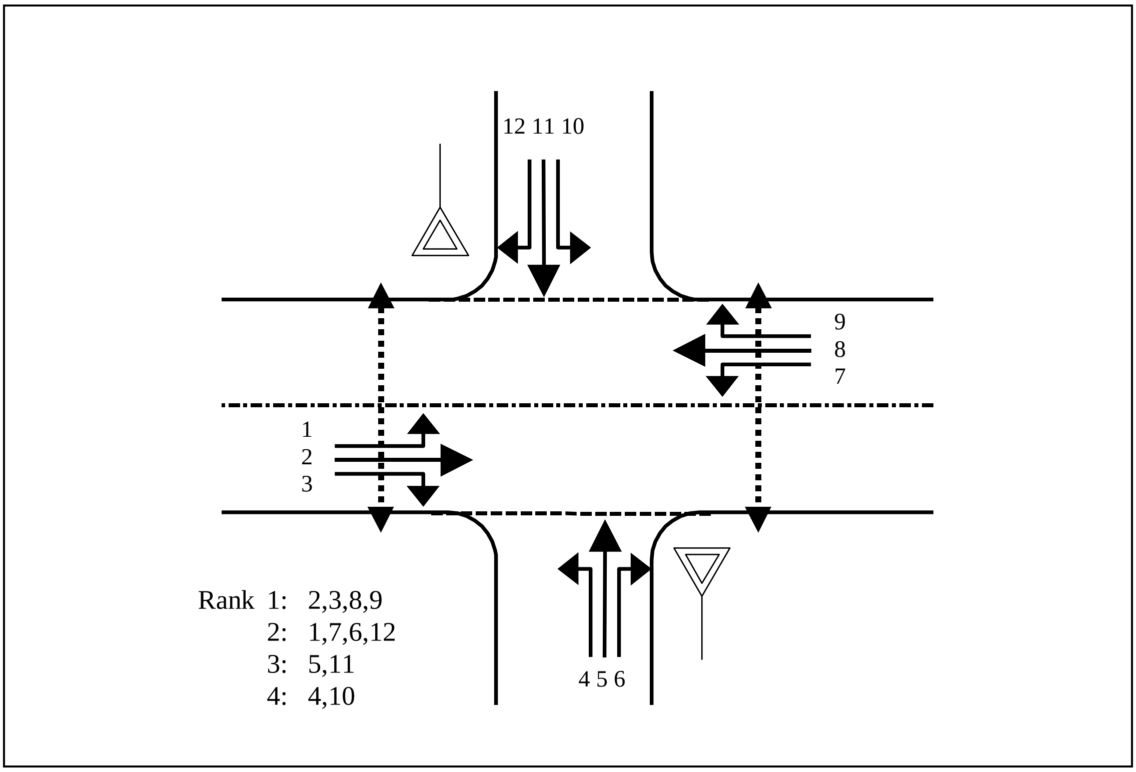


Figure 9 - Streams at unsignalized intersections

No. of the Subject stream s	Rank of the subject stream r	No. of streams of rank r-1	No. of streams of rank r-2	No. of streams of rank r-3	Note.
1	2	8,9			left from left
2	1				through from left
3	1				right from left
4	4	11	1,7,12	2,8	subject left
5	3	1,7	2,8,9		subject through
6	2	2			subject right
7	2	2,3			left from right
8	1				through from right
9	1				right from right
10	4	5	1,7,6	2,8	opposing left
11	3	1,7	2,3,8		opposing through
12	2	8			opposing right

Table 2 - Hierarchy of streams at a ideal unsignalized intersection

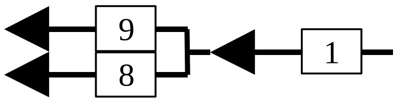
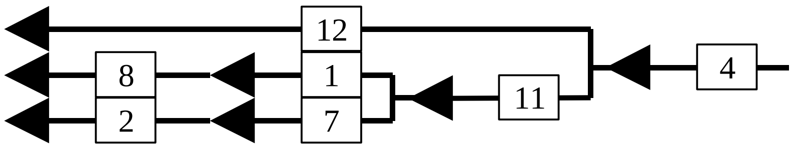
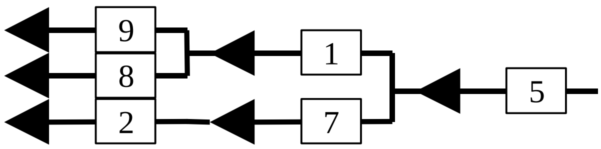
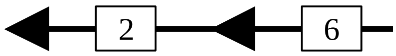
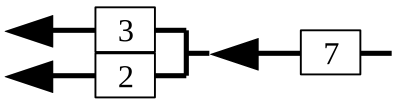
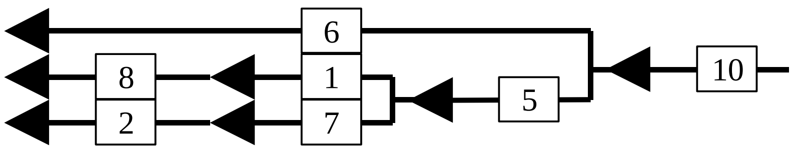
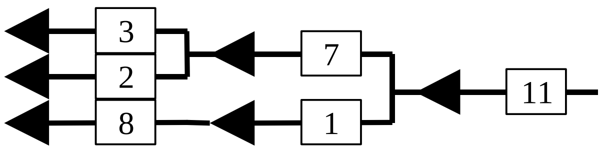
No. of stream	Rank 1 · Rank 2 · Rank 3 · Rank 4	No. of all higher-ranked streams
1		8+9
2		pedestrians
3		pedestrians
4		2+8 +1+7+12 +11
5		2+8+9 +1+7
6		2
7		2+3
8		pedestrians
9		pedestrians
10		2+8 +1+7+6 +5
11		2+3+8
12		8

Table 3 - Scheme for calculating the queue-free states in the higher-ranked streams

The relationship between queues in the higher-ranked streams (parallel groups and/or serial sequences) can be illustrated in Table 3 according to their geometrical position.

The capacity of the streams must be calculated according to the precedence of ranks. That means, at first the capacities should be calculated for all steams of rank 1 (if a queue is expected there), then for streams of rank 2 and so on.

For instance, for calculating the capacity of stream 4 (subject left-turning stream, rank 4), at first the capacities of streams 2 and 8 (rank 1), then the capacities of streams 1,7, and 12 (rank 2), and then the capacity of stream 11 (rank 3) must be calculated in advance (see also Table 3, row 4).

Thus, for stream 4, the probability of queue-free state in all higher-ranked streams is

$$(p_0)_{T,\,forstream4} = \left(\frac{1}{1 + \dfrac{1 - \left(\dfrac{1}{1+\dfrac{1-p_{0,1}}{p_{0,1}}+\dfrac{1-p_{0,8}}{p_{0,8}}}\right)\cdot\left(\dfrac{1}{1+\dfrac{1-p_{0,2}}{p_{0,2}}+\dfrac{1-p_{0,7}}{p_{0,7}}}\right)}{\left(\dfrac{1}{1+\dfrac{1-p_{0,1}}{p_{0,1}}+\dfrac{1-p_{0,8}}{p_{0,8}}}\right)\cdot\left(\dfrac{1}{1+\dfrac{1-p_{0,2}}{p_{0,2}}+\dfrac{1-p_{0,7}}{p_{0,7}}}\right)} + \dfrac{1-p_{0,10}}{p_{0,10}}} \right) \cdot p_{0,12} \tag{28}$$

where $p_{0,i}$ is the probability that in stream *i* no queue occurs. Equation (28) is a very complicated equation because in this equation also queues in streams of rank 1 are considered. In the real world, however, there are normally no queues in streams of rank 1 except pedestrians crossing the major street should be considered as streams of higher priority. If it is not the case, the probabilities of queue-free state in streams of rank 1 can be set to 1. Setting $p_{0,2}$ and $p_{0,8}$ equal to 1 for no queues in streams 2 and 8, the Equation (28) yields

$$(p_0)_{T,\,forstream4} = \left(\frac{1}{1 + \dfrac{1-p_{0,1}\cdot p_{0,7}}{p_{0,1}\cdot p_{0,7}} + \dfrac{1-p_{0,10}}{p_{0,10}}} \right) \cdot p_{0,12} \tag{29}$$

Thus, the capacity of stream 4 is

$$C_4 = \left(\frac{1}{1 + \dfrac{1-p_{0,1}\cdot p_{0,7}}{p_{0,1}\cdot p_{0,7}} + \dfrac{1-p_{0,10}}{p_{0,10}}} \right) \cdot p_{0,12} \cdot C_{basic,4} \tag{30}$$

6 SUMMARY

A new theory for estimating the probability of queue-free state in higher-ranked streams is presented. The theory is verified through simulations. The derived theory for estimating the probability of queue-free state in higher-ranked streams can be used for queue-systems with

- streams of arbitrary high rank,
- arbitrary many higher-ranked streams of different ranks,
- any configurations of streams (in parallel groups or serial sequences) for higher-ranked streams, and
- any predefined queue-free states in higher-ranked streams.

A direct application of this theory is the estimate of the impedance factor for streams of rank 4 at unsignalized intersections. In this case, the expression according to the new theory is much simpler and more accurate than the approach in the HCM (1994, 1997).

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