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THE CONTRIBUTION TO THE PROCEDURE OF CAPACITY DETERMINATION AT UNSIGNALIZED PRIORITY-CONTROLLED INTERSECTIONS

ABSTRACT

The problem of minor vehicles crossing or merging into the major stream at unsignalized priority-controlled intersections is well-known. Numerous solutions involve various assumptions concerning the major headway distributions, number of major lanes, critical gap distributions, etc. Such cases can be divided into two main groups: intersections with two streams (one major and one minor stream) and intersections with more than two streams (more than one major stream and one minor stream). At roundabouts, also at single-lane roundabouts, there are similar problems like the ones at other unsignalized priority-controlled intersections. A vehicle at the roundabout approach can only cross the pedestrian crossing when a sufficient time-gap between two pedestrians (or cyclists) is provided. A vehicle at the roundabout entries can only merge into the major stream when a sufficient gap between the two vehicles in the major stream is provided. Because of that, single-lane roundabouts can also be treated as unsignalized intersections with two major lanes: the first one in its circulatory roadway and the second one on the pedestrian crossing.

KEYWORDS

unsignalized intersection, roundabout, capacity, two major streams, pedestrians, critical gap

1. INTRODUCTION

Unsignalized intersections are the most common type of road junctions in highway transportation systems. The capacity at these intersections is thereby one of the most researched topics.

At unsignalized intersections there are traffic streams of different rank in the priority hierarchy, and usually dependent on the stream considered, different queuing systems result. For the purpose of calculating the capacity of these queuing systems different procedures should be used.

The procedures of calculating the unsignalized intersections capacity can be basically divided into two main groups:

- calculation of simple queuing system with two streams (one major and one minor stream),
- calculation of comprehensive queuing system with more than two streams of different rank in the priority regulation.

There is a large variety of calculation methods in the first group. Firstly, there are mathematical solutions based on the theory of stochastic processes and gap-acceptance. In the second group there is merely one pragmatic procedure for practical uses. This methodology was developed in Germany and has found broad applications in other countries as well.

2. STATE-OF-THE-ART FORMULAS

Different authors have come up with different capacity formulas for the cases of more than one major lane (in cases when lanes are not superposed).

In the early seventies Tanner extended his formula to the n-lane case. In the eighties Golias derived the capacity formula for the case of two major lanes with differing critical gaps and exponentially distributed headways. In the nineties Hagring presented a generalised formula for the capacity of minor road movement at priority intersection with more than one major lane. He pointed out that the capacity can vary substantially according to how different major lanes are accounted for. However, the problem regarding the usage of formula is that critical gaps are generally provided not for each major lane but only for a major flow as a whole.

The recently carried out researches by Sullivan and Troutbeck have shown that the M3 distribution, introduced earlier by Cowan, provides a good fit to observed headway distributions.

Troutbeck derived the capacity formula for the case of two major lanes with M3 distributed headways [1].

A few years ago a universal procedure for the capacity determination at unsignalized priority controlled intersections was presented by Ning Wu [2]. The procedure can handle all possible stream and lane configurations (e. g. number of lanes and ranks of streams, etc.) at unsignalized intersections.

3. UNSIGNALIZED PRIORITY-CONTROLLED INTERSECTIONS WITH ONE AND MORE THAN ONE MAJOR STREAM

A queuing system with two crossing streams (Fig. 1) is being considered. The major stream has priority and the vehicle can drive through without stopping at the intersection. The minor stream has to give way to the major stream and stops accordingly.

A vehicle on the minor road can only depart crossing the major road (or merging into the major stream) when a gap between the two vehicles in the major stream is provided.

The classic procedure for the determination of the capacity is based on the calculation of the distribution of gaps in the major stream and on the calculation of the number of vehicles which can depart during a gap within the major stream [2]. The capacity of the minor stream is given by:

$$C=q_p \int_0^\infty f(t)g(t)dt \tag{1}$$

where:

- C – capacity of the minor stream in vehicle per unit of time,
- $f(t)$ – probability density of gaps t in the major stream,
- $g(t)$ – function for the number of vehicles which can depart during a gap of the length t,
- q_p – traffic intensity per unit of time in the major stream.

The equation indicates the sum of vehicles departing during all gaps in the major stream.

According to the function $f(t)$ and $g(t)$ different formulas for the determination of capacity can be used.

3.1. Assumption modelling for *f(t)*

For the function of probability density of gaps $f(t)$ two assumptions modelling the traffic flow in the major stream are presupposed:

a) free traffic flow in the major stream (a vehicle does not influence the vehicles driving behind); the arrivals of successive vehicles are coincidental and absolutely independent of each other,

b) bunched traffic (between the two successive vehicles a minimum gap has to be held; a different distribution of gaps compared to that of the free traffic flow can be obtained.

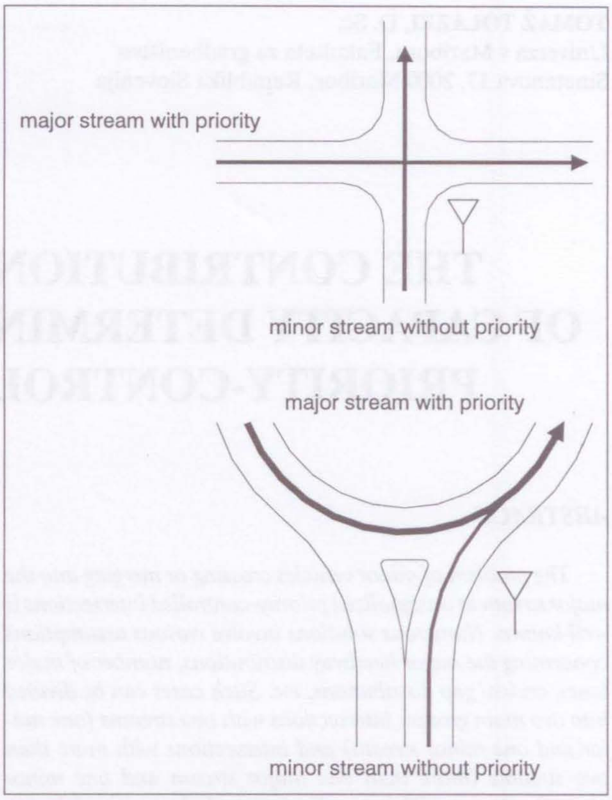

Figure 1 - Unsignalized priority-controlled intersections

Cleary, these assumptions are only referential under the predefined conditions.

If arrivals of vehicles in the major stream are considered as completely coincidental (free), the probability density of gaps t between the two vehicles is

$$f(t)=q_p e^{-q_p t} \tag{2}$$

where q_p (veh/s) means the traffic intensity in the major stream; i. e. the gaps t are negative-exponentially distributed.

If arrivals of the vehicles in the major stream are not stochastic but depend on the vehicle in front, then the traffic in the major stream is no longer completely free - because a vehicle must keep a minimum gap to the vehicle in front and drive in succession (bunched traffic). In that case the distribution of gaps in the bunched major stream can be described as the shifted - negative - exponential distribution.

3.2. Assumption modelling for the *g(t)*

For the functions for the number of departures from the minor stream crossing or merging into the major stream usually two models with two different assumptions are available:

a) discrete departure from the minor stream,

b) continuous departure from the minor stream.

For the case of discrete departure it is assumed that within the major stream the gap t with the length $t_g \leq t < t_g + t_f$ enables the departure of one vehicle, the gap t with the length $t_g + t_f \leq t < t_g + 2t_f$ enables the departure of two vehicles, the gap t with the length $t_g + 2t_f \leq t < t_g + 3t_f$ enables the departure of three vehicles, and so on (where t_g is the critical gap and t_f is the move-up time).

For the case of continuous departure it is assumed that the departure of a vehicle is a continuous process which is carried out during the time interval of the length t_f. The average departure time of the first vehicle equals t_g.

Systems with more than one major stream can be managed in a similar way [2]. The traffic flow within the major stream can be divided into four states (queuing, bunching, single vehicle and no vehicle) for which the probabilities are calculated separately.

The traffic states in major streams with parallel configuration (Fig. 2) are completely independent of each other.

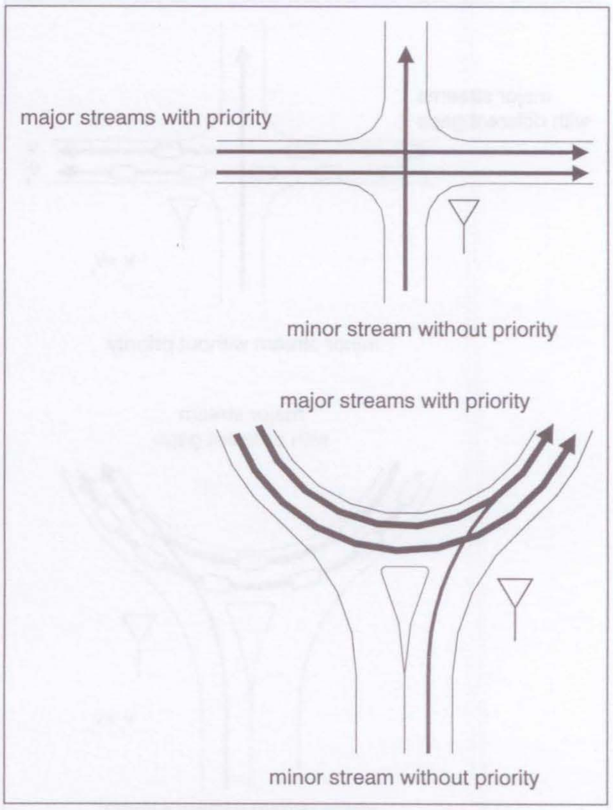

Figure 2 - Systems with two major streams with parallel configuration

4. UNIVERSAL PROCEDURE FOR THE CAPACITY DETERMINATION AT UNSIGNALIZED INTERSECTION

In 1998 Ning Wu introduced a universal procedure for the systems with more than one major stream for continuous and discrete departure [2]. The new procedure for the determination of capacity at unsignalized intersection can be applied in all conditions (for the arbitrary number of major streams with different critical gaps, high ranks of the minor stream and queuing and bunching saturations in the major stream).

The procedure takes into consideration most of the parameters at unsignalized intersections. However, the author suggests that for practical purposes the procedure should be calibrated and validated with measurements or simulations.

The procedure for the determination of capacity at unsignalized intersections can also be applied for roundabouts with n_e traffic lane approaches to a roundabout and with n_c circulation lanes:

$$q_e = n_e \left(1 - \frac{q_c \tau}{n_c}\right)^{n_c} \frac{1}{t_f} \exp(-q_c(t_0 - \tau)) \tag{3}$$

where:

- q_e – total capacity of the approach (= C) (veh/s),
- q_c – total traffic intensity in the circulation lanes (veh/s),
- t_o – zero - gap ($t_o = t_g - t_f/2$) (s),
- t_g – critical gap (s),
- t_f – move-up time (s),
- τ – minimum gap between two vehicles driving in succession (s),
- n_e – number of lanes to a roundabout (at the entrance),
- n_c – circulation lanes.

The level of convenience of the above-mentioned equation was verified on the roundabouts in Germany. It was established that $t_g = 4.12$ s, $t_f = 2.88$ s and $\tau = 2.10$ s.

The fact that Wu's new procedure is included in the German HCM 2000 proves its appropriateness [2].

In 1998 Hagring presented also a generalised formula for the capacity of minor road movement at unsignalized priority-controlled intersections with more than one major lane. It was established that the capacity can vary substantially depending on how different major lanes are accounted for. The problem regarding the application of the formula is that critical gaps are generally provided not for each major lane separately, but rather only for the major flow as a whole.

5. ESTIMATION OF CRITICAL GAPS IN TWO MAJOR STREAMS

There are some situations where critical gaps differ between the lanes (e. g. at roundabouts with more than one circulation lane, two major lanes at T-junctions, etc.) (Fig. 3)

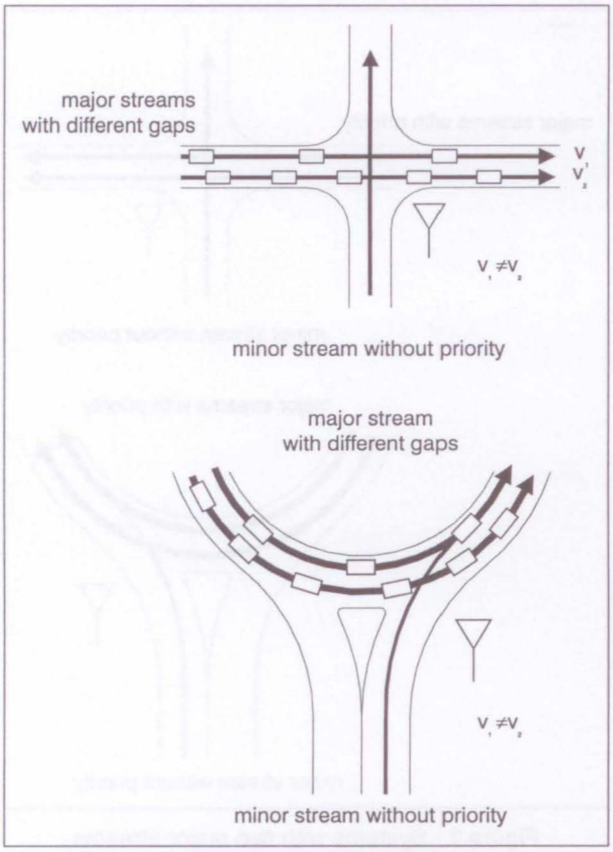

Figure 3 - Situations where critical gaps differ between the lanes

The findings of the researches carried out in the United Kingdom (left-side driving) regarding T-junctions show that the critical gap in the near lane was always larger than the one in the far lane. In Sweden (with right-side driving) it is commonly observed that right-turning drivers which are about to enter the two-lane roundabouts tend to neglect vehicles in the far lane, at least in larger roundabouts, since no conflict will occur among these vehicles [3].

Assuming that a minor-stream driver is waiting to merge into a roundabout with two major lanes (Fig. 4), such a situation can be dealt with by using three different models [3]:

- the first model assumes that the allocation of vehicles to the two major lanes is of no importance to the minor-stream vehicles, and the critical gap is independent of the lane allocation;
- the second model assumes that the allocation of vehicles to the two major lanes is relevant to the minor-stream vehicles but that there is no reason for assuming that the major lanes should differ in their critical gap;
- the third model assumes that the allocation of vehicles to the two major lanes is relevant to the minor-stream vehicles and that the major lanes differ in their critical gaps.

Figure 4 - A minor-stream driver waiting to merge into a roundabout with two major lanes

Another approach is modelling the dependence between the critical gap for the whole population. Three hypotheses [3] for the correlation of critical gaps can be formulated at the population level:

- there is no correlation between the critical gaps between vehicles of different lanes (it can be motivated by the presence of drivers who differ in their driving skills),
- drivers who accept short gaps in the near lane tend to accept short gaps in the far lane as well (careful drivers with a need for longer gaps in both lanes),
- drivers who accept short gaps in the near lane tend to accept long gaps in the far lane (a short gap in one lane which is a difficult situation to deal with results in the need of being an experienced driver for a longer gap in the other lane).

It is commonly believed that the third hypothesis is the most corresponding one for roundabouts with more than one circulatory roadway, since the speeds on the inside circulatory roadway are generally higher than those on the outside circulatory roadway.

Outside circulatory roadway is generally used only by vehicles filling or emptying the roundabouts. On the other hand, all other vehicles use the inner circulatory roadway; since they are not doing any traffic manoeuvring but only driving in the circle, their speeds being higher (than those of vehicles on the outside circulatory roadway). This causes longer accepted gaps.

6. CAPACITY DETERMINATION OF SINGLE-LANE ROUNDABOUTS AT UNSIGNALIZED PRIORITY-CONTROLLED INTERSECTIONS WITH TWO MAJOR LANES

At roundabouts, also at single-lane roundabouts (Fig. 5), similar problems like the ones at other unsignalized priority-controlled intersections can be

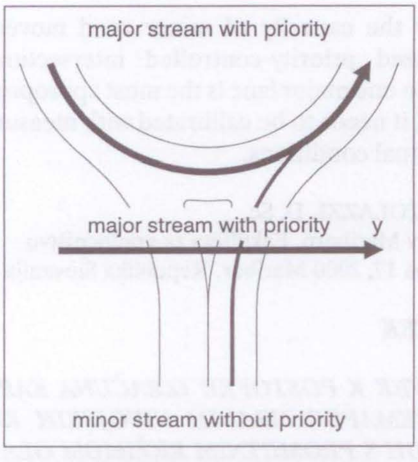

Figure 5 - Single lane roundabout - system with two major lanes

encountered; namely, the problems of minor vehicles crossing (pedestrian and cyclists streams) and merging into the major (motor vehicle) stream [4].

A vehicle at the roundabout approach can only depart crossing the pedestrian crossing when a gap between the two pedestrians (or cyclists) is provided. A vehicle at the roundabout entrance can only merge into the major stream when a gap between two vehicles in the major stream (two successive vehicles) is provided.

Namely: vehicles at the roundabout approach have to give way to the pedestrians and cyclists (first major lane) and because the minor stream at the entrance has to give way to the major stream at the circulation lane (second major lane), it follows hence that the single-lane roundabout can be treated as an unsignalized priority-controlled intersection with two major lanes, and as a system with the major stream with parallel configuration.

This is the main idea and the essence of this contribution.

The traffic flow within the major stream can be divided into four states (queuing, bunching, single vehicle and no vehicle) for which probabilities can be calculated separately.

The traffic states in the major stream with parallel configuration are completely independent of each other (pedestrian stream / motor vehicle stream).

The above findings make Wu's universal procedure for systems with more than one major stream for continuous and discrete departure convenient even in such cases.

More appropriate way of dealing with such cases is Hagring's generalised formula for the capacity of minor road movement at unsignalized priority-controlled intersections with more than one major lane:

$$C=\Lambda\prod_{i}\frac{\alpha_i q_i}{\lambda_i}\frac{e^{-\sum\limits_k \lambda_k T_k}}{e^{-\Lambda\Delta}(1-e^{-\sum\limits_m \lambda_m T_{0m}})} \quad (4)$$

where:

Λ – sum of intensities of the exponential part of a distribution ($\Lambda = \Sigma\,\lambda_i$),

λ_i – intensity of the exponential part of a distribution (the intensity for longer gaps in lane i, i. e. $t > \Delta$),

α_i – proportion of free vehicles,

q_i – volume-flow in lane i (veh/s),

Δ – minimum headway between vehicles (s),

T_i critical gap in lane i (s),

T_{0i} – follow-up time in lane i (s),

m – number of lanes (m =1, ...n),

k – number of vehicles crossing each lane,

i – index for lanes.

Still, there is a problem regarding the application of the formula because the critical gaps are generally provided not for each major lane separately, but rather only for the major flow as a whole.

Therefore, Hagring's equation has to be extended with the third approach model (assuming that the allocations of vehicles to the two major lanes are relevant to the minor-stream vehicles and that the major lanes differ in their critical gaps).

At roundabouts with more than one circulatory roadway, another fact needs to be taken into consideration; namely, drivers who accept short gaps in the near lane tend to accept long gaps in the far lane (a short gap in one lane, which is a difficult situation to deal with results in the need of being an experienced driver for a longer gap in the other lane); as already shown in chapter 4.

The same situation occurs at single-lane roundabouts if treated as systems with two major streams. Because speeds of vehicles are higher than those of pedestrians the acceptable gaps on the first major stream are lower than those on the second major stream. Another reason for this is that a pedestrian is exposed to the vehicle, so drivers attend smaller gaps.

Thus, it is better to use the modified equation suitable for systems with n lanes and different critical gaps:

$$C=\Lambda\prod_{i}\frac{\alpha_i q_i}{\lambda_i}\frac{e^{-\sum\limits_k \lambda_k T_k}}{e^{-\Lambda\Delta}(1-e^{-\Lambda T_0})} \quad (5)$$

This type of procedure takes into consideration the actual happening at a roundabout and truth occurs of all participants [1]:

- the procedures for calculating the capacity of unsignalized intersections are divided as a calculation of a comprehensive queuing system with more than two streams (two major and one minor stream) of different rank in the priority regulation;
- at roundabouts we usually deal with bunched traffic (minimum gap has to be kept between two succes-

sive vehicles; different distributions can be obtained compared to the distribution of gaps in the free traffic flow);
- critical gaps differ between the lanes;
- drivers who accept short gaps in the near lane tend to accept long gaps in the far lane as well (a short gap in one lane which is a difficult situation to deal with results in the need of being an experienced driver for a longer gap in the other lane).

However, the last equation needs to be calibrated and validated with measurements using actual conditions, since drivers behave quite differently from one country to another.

7. EXPERIMENT CARRIED OUT AT THE SLOVENE ROUNDABOUTS

Just a few weeks ago the research covering the capacity of Slovene roundabouts and the influence of pedestrian (and cyclist) stream on their capacity was concluded. One of the aims of the research was to determine which equation for the capacity determination is the most appropriate for the roundabouts in the Slovene circumstances.

Seven single-lane roundabouts across the country were included in the research.

It was established that the average Δ = 2.4 s, T_p = 4.2 s, T_v = 4.8 s and T_0 = 2.9 s where T_p and T_v are critical gaps in pedestrian and vehicle streams.

8. CONCLUSION

At roundabouts, also at single-lane roundabouts, we deal with the same problem like the one at other unsignalized priority-controlled intersections; namely, the one of minor vehicles crossing or merging into the major stream.

Because the vehicles at the roundabout approach have to give way to the pedestrians and cyclists (first major lane), and because the minor stream at the entrance has to give way to the major stream at the circulation lane (second major lane), it follows that a single lane roundabout can be treated as an unsignalized priority-controlled intersection with two major lanes and as a system with major stream with parallel configuration.

Such cases can be treated by the universal procedure for systems with more than one major stream for continuous and discrete departure. However, the problem regarding the application of the formula remains since the critical gaps are generally provided not for each major lane separately but only for the major flow as a whole.

As critical gaps usually differ between the lanes of a roundabout it seems that Hagring's generalised formula for the capacity of minor road movement at unsignalized priority-controlled intersections with more than one major lane is the most appropriate one; however, it needs to be calibrated with measurements under actual conditions.

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POVZETEK

PRISPEVEK K POSTOPKU IZRAČUNA KAPACITETE NESEMAFORIZIRANIH NIVOJSKIH KRIŽIŠČ, UREJENIH S PROMETNIM REŽIMOM GLAVNE IN STRANSKE PROMETNE SMERI

Problematika križanja ali vključevenaja stranskega prometnega toka v nivojskih križiščih, kjer je prometni režim urejen z glavno in stransko prometno smerjo, je znan.

Številni pristopi vsebujejo različne predpostavke, ki zadevajo porazdelitev glavnega prometnega toka, število prometnih pasov na glavni prometni smeri, kritično časovno praznino ...

Take sisteme lahko razdelimo v dve glavni skupini: križišča z dvema tokoma (enim glavnim in enim stranskim) in križišča z več kot dvema tokoma (več kot dva glavna prometna toka in en stranski prometni tok).

V krožnih križiščih, tudi v enopasovnih, obstajajo enaki problemi, kot pri drugih nivojskih križiščih, urejenih s prometnim režimom glavne in stranske prometne smeri.

Vozilo na uvozu v krožno križišče se lahko priključi v glavni prometni tok le v primeru, ko je časovni presledek med dvema pešcoma (ali kolesarjema) zadosti velika.

Vsled tega lahko tudi enopasovna krožna križišča obravnavamo kot nesemaforizirana križišča z dvema glavnima prometnima tokoma: prvim v krožnem vozišču in drugem na prehodu za pešce.

KLJUČNE BESEDE

nesemaforizirana križišča, krožna križišča, kapaciteta, dva glavna prometna toka, pešci, kritična časovna praznina

LITERATURE

[1] **O. Hagring**: *A further generalization of Tanner's formula*. Transportation Research Part B: Methodological. Elsevier Science. Exeter. England. Volume 32 b. No. 6, 1998

[2] **N. Wu**: *A universal procedure for capacity determination at unsignalized priority controlled intersections*. Transportation Research Part B: Methodological. Elsevier Science. Exeter. England. Volume 35 b. No. 6, 2001

[3] **O. Hagring**: *Estimation of critical gaps in two major streams*. Transportation Research Part B: Methodological. Elsevier Science. Exeter. England. Volume 34 b. No. 4, 2000

[4] **T. Tollazzi**: *Reduction of the roundabout capacity due to a strong stream of pedestrian and/or cyclists*, Promet - Traffic - Traffico, Volume 11, No. 1, 1999