Use of Simulation to Analysis of Impedance Impact at Unsignalized Intersections

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ABSTRACT

The paper presents a simulation model of the priority type intersection and its application to study of various aspects of an impedance effect related to hierarchical manner of vehicle departures. The first part describes submodels of the demand flows at unsignalized intersection approaches. The second part presents results of simulation studies of impacts on impedance of the following factors: movements of the 3rd and 4th rank, selected traffic parameters and filtering of flow demands by traffic signals. The studies gave a basis for development of general model of impedance impacts and allowed deriving functions correcting the total impedance effect.

1. INTRODUCTION

In investigation of relationships describing operation of unsignalized intersections used are both: analytical and simulation studies. Computer simulation seems more useful tool as it allows for modelling of certain features of road traffic, which cannot be described in analytical way. Simulation allows also for easy derivation of relationships between the performance measures of intersection operation and parameters of the arrival and departure processes.

In the paper described is the simulation model of unsignalized intersection. In particular presented are the most important elements of the demand process, which can not be expressed in analytical way. Some detailed results of simulation studies related to an effect of impedance are also given. The investigations included searching for a function for correcting a multiplicative model of impedance of the 3rd and 4th rank movements and studies of impacts of:

- selected traffic parameters on the impedance of lower rank movements and
- traffic flow demand filtered by adjacent traffic signals on impedance.

2. THE SIMULATION MODEL

The simulation model was constructed on the basis of own field studies conducted for an identification of the traffic processes at priority type intersection and for quantification of the model parameters. It was assumed that inflow of vehicles to an intersection approach does not depend on a current traffic situation at the intersection. It is realized for the three movements and the demand flow is divided into three traffic streams. The simulation model of an intersection without traffic signals uses the event by event technique and vehicles entering the system (the generation cross section) are transferred to join the end of queue (cross section moving with the end of queue) and then to the decision cross section (decisions related to performing maneuvers). The progress of traffic flow is monitored in three cross sections. In the model the following elementary processes can be distinguished:

- **demand process** — including generation of headways between vehicles arriving to an intersection approaches and their transforming from first to the following decision cross sections — including queuing, if it takes place,
- **departure (service) process** — including performing of assigned maneuvers by vehicles crossing the decision cross sections.

The procedure of vehicle generation at intersection approaches was developed in order to represent features important for the study of impedance, i.e.:

- various types of traffic flow non-stationarity — including stationary profiles, parabolic profiles, six typical flow profiles derived from field measurements and described by mathematical step functions and also two measured profiles,
- creation of platoons of vehicles in the demand flows, with account for various levels of traffic constraining and possible changes of traffic platoon parameters,
- arrivals of vehicles from adjacent intersections with traffic signals — defined by signal settings, variable traffic flow patterns and by variable distances between intersections with and without traffic signals.

3. ELEMENTS OF THE DEMAND PROCESS

3.1 Non-Stationarity of Flow Demands

As the construction of a reliable model for a non-stationary process is very difficult, a fact that time-series of demand flow rates are in a way stationary was used as a basis for the assumption of traffic flow stationarity in short time intervals. Therefore, in the procedure of generation of time headways, step changes of traffic flow intensity according to a given function were applied, or input values obtained from measurements were used. Input intensities are relative values of traffic flow demand intensity in succeeding observation intervals. Study of an impact of these time interval lengths on consistency of generated streams with observed streams, showed that intervals of stationarity t_a should not be longer than 5 minutes. Depending on the length of interval t_a, two procedures of generation were assumed. In the case of the stationarity intervals of ten seconds length, the generated time headway can be significantly longer than t_a. The basic problem is how to get a consistency of assumed and generated values of stream intensity (i.e., parameter of distribution of time headways between vehicles). The way of solving this problem and the appropriate generation procedure was presented elsewhere (Chodur and Tracz 1984). The model implements a few types of changes of traffic flow intensity in time; from parabolic profiles (with various rations of maximum to average intensity within the analysis period), through sinusoidal profiles, step profiles to empirical profiles.

3.2 Representation of Traffic Platooning in Traffic Flow

Various levels of traffic constraints in traffic flow, reflecting for example different than exponential distributions of time headways between vehicle were included in the model. Considering ways of development of the time headway generation procedure, rejected were methods based on various theoretical distributions as:

- there are difficulties in determining of general recommendations related to selection of type of distribution consistent with an empirical distribution,
- for a few theoretical distributions it is not possible to determine relationships between measured traffic parameters and parameters of distribution.

For the described reasons in the time headway generation procedure applied was a model of traffic on a road section without possibility of overtaking (Chodur et al. 1990). Simplicity of interpretation of traffic freedom and constraints and possibility of linking all of the model elements with results of empirical studies, decided on the model choice. Moreover, an evaluation of consistency of generated time headways, with empirical distributions of time headways confirmed better fitting of distribution of headways generated according to the developed procedure in comparison with earlier used generators based on theoretical distributions.

3.3 Filtering of Traffic Flow by Traffic Signals

In urban street network adjacent intersections with traffic signals can have a significant impact on capacity and traffic performance of unsignalized intersections. It results from grouping of vehicles in queues during the red signal phases at signalized intersection and changes in distribution of headways between vehicles in streams of vehicles arriving to priority type intersection. A cyclic recurrence of a set of short time headways (between vehicles from a queue) and a set of long time headways (between vehicles departing freely during the green phase) is characteristic for the demand process at an approach to a priority intersection. It is not possible to model real sequence and cyclic recurrence of headways in the flow leaving an intersection with traffic signals besides of consistency of probability density function with empirical distribution of headways. Numerical modelling offers a good tool to solve this problem. In order to make an accurate representation of the traffic flow demands filtered by traffic signals the following elements of the system are modelled:

1. **Traffic flow leaving a signalized intersection**. An intersection with traffic signals groups vehicles arriving during the red signal and departure of a queue and next produced platoon of vehicles leaves an intersection. For modelling of traffic flow at a signalized approach a model made was applied for a signalized intersection. A vector including departure times is made (using a computer program SIGNAL) and it consists of the following traffic streams:

- ***vehicles moving through*** downstream the road to the considered priority intersection (departing during green light and assigned to the considered direction of traffic). Departure headways for vehicles leaving the approach from the queue are generated from the normal distribution with empirical parameters,

- ***vehicles turning right*** from a cross road during: green light (traffic of these vehicles is modelled in a simplified way by assuming fixed follow-up times) and turning on red period (green arrow). Turn on red departures are modelled on the basis of a gap-acceptance model.
- ***vehicles turning left*** from a cross road during a separate phase for this movement.

The departure follow-up times included in the vector are then adjusted by taking into account travel time between the signalized and priority type intersections. This vector is used for determining of vehicles arrival times to the consider approach.

2. **Passing from the signalized intersection to the priority type intersection**. Vehicles travel with various speeds causing a platoon dispersion. Macroscopic model of traffic along a section of road without overtaking was used to model this traffic. At the beginning of the section virtual travel times are assigned and these times decide on platoon dispersion or creation. The time headways in the constrained movement are generated from the triangular distribution with empirical parameters. Comparisons of generated distributions of this travel time with measured distributions of headways in filtered traffic flow allowed for reasonable calibration of the model.

Finally the time headway vector represents the traffic flow filtered by adjacent traffic signal settings with various input parameters (data input to the model) and arriving to the consider approach of the priority type intersection**.** It is possible to model one- or two-side impact of traffic signals and various offsets between signal settings.

3.4 Impact of the Demand Flow Model on Simulation Results

Calculations of capacity of lower rank movements were conducted in order to study quantitative and qualitative impacts of various realizations of the demand process at individual approaches of a priority type intersection. This simulation study confirmed that the type of model for the demand process affects the calculation results of capacity and measures of performance. Constraints of traffic freedom, expressed by the proportion of the platoon traffic in the demand flow and by the character of variability of conflicting traffic flow are essential. In general for cases of constrained traffic flows with various levels of platooning, higher values of capacities were obtained than for free stationary traffic flow demands, described by shifted exponential distribution. These differences, expressed by a capacity increase ratio can be significant. Results of the conducted studies show that, depending on the level of traffic constraining, and traffic conflicting volume, the capacity increase rate can range from 1.03 to 1.40. Impact of traffic flows filtering by adjacent traffic signals on capacity of minor road approaches is even larger and significantly depends on one- or two-side impact and on offset (Chodur et al. 1994).

4. IMPEDANCE RELATED TO THE HIERARCHICAL MANNER OF VEHICLE DEPARTURES

The problem of including the impedance — defined as in HCM (1997) in capacity computation methods is still a vexing issue among traffic engineering experts (Brilon et al. 1997; Tracz and Chodur 1991; HCM 1997). The investigations of the impedance effect based on the analytic models are dominant. The authors claim that more detailed study of the impedance problem is possible with use of a simulation model (Tracz and Chodur 1991). Simulation models offer the possibility of estimating the impact of various types of flow demands on the value of the impedance coefficient (used in calculation methods), including also the effects of traffic signals. In the Tracz and Chodur (1991) procedure for an analysis of an impact of impedance on capacity of lower rank movements with use of simulation studies can be found. This paper includes also graphs of the impedance factor for individual impeding movements from Polish and foreign studies. Below the results of a completed study involving impedance models for individual impeding movements adopted to the scheme are presented.

In order to determine the potential capacities of minor movements it was assumed that the conflicting flow consists only of 1st (Figure 1) rank movements. In practice the conflicting flow can include also 2nd and 3rd rank movements and vehicles perform their maneuvers in the prioritized manner, when traffic becomes congested in a high-priority movement. In some intervals it can impede lower priority movements (i.e., streams of ranks 3 and 4). It causes a decrease of their capacities in relation to the situation assumed at the beginning, i.e., homogeneous conflicting flow consisting of 1st rank movements. The effect of impedance is expressed by the adjustment factor ($f_d = C/C_p$). This rate is determined for two cases of the conflicting flow; first, real flow including impeding movements (C) and second, including only 1st rank streams with the equivalent flow equal to the real flow volume (C_p). Volume to capacity rate ($\rho = V/C$) of the impeding movement was assumed as the basic variable, which affects the degree of impedance.

4.1 Impedance Models

The charts of the impedance factor for situations with and without separate left turning lane on the major road are presented in Figure 2. The determined regression models of impedance by individual impeding movements are as follows:

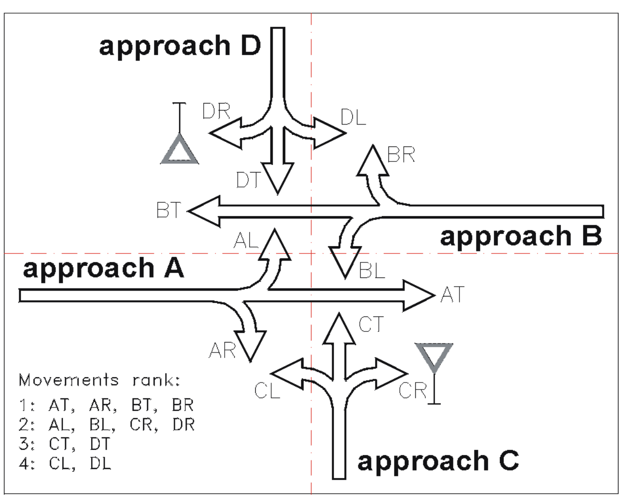

FIGURE 1 Notations of movements at a priority type intersection.

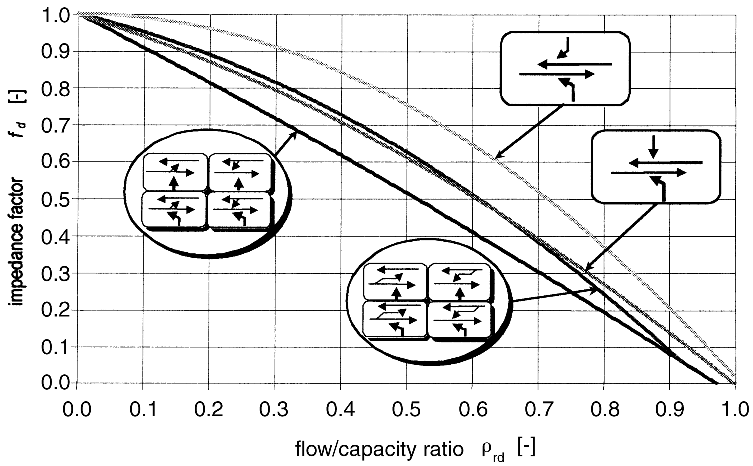

FIGURE 2 Charts of the impedance factors for individual impeding movements.

- major street left turn movement without separate lane:

$$f_d = 1 - 0.127 \cdot \rho^2 - 0.906 \cdot \rho \qquad \text{at} \qquad R^2 = 0.892 \tag{1}$$

- major street left turn movement with separate lane:

$$f_d = 1 - 0.655 \cdot \rho^2 - 0.421 \cdot \rho \qquad \text{at} \qquad R^2 = 0.945 \tag{2}$$

- through movement from the opposite non-priority approach:

$$f_d = 1 - 0.453 \cdot \rho^2 - 0.547 \cdot \rho \qquad \text{at} \qquad R^2 = 0.886 \tag{3}$$

- right turn movement from the opposite approach:

$$f_d = 1 - 0.975 \cdot \rho^2 - 0.00483 \cdot \rho \qquad \text{at} \qquad R^2 = 0.834 \tag{4}$$

4.2 Total Effect of Impedance

For through and left turn movement from the minor road, two or four impeding movements should be taken into account. Below models for total impedance of 3rd and 4th rank movements with presence of a separate lane for left turning movement from the major road are suggested.

4.2.1 Third rank non-priority movements

Third rank movements (straight through movement from a minor road) can be impeded by two left turning movements from the major road. The impedance factors for left turn movement from the approaches A and B were derived from the obtained relationships [(Equations (1) and (2)] after calculation of capacity utility rates. These rates were determined for the movements ρ_{AL} (Q_{AL}/C_{AL}) and ρ_{BL} (Q_{BL}/C_{BL}) on the basis of the impeding movement flow volume and a movement capacity derived from simulation for various rates of left turn movement from the opposing approach. Calculations were conducted for various combinations of left turns from approaches A and B: from $u_{AL} = u_{BL} = 0\,\%$ to $u_{AL} = u_{BL} = 60\,\%$ with a 5 % step. Figure 3 presents a comparison of total impedance f_d with impedance determined according to the multiplicative model ($f_{dAL} \cdot f_{dBL}$) (Tracz and Chodur 1991).

It can be seen that the product of the impedance factors of left turn movements from the major road $f_{dAL} \cdot f_{dBL}$ do not quite confirm to the values of the total impedance factor f_d and therefore a correction function was investigated in order to obtain a better model.

Regression analyses were used to derive the following correction function for the product of the impedance factors (multiplicative model: $f_{d3} = f_{dAL} \cdot f_{dBL}$) for the case of a separate lane for left turn movement from the major road:

$$f'_{d3} = 1.31 \cdot f_{d3} - 0.25 \tag{5}$$

where:

f'_{d3} = corrected product of the impedance factors for 3rd rank movement (CT or DT), and

f_{d3} = product of the impedance factors for the left turn movement from the major road $f_{dAL} \cdot f_{dBL}$

4.2.2 Fourth rank non-priority movements

Fourth rank non-priority movements (left turn movements from the minor road) are impeded by the left turn movements from the major road as well as through and right turn movements from the opposing minor road approach. The impedance factors for left turning movements from approaches A and B and through and right turn movements from the approach D were determined in a similar way as for the 3rd rank minor movements.

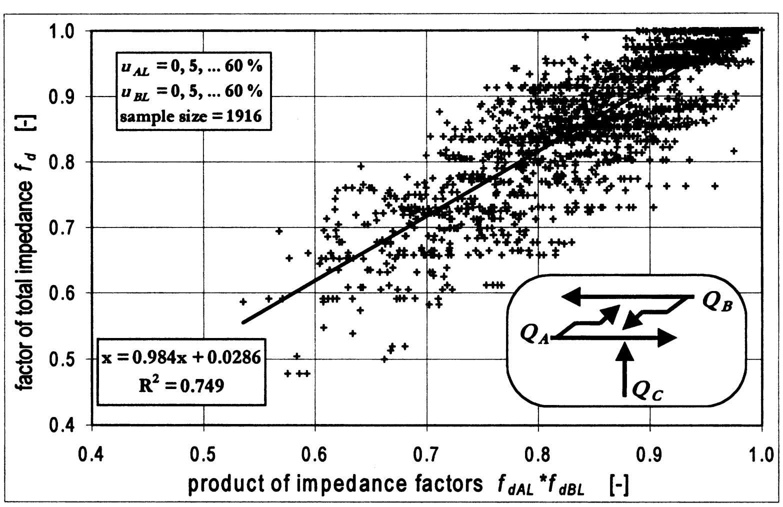

FIGURE 3 Comparison of the effects of total impedance with impedance calculated as a product of: $f_{dAL} \cdot f_{dBL}$ for the case of separate lanes for left turn movements.

Comparison of the total impedance factor f_d and the product of the impedance factors determined for the component impeding movements (the multiplicative model: $f_{d4} = f_{dAL} \cdot f_{dBL} \cdot f_{dDT} \cdot f_{dDR}$) is shown in Figure 4a. Calculations that were made for a 50 % rate of impeding through and right turning movements from the opposing approach and the case with separate lane for left turning movement from the opposing minor approach. In Figure 4b, results are presented of calculations made for 30 % rate of impeding through and right turning movements from the opposing approach and 40 % of left turning movement — a case with shared lane. The described model of total impedance has been used in the Polish capacity calculation method for major/minor priority intersections.

In searching for a correction function to obtain a better model, proposals of other authors (Tracz and Chodur 1991) were tested. Application of the correction functions described in the HCM (1997) and by Wu (1998) did not give satisfactory results. Searching aimed at such correction of the product of impedance factors, that gives values of f_{d4}' consistent with the impedance coefficient obtained from simulation. These functions correct a product of the impedance factors for 3 impeding movements (left turn movements from the major road and through movement from the minor opposing approach). For a value of this product equal 1.0 the functions do not give any corrections — a range of the correction increased with decreasing of the product value. Mathematical analysis led to a development of the following functions adjusting the multiplicative model (i.e., a product of the impedance factors: $f_{d4} = f_{dAL} \cdot f_{dBL} \cdot f_{dDT} \cdot f_{dDR}$):

– for a separate lane for the left turn from the opposing minor road approach:

$$f'_{d4} = 1.08 \cdot \ln(f_{d4}) + 1.14 \quad (6)$$

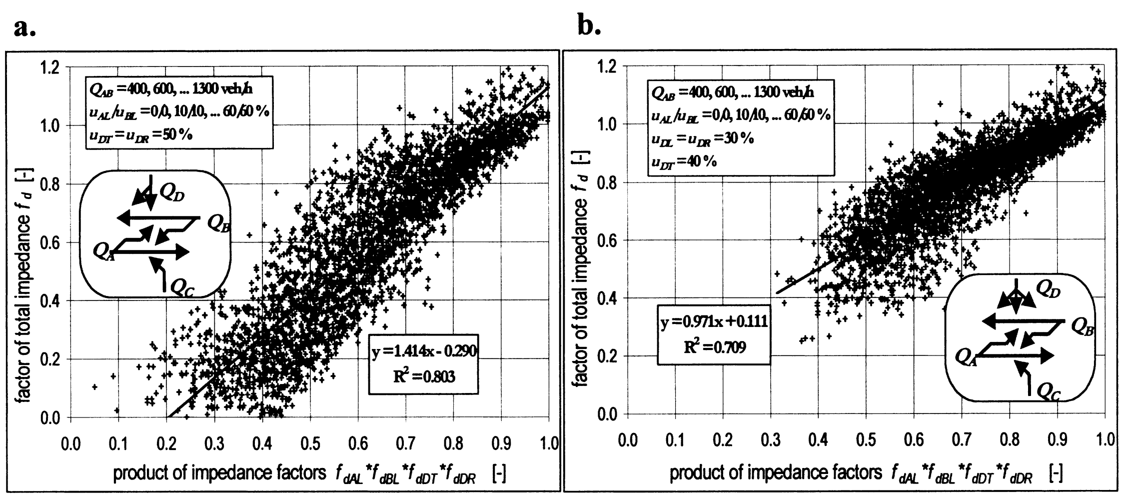

FIGURE 4 Relationship between the total impedance factor f_d and the product of impedance factors of impeding movements: $f_{dAL} \cdot f_{dBL} \cdot f_{dDT} \cdot f_{dDR}$ for the left turn movement from the opposed minor approach from (a) separate left turning lane and (b) from a shared lane.

– for shared lane for the left turn and impeding movements from the opposing minor road approach:

$$f'_{d4} = 0.909 \cdot \ln(f_{d4}) + 1.13 \tag{7}$$

where:

f'_{d4} = adjusted product of the impedance factors for the individual impeding movements for the 4th rank movements (CL or DL),

f_{d4} = the product of the impedance factors for individual impeding movements (left turns from the major road and through and right turns from the opposing minor road approach – $f_{dAL} \cdot f_{dBL} \cdot f_{dDT} \cdot f_{dDR}$ (4th rank movements – CL or DL).

It should be added that the analysed models (Sections 4.1 and 4.2) represent average traffic conditions at the intersection (traffic volumes, directional composition). A significant dispersion of the effects of impedance at the particular values of ρ, forced the authors to investigate other factors describing this variability.

4.3 Investigation of an Impact of Traffic Parameters on Impedance

Traffic flow volume and the directional distribution of the major road traffic, as well as the lane assignment at the opposite minor road approach were selected as factors, which can have an additional impact on impedance effects.

4.3.1 Impact of traffic flow volume on a major road.

Results of simulation calculations have showed an impact of the major road traffic volume Q_{AB} on the obtained results. The range of the impact can be seen from analysis of charts in Figure 5 (for the impeding left turn movement from the major road) and Figure 6 (for impeding movements from the opposing minor approach).

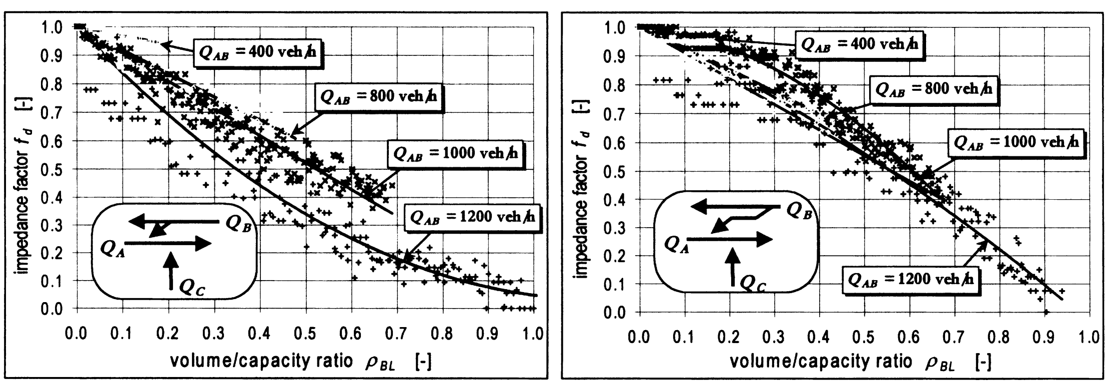

FIGURE 5 Impact of major road volume on effects of impedance by left turning movement from the major road (without and with separate lane).

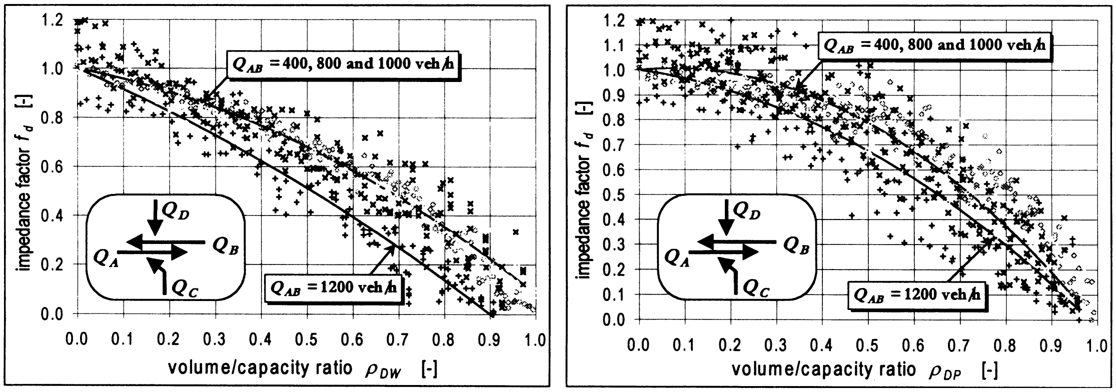

FIGURE 6 Impact of major road volume on effects of impedance by through and left turning movement from the minor road.

Analyses of the results allows to formulate the following conclusions:

- at the greater traffic volume on the major road Q_{AB}, a larger impact of the impeding movements can be seen (value of the impedance factor f_d decreases), what can be linked with the higher probability of building up queues by impeding movement vehicles,
- in case of impeding by the left turn movements from the major road, the larger impact of traffic volume Q_{AB} can be observed at the shared lane for these movements with the through movement,
- in case of impeding by the opposing movements from minor road approach, impact of traffic volume Q_{AB} increases at values of Q_{AB} > 1000 veh/h; a dispersion of the impedance factor f_d increases with the increase of Q_{AB} volume.

4.3.2 Impact of the adjacent signalized intersections.

Filtering of traffic flows arriving to unsignalized intersection from adjacent signalized intersections affects not only capacity of lower rank movements, but also affects impedance of lower rank movements. This problem is presented in Section 4.4.

4.3.3 Impact of shared opposing lane for the left turn movement and impeding movement.

For the two impeding movements from the opposing minor approach (through and right turn movements from the approach D) calculations were performed in order to check an impact of the left turn movement (DL) from the shared lane on the analyzed impeding movements. Opposing left turn movement is not an impeding movement, but its vehicles arriving to the first position in queue block vehicles of two other impeding movements; through and right turning movements. Figures 7 present charts of relationships of the impedance factor f_d and the ratio of capacity utilization ρ of the impeding movements, i.e., through and right turn movements from approach D at various rates of left turning vehicles at this approach D (u_{DL} = 0, 15, 25, 35 and 50 %).

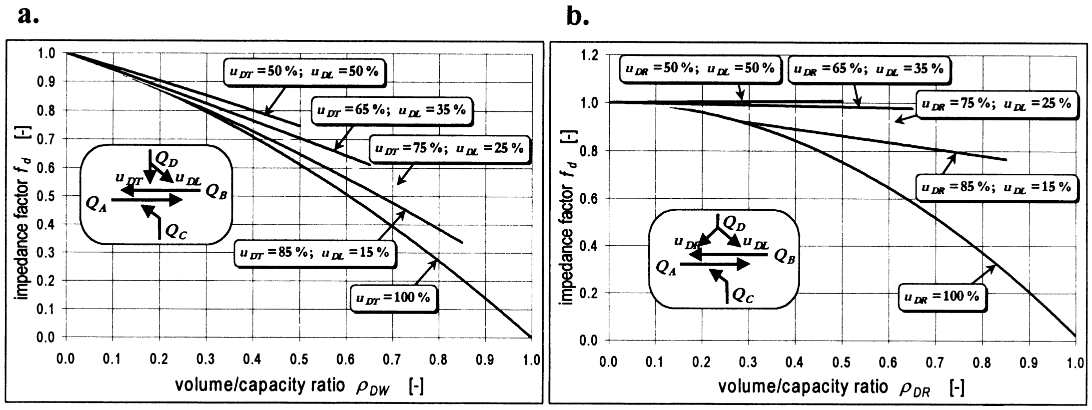

FIGURE 7 Impact of left turn movements on effects of impedance by (a) through and (b) right turn movements from the opposing minor street approach.

The obtained relationships show, that with an increasing rate of the left turn movement u_{DL} from the approach D, the impedance factor increases and the impact of the impeding movements on capacity decreases. Impact of the left turn movement from the approach D is greater for the impeding right turn movement from the approach D and at value of u_{DL} = 50 %. Blocking of the impeding movements by the left turn movement from the opposing minor approach was partly included in the models of total impedance.

The possibility for passing of waiting through and left turning vehicles from approach D by the right turning vehicle in the flaring zone (due to curvature) can also have an impact on the impedance effect. As in this case there is a shared lane and only the first vehicles in the queue can use the flaring zone, it is suggested to take the average value of impedance factor between separate and shared lane cases.

4.4 Effect of Impedance at Demand Flows Filtered by Traffic Signals

Potential impact of the adjacent traffic signals — producing filtered traffic flow demands at the considered priority intersection on impedance was also investigated. In comparison to the analytical models, the impact of adjacent traffic signals should not be significant if capacity of the impeding movements is correctly estimated. In these models only capacity of the impeding movements determines the probability of a state without a queue and possibility of departures of the impeded movement vehicles. In the analytical models random arrivals of vehicles are assumed. In practice, major road flows and particularly the impeding movements can be characterized as partly random, since a part of the vehicles arrive in cyclic platoons from adjacent traffic signals. It can result in significant differences between a theoretical model and real progression of traffic.

The effect of impeding of minor road movements by a 2nd rank stream was investigated in detail. This concerns the left turn movement from the major road at 3-arm intersection affected by adjacent traffic signals. There is a shared lane for through and left turn traffic. Various ratios of capacity utilization of the impeding movement and various values of offset ϕ (Figure 8) between platoons arriving to major road approaches of the priority intersection from adjacent signalized intersections were modelled.

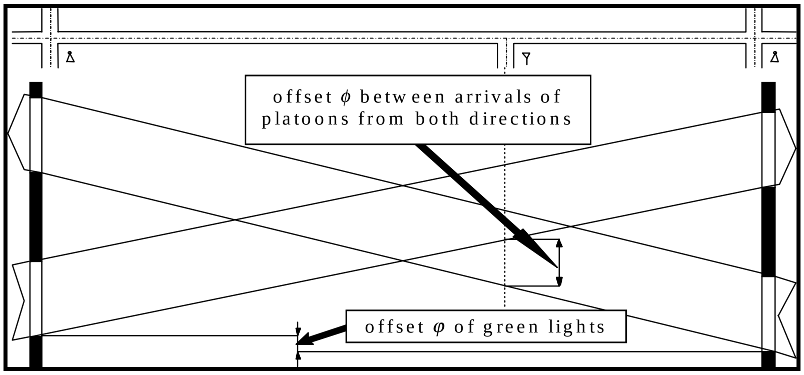

FIGURE 8 Illustration of offsets φ and ϕ.

Figure 9 presents relationships between the impedance factor f_d and the ratio ρ of utilization of capacity of the impeding left turning movement from the major road for the major road volumes Q_{AB} = 700 and 1300 veh/h. The impact of the flow filtering is presented at bi-directional impacts of traffic signals, i.e., at cycle length c = 70 and 90 s and at extreme cases of impacts of offset $\phi = 0$ and 0.5 c. For comparison, the charts show also relationships derived for the random arrivals.

For all of the considered cases, i.e., for an isolated intersection (random demands) and for intersections affected by adjacent traffic signals (filtered demands), the impedance increases with the increase of the ratio ρ of the impeding movement utilization. It takes various values for the same ρ depending on the type of arrivals on the major road (random or filtered by traffic signals) and on the offset ϕ.

In relation to the random arrivals, the adjacent traffic signals can both increase or decrease the impedance depending on the offset ϕ. In practical ranges of left turn rates from the shared major road lane, greater impedance (up to 15 % greater than at random arrivals) occurs with simultaneous arrivals of traffic platoons from adjacent traffic signals (at $\phi = 0$ s). Despite of increased impedance by the left turn movement from the major road, capacity of minor road is still greater than at random arrivals on the major road.

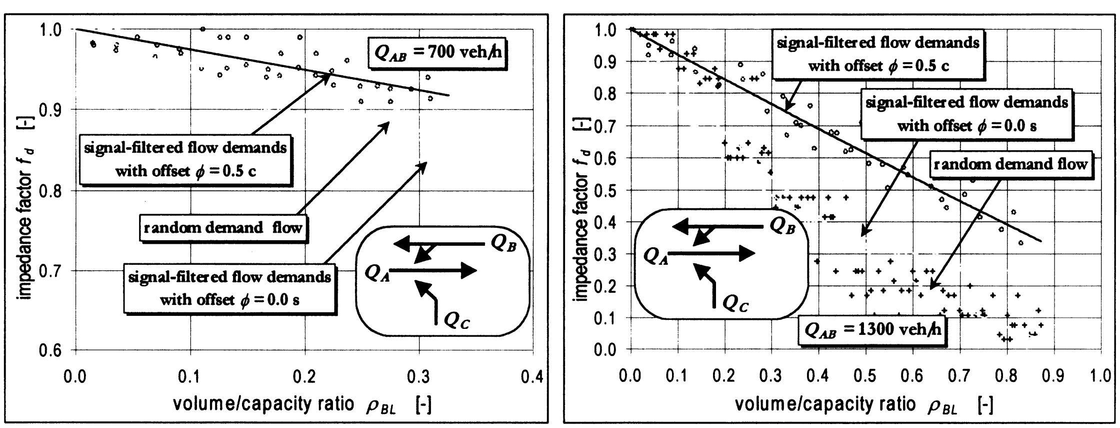

FIGURE 9 Comparison of impedance factors computed for various modelled flows demands.

Alternate arrivals from adjacent traffic signals ($\phi = 0.5$ c) decreases effects of impedance by major road left turn. Reduction of minor road approach capacity with increasing ratio of left turning vehicles from the lane is smaller in relation to the case with random arrivals. In this case ($\phi = 0.5$ c) capacity of minor road approach is higher than at random arrivals only at high ratios of left turning vehicles from the major road.

5. CONCLUSIONS FROM THE SIMULATION STUDIES

Total impedance, determined by the multiplicative model product of impedance factors, according to results of simulation is overestimated at low capacity utilization of the impeding movements and underestimated at high capacity utilization. The derived correcting functions improve estimation of the total impedance factor from the multiplicative model for the 3^{rd} rank movements and 4^{th} rank movements.

Impacts of adjacent traffic signals, producing filtered flow demands at priority intersection approaches are comprehensive. Therefore in a practical method of capacity estimation adjustment for impedance of the potential capacity determined for the simple case of crossing of priority and lower rank streams is not sufficient and effects of impact of adjacent traffic signals also should be taken into account. Correction of the impedance factor should be proportional to the offset of platoons arrivals (i.e., offset ϕ) and the lengths of the platoon.

It should be pointed out that the size of impedance is significantly affected by the lane assignment and by sharing or not of a traffic lane by impeding and not impeding movements as well as by such factors as traffic volume and its directional distribution on major road and by flow demands filtered by adjacent traffic signals. Including all these impacts is possible by applying the simulation model.

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