Model of Running Time Disturbances for Buses Using Designated Lanes on Approaches to Junctions Equipped with Traffic Signals

Marek Bauer
Department of Transportation Systems
Cracow University of Technology
Cracow, Poland
e-mail: mbauer@pk.edu.pl

***Abstract*—The efficiency of designated bus lanes is very differentiated. This is an effect of the influence of many disturbing factors and the lack of determination and consequence in privileging buses. Problems are mostly seen on the approaches to junctions equipped with traffic signals. In this paper, the factors influencing onto bus running conditions on the designated lanes were classified, as well as the model of bus traffic disturbances at approaches to junctions with traffic signals. The partial elements of the model (e.g., queue clearing time, stopping time in bus lane at approach to junction) were estimated with regression models using. Also, the methods of reducing losses of bus travel time at approaches to junctions were presented. Finally, the micro simulation of bus running time at approaches to junctions with traffic signals in different traffic conditions were executed. Was proved that the reduction of queues in bus lanes may be achieved through shortening the section of the bus lane which is open for vehicles taking a right turn or through the separation of additional, external traffic lane for turning right vehicles, off the bus lane.**

Keywords-bus lane; signalized junction; running time.

I. INTRODUCTION

Designated bus lanes belong to a group of efficient measures designed to privilege public transport vehicles. Agrawal, Goldman and Hannaford [1] described a large set of advantages for the adoption of designated bus lanes. Bus travel conditions are significantly better in dedicated lanes than in lanes used by other vehicles. Dedicated lanes enable attaining higher travel speeds, favor improved punctuality and regular bus runs [2]. Thus, they boost the attractiveness of the public transport, which translates into an increased number of passengers travelling by buses using dedicated traffic lanes. They help in better bus routing (Molecki, [3]) and strongly increase the capacity of the whole public transport systems, as described by Fernandez and Planzer [4]. However, even upon dedicating a traffic lane, the preservation of consistent, beneficial travel conditions for buses is impossible in many cases. Schedule speeds in the aforementioned segments are significantly higher than speeds which would be attained if bus lanes were absent and buses travelled in open-access lanes among other vehicles. It would be expected that average schedule speeds, even in a section so greatly encumbered with public transport vehicle traffic, should at least amount to 20 [km/h]. Therefore, we should ponder upon the causes – specifically, what are the factors disturbing bus traffic in dedicated lanes and how can they be prevented. A simulation approach can be very helpful in solving such problems. Micro simulation models describing bus movement on designated bus lanes were presented in [5], [6] and [7].

In Section 2, we present the factors influencing buses running on the sections with designated bus lanes. In Section 3, we present the model of bus traffic disturbances at approaches to junctions with traffic signals. Sections 4 and 5 explain the results of estimations of queue clearing time and queue motion time. Section 6 presents the methods of reducing bus time losses at approaches to signalized junctions. In Section 7, an example of possible simulation results is presented. Finally, Section 8 presents the conclusion of the paper.

II. DISTURBANCES IN SECTIONS EQUIPPED WITH BUS LANES

Running time of buses was considered in many publications, e.g., by Diab and El-Geneidy [8]. Bus traffic disturbances result from a complex influence of many factors, which more or less affect bus travel times, also in sections with dedicated bus lanes. Many of the factors are of random nature and these factors are greatly responsible for travel disturbances. These are:

- Factors related to traffic in dedicated bus lanes – this is a group of factors with the highest influence on bus travel conditions within sections, junctions and bus stops: the size, the variability and the structure of traffic volumes of buses and other vehicles (taxis and other vehicles authorized to use the lane), the size, the variability and the structure of traffic volumes of vehicles using the lane at the approach to a junction in order to take a right turn.
- Behavioral factors encompassing behaviors of all road users including bus drivers (driving skills, discipline, psychophysical characteristics), caused by the size of the current advancement or delay in reference to the time table – motivating towards a slower or a faster bus driving.

 ISBN: 978-1-61208-371-1

- Environmental factors, among which are: season, daytime, day type, atmospheric conditions.

Additionally, disturbances on sections with bus lanes may result from factors of a directly deterministic nature, which themselves are not sources of disturbance; on the contrary, they represent solutions, whose goal was to aid the operation of bus transport. The influence of deterministic factors on bus travel disturbances results, most often, from either insufficient range and consistency in implementing particular infrastructural solutions or their low resistance to intensified activity of random factors. Disturbances may also result from a traffic organization which is insufficiently promoting public transport vehicles and from incorrect planning of services. Deterministic factors may be generally classified as follows:

- Factors related to the infrastructure of designated bus lanes, such as: the width and the length of the section, the scope and the manner of separation from open-access lanes (use of markings or, additionally, physical separation e.g., green lane, concrete or plastic separators).
- Factors related to other elements of the infrastructure of streets with designated bus lanes: the number of traffic lanes in the street section, the amount of junctions with and without traffic signals, the number and location of designated pedestrian crossings.
- Factors related to the infrastructure of junctions and bus stops located within bus lanes, such as: the type of the traffic organization at junctions, the manner of conduct of conflict-point maneuvers, the number of traffic lanes (especially at the approach), the location of the stop (near side or far side the junction area), the occurrence of stop lines and possibly the distance between the line and the bus-stop shelter, the position of the stopping position in relation to the face of the stop, the amount of stands and their location, the width of the side platform, the location of neighboring pedestrian crossings.
- Factors related to the traffic organization, especially at approaches to junctions: the manner of the traffic organization at the junction, including the type of control, the scope and the form of assigning priorities in traffic signals, the quality of signaling, the dedicated traffic lane availability monitoring.
- Factors related to the transit organization, including: the frequency of bus runs and other public transport vehicles, the level of viability of time tables, the scale and the scope of dispatch control; the frequency of inspections checking the quality of transit services, the form of ticket distribution (an on-board ticket machine, tickets sold by the driver).
- Rolling stock factors – the technical characteristics of the fleet influencing the attainability and the upkeep of the desirable speed (the ability to accelerate and brake) and the efficiency of passenger alighting and boarding processes (the capacity of the vehicle, the bus floor height at entrances and other parts of the bus, the number of doors and their width, the number of entrance steps, the sitting and standing area structure and arrangement), failure frequency.

Some of the influences (e.g., drivers' psychophysical and motoric characteristics) are almost unmeasurable in real conditions, while other influences (e.g., the number of passengers giving way to passengers alighting from the bus) are hard to study due to technical issues in executing sufficiently accurate measurements. Rarely do the bus travel disturbances result from a single, easily distinguishable factor. It is most often a cumulated effect of numerous factors, especially in junction areas. The current paper contains the analysis of the issue of time wasted by buses which are stopped in queues at approaches to junctions with traffic signals.

III. Model of Bus Traffic Disturbances at Approaches to Junctions with Traffic Signals

Assigning right curbside bus lanes, which may be also used by vehicles taking a right turn at the nearest junction, is a very popular solution in European cities. The dedicated lane is open for vehicles taking a right turn in a set distance from the stop line, which helps car drivers to avoid a complicated relation at the approach to the junction. Hence, the traffic stream at the approach has a mixed nature [9] and its structure and length greatly defines the conditions for the bus travel through the junction.

The reference point of this analysis is a single stop-to-stop section with only one signalized junction located in the final part of the section. This section can be divided into two units (Figure 1): the longer part of the section between the head of the bus stop and the stopping line at the approach of junction (S_1) and the smaller part of the section – between junction stopping line and the head of the next bus stop (S_2). In this case, both bus stops are located far side signalized junction. This approach enables a comparison of time lost in a single intersection in relation to undisturbed running time of the section.

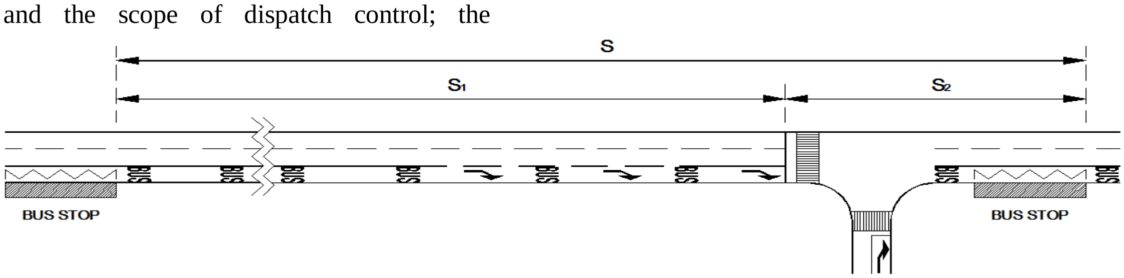

Figure 1. Description of model: stop-to-stop section with designated bus lane and one signalized junction in final part of this section.

A. Undisturbed bus riding the bus lane through the signalized juntion

If vehicles taking a right turn appear at the green signal and are able to leave the bus lane smoothly (the situation at the exit of the junction allows it), then the blockage of buses is occasional. This situation is presented in Figure 2; traffic volume on the bus lane is small, and even in case of significant parallel stream of pedestrians, the bus is able to cross the junction with desired speed.

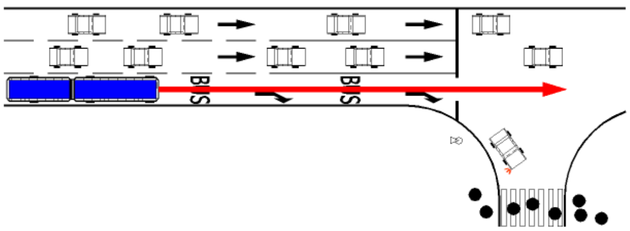

Figure 2. Small traffic volume on the bus lane at the approach to signalized junction, without significant influence onto bus movement.

This is the most convenient situation for passengers of a bus. In case of not extremely long sections, running time consists of acceleration time (during departure from stop), time of running with desired speed and deceleration time before next stop. Acceleration and deceleration times can be estimated with acceleration and deceleration rates - most often, they are values in the range from 0.6 to 1.1 [m/s^2]. The running time of the main part of the section depends mainly on speed limits. In [10], average bus running time T_r [s] on the section with designated bus lane, in close to free traffic conditions, was described as the function of stop-to-stop section's length L [km]:

$$\overline{T}_r = 0.065 \cdot L + 21 \qquad (1)$$

For such a function, the best fit to the results of measurements carried out on the sections equipped with bus lanes in case of close to free bus traffic conditions, in two Polish cities (Cracow and Warsaw) – has been provided. This model is very useful in meso scale transportation planning, but it is not possible to evaluate bus traffic conditions at the approaches to the signalized junctions.

Therefore, we decided to carry out a more detailed analysis with the section travel time separation for: the acceleration time during departure from stop, the time of running with desired speed and deceleration time, just before the next stop on the section. This kind of stop-to-stop running time description has been proposed by Vuchic [11]. There were taken into consideration two cases of bus running in the middle part of the stop-to-stop section:

- Running with (desired) constant speed, chosen by bus driver;
- Running with no constant speed, with coasting – which is an effect of economic driving with respect to energy consumption. In this case, motion at a constant deceleration takes place over almost the entire length of the section.

In the first case, the bus running time can be estimated by using the formula:

$$T_r = \frac{S}{v_{\max}} + \frac{v_{\max}}{2}\left(\frac{1}{a} + \frac{1}{b}\right) \qquad (2)$$

where:
T_r – running time of the section [s];
S – length of the stop-to-stop section [m];
v_{max} – maximum speed on the section [m/s];
a – average acceleration rate[m/s^2];
b – average deceleration rate[m/s^2].

Whereas, in the second case, it is:

$$T_r = v_{\max} \cdot \left(\frac{1}{a} + \frac{1}{b}\right) + v_c \cdot \left(\frac{1}{b} - \frac{1}{c}\right) \qquad (3)$$

where, additionally:
v_c – speed at the end of the coasting interval [m/s];
c – constant deceleration rate until braking must be applied [m/s^2].

Both formulas have been used in stop-to-stop running time calculations for sections with lengths ranging from 350 to 800 [m] – the same range of sections' lengths was used in (1). In case of running with constant speed, the best fitting to the measurements' results was obtained for acceleration rate equals to 0.70 [m/s^2], deceleration rate 0.80 [m/s^2] and maximum speed 54.0 [km/h]. Whilst, in case of stop-to-stop running with coasting, there were obtained – successively: 0.70 [m/s^2], 0.75 [m/s^2] and 59.5 [km/h]. Additionally, constant deceleration rate equals 0.1 [m/s^2]. Results of this comparison are presented in Figure 3.

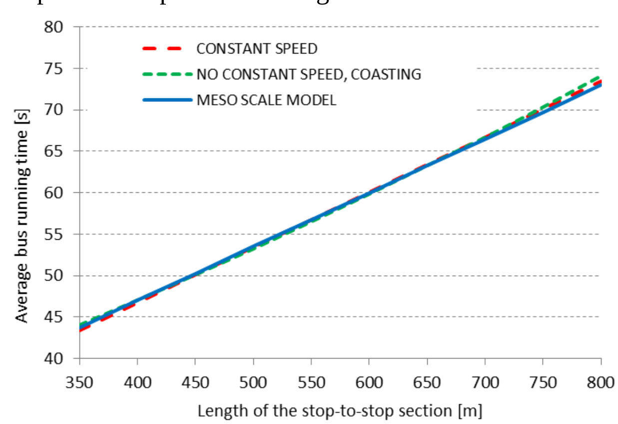

Figure 3. Comparison of stop-to-stop section running times in dependence of the length of the section and the method of running time estimation.

Generally, (1) and (2) could be used in bus running time description. Taking into account adaptation to changes in speed, registered in short intervals, it was decided that the model with constant speed will be used in further analysis.

 ISBN: 978-1-61208-371-1

B. Bus stopping on the first position at the approach of the signalized junction

When the bus has to stop at the stopping line and there is no vehicle in front of it – the amount of time lost depends mainly on the length of the red signal. This situation is presented in Figure 4.

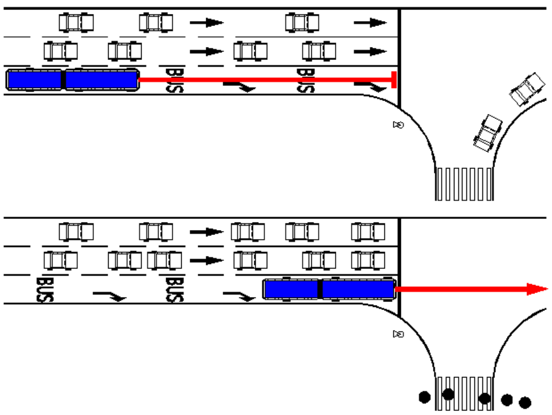

Figure 4. Bus stopping at the approach of the signalized junction, due to the red signal.

In this case, the running time is the sum of the time period from the moment of departure from stop to the moment of stopping at the junction stopping line (t_{S1}), the time of waiting for a green signal (t_w) and the time period from the moment of bus starting from junction stopping line to the moment of stopping the bus at the bus stop (t_{S2}):

$$T_r = t_{S_1} + t_w + t_{S_2} \tag{4}$$

The time period from the moment of departure from stop to the moment of stopping at the junction stopping line can be estimated from (2) for S_1 distance. The waiting time at the red signal usually results from a lack of implementation of traffic signal prioritization at the approach to the junction. It should be determined as an average value based on traffic lights structure. In order to determine the time period from the moment of bus starting from junction stopping line to the moment of stopping at the bus stop, the following formula can be used:

$$t_{S_2} = \sqrt{\frac{2 \cdot (\bar{a} + \bar{b}) \cdot S_2}{\bar{a} \cdot \bar{b}}} \tag{5}$$

where:
S_2 is the length of the section between junction stopping line and the stop [m].

Most frequently, (5) is used for stop-to-stop running time estimation, when the length of the section is shorter than the critical distance – the running time is composed exclusively of acceleration and deceleration times, because it was assumed that the junction is located at final part of the stop-to-stop section; such an approach is empowered. Finally, the stop-to-stop running time in case of bus stopping on the first position at the approach of the signalized junction one can estimate by using the formula:

$$T_r = \frac{S_1}{v_{\max}} + \frac{v_{\max}}{2}\left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}}\right) + t_w + \sqrt{\frac{2 \cdot (\bar{a} + \bar{b}) \cdot S_2}{\bar{a} \cdot \bar{b}}} \tag{6}$$

where:
S_1 – length of the section between head of the stop and the junction stopping line[m];
S_2 – length of the section between junction stopping line and the following stop [m].

C. Bus stopping in the queue at the approach of the signalized junction

When traffic volume of right turning vehicles at the junction is significant, buses often stop in the queue. This may result in a significant increase of time lost, especially when the queue is long and/or the parallel pedestrian stream is blocking vehicles turning right. Figure 5 shows this phenomenon.

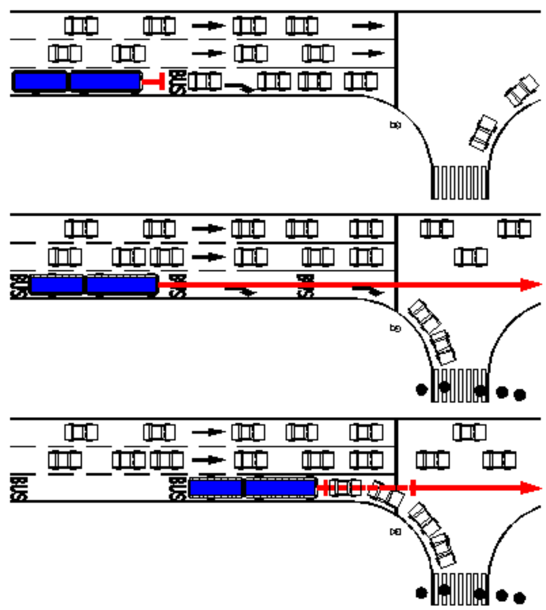

Figure 5. Bus stopping in the queue at the approach of the signalized junction.

If the number of vehicles at the approach is low (usually, no more than 2-3 vehicles) and time lost narrows down to the time needed to stop at the red signal, and the time necessary to clear the queue amounts to several seconds. If, for example, there are two vehicles stopped in front of a bus, after the signal changes to green, they commence a right turn and stop in front of a pedestrian crossing, causing no blockage for the bus, which also resumes the travel.

However, the situation changes significantly, when at the same approach to the junction, the flow of vehicles taking a right turn is longer than the accumulation section before the pedestrian crossing. Then, each consecutive vehicle preceding the bus in the queue will block its motion and force an additional halt. The loss of time resulting from the time necessary to clear the queue will extend. Certainly, if the halt was short, the length of the time lost at the junction would be acceptable. However, if the length of the queue is significant and the traffic situation at the exit of the junction (influenced by a congestion or, more often, by pedestrian movement at the parallel crossing) prevents the queue from clearing smoothly, the bus will lose a significant amount of time. At worst, it will lose the opportunity to cross at the current green signal and the time lost will be extended further due to the necessity to wait for next green light.

When a bus stopping at the approach to the signalized junction takes place in the queue (K), two additional time processes have to be introduced. These are:

- Queue clearing time (t_{qc}), defined as the time period from the moment the green signal appears to the moment the bus moves onward from the queue;
- The bus queue motion time (t_{qm}), concerning the queue which formed in front of the bus at the approach to the junction, which is counted from the moment the bus moves onward from the queue to the moment it crosses the stop line at the junction.

In Polish conditions, it is often assumed that every car in the queue equals 6.0 [m] in average. Other kinds of vehicles should be recalculated for cars (e.g., one heavy goods vehicle or one articulated bus in queue – equals 3 cars). If K=1 or K=2, there is no additional blockage for the bus, and the bus running time can be calculated using the formula:

$$T_r = \frac{S_1 - 6K}{v_{\max}} + \frac{v_{\max}}{2}\left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}}\right) + t_w + t_{qc} + \sqrt{\frac{2\cdot(\bar{a}+\bar{b})\cdot(S_2+6K)}{\bar{a}\cdot\bar{b}}} \quad (7)$$

Whereas, when K>2:

$$T_r = \frac{S_1 - 6K}{v_{\max}} + \frac{v_{\max}}{2}\left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}}\right) + t_w + t_{qc} + t_{qm} + \sqrt{\frac{2\cdot(\bar{a}+\bar{b})\cdot S_2}{\bar{a}\cdot\bar{b}}} \quad (8)$$

The queue clearing time and the queue motion time – depend mostly on the amount of vehicles placed in front of the bus and on the traffic situation at the exit caused by the pedestrian traffic at the crossing parallel to the bus lane.

IV. DEPENDENCE BETWEEN QUEUE CLEARING TIME AND LENGTH OF QUEUE

The study on the influence of the length of a queue on the queue clearing time includes the total number of 415 halts at approaches, including 105 instances of queues consisting of 1 to 20 vehicles. The best match was achieved by a simple nonlinear regression model:

$$t_{qc} = \sqrt{18.9 + 2.0\cdot K^2} \quad (9)$$

A graphic representation of the model, matched with the measurement data output, is shown in Figure 6, which also includes the confidence interval (marked with dotted lines), based on a level of confidence of 95%.

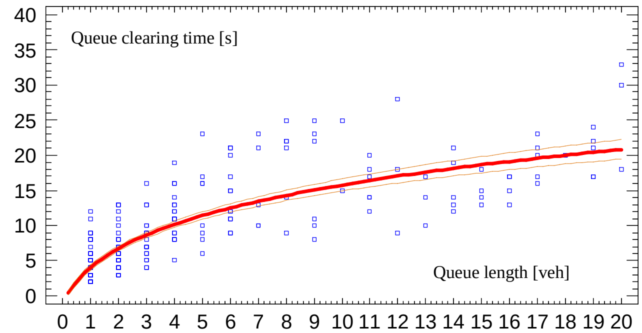

Figure 6. Dependence of queue clearing time from queue length.

The correlation coefficient for this match amounted to 0.93, which translates into a strong relation between the variables.

V. ESTIMATION OF BUS QUEUE MOTION TIME

Moreover, the analysis of the influence of the length of a queue on the queue motion time includes the results of 1237 bus halts at approaches to junctions, including 263 instances of queues consisting of 1 to 20 vehicles. The analysis does not concern instances in which the buses did not manage to cross the junction during a single signal cycle; those instances will be contained in future research. The best match between a regression model and the measurement data output was achieved with a nonlinear regression model:

$$t_{qm} = (2 + 0.856\cdot \ln K)^2 \quad (10)$$

A graphic representation of the model, matched with the measurement data output is shown in Figure 7.

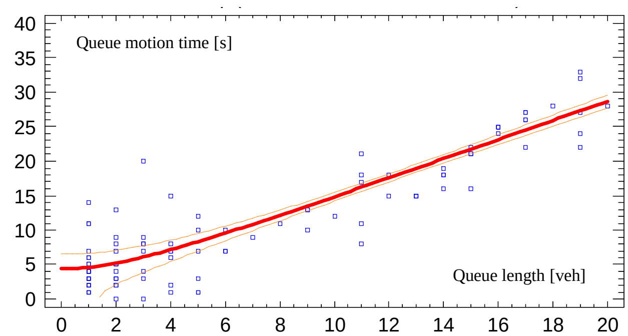

Figure 7. Dependence of queue motion time from queue length.

This time, the correlation coefficient for this fitting amounted to 0.84, which can be considered a strong relation between queue motion time and the length of queue.

VI. METHODS OF REDUCING LOSSES OF BUS TRAVEL TIME AT APPROACHES TO JUNCTIONS

A reduction of queues in bus lanes at approaches to junctions may be achieved through shortening the section of the bus lane which is open for vehicles taking a right turn. If it is too long, the possibility of extending a queue in which a bus may be halted increases. Shortening this section allows to regulate the length of a queue in front of a bus at the approach to a junction – upon the implementation of this solution, vehicles taking a right turn would have to use the open-access lane until the place where the bus lane is open for those taking a turn, which would lead to a decrease in the number of vehicles placed in front of a bus at the approach to a junction. It is a solution which may be recommended for areas of particularly long time lost, where the probability of the queue not being cleared throughout the duration of the green signal – is substantial. Buses often need to wait for the next green traffic signal. Significant reduction of time lost can be also achieved by the activation of a right-turn green arrow at the approach to the junction, which will enable a partial queue clearance during the green signal.

A very efficient solution can be the separation of additional traffic lane for turning right vehicles – outside the bus lane (if it is spatially possible). In that case, the influence of disturbances caused by an excessive traffic of vehicles taking a right turn on the bus traffic is being practically eliminated. The only contact between these vehicles and the bus lane is when they cross it. If the number of vehicles taking a right turn is so great that the queue for the right turn starts in an open-access lane, assigning even two lanes outside the bus lane while simultaneously taking care of a clear signing for the bus lane is worth considering.

VII. EXAMPLE OF BUS RUNNING TIME SIMULATION ON THE SECTION EQUIPPED WITH BUS LANES, WITH ONE SIGNALIZED JUNCTION

Four scenarios of bus operation on single stop-to-stop section at a length 500 [m], equipped with designated bus lane were taken into consideration. On the whole length of this section, only one signalized junction is located. At the approach to this junction, all vehicles turning right use this bus lane. The length from the stop to the stopping line of the junction is 440 [m]. The following scenarios are considered:

- Scenario S1: bus crosses the junction with constant speed, without stopping at approach to the junction;
- Scenario S2: bus stops at the junction stopping line, on the first position (no queue);
- Scenario 3: bus stops in third place in the queue at the approach to the junction (K=2);
- Scenario 4: bus stops in sixth place in the queue at the approach to the junction (K=5).

Table I presents the values of the time lost per bus, in the considered scenarios. In scenarios 2, 3, and 4, the time of waiting for the green signal is relatively short – it is 20 [s]. Even, if we ignore it, the time lost in scenarios S2, S3 and S4 in comparison to S1 are significant.

TABLE I. SIMULATION RESULTS

Scenario	Bus running time, without t_w [s]	Total bus running time [s]
S1	53.4	53.4
S2	67.4	87.4
S3	73.4	93.4
S4	85.1	105.1

The length of the queue is important as well, its shortening about 3 vehicles (S3 and S4) saves almost 12 [s] per bus. Having considered the number of passengers on a bus, assuming that section is used only by 1000 [pers./h] – the difference between scenarios S1 and S4 in losses of passengers' time during only one hour – amount to 14.36 [h].

VIII. CONCLUSION AND FUTURE WORK

Familiarity with mechanisms of origin of bus traffic disturbances may be helpful in implementation of fully efficient means of bus privileging in traffic. Long queues of vehicles result in far-off positions of buses at the approaches to signalized junctions, and consequently, in time lost for buses. Limitation of the time lost can bring serious benefits for passengers and public transport operators. The results of the presented analysis can be used to improve bus traffic in Polish cities. They may also constitute a word of warning against the implementation of too long sections of shared-access to bus lanes. The methodology can be used also in other countries, it is only necessary to carry out the control tests of the queue clearing time and the queue travel time, taking into account the local conditions of bus traffic. In further studies, the model will be complemented by a priority in traffic lights.

REFERENCES

[1] A. W. Agrawal, T. Goldman, and N. Hannaford, "Shared-Use Bus Priority Lanes on City Streets: Approaches to Access and Enforcement," Journal of Public Transportation, vol. 16, no. 4, 2013, pp. 25-41.

[2] A. Tirachini and D. A. Hensher, "Bus congestion, optimal infrastructure investment and the choice of a fare collection system in dedicated bus corridors," Transportation Research Part B: Methodological, vol. 45, issue 5, 2011, pp. 828–844.

[3] A. Molecki, "The Meaning Of Different Limiters Relations For Defining Public Transport Routes Capacity," Transport Problems, vol. 1, 2007, pp. 95-100.

[4] R. Fernandez and R. Planzer, "On the capacity of bus transit systems," Transport Reviews: A Transnational Trans-disciplinary Journal, vol. 22, issue 3, 2002, pp. 267-293.

[5] X. Chen, L. Yu, L. Zhu, J. Guo, and M. Sun, "Microscopic Traffic Simulation Approach to the Capacity Impact Analysis of Weaving Sections for the Exclusive Bus Lanes on an Urban Expressway," Journal of Transportation Engineering, vol. 136, issue 10, 2010, pp. 895–902.

[6] V. T. Arasan and P. Vedagiri, "Bus Priority on Roads Carrying Heterogeneous Traffic: a Study using Computer Simulation," EJTIR, 8, no. 1, 2008, pp. 45-64.

[7] L. A. Koehler and W. Kraus Jr., "Simultaneous control of traffic lights and bus departure for priority operation," Transportation Research Part C, vol. 18, 2010, pp. 288–298.

[8] E. I. Diab and A. M. El-Geneidy, " Understanding the impacts of a combination of service improvement strategies on bus running time and passenger's perception," Transportation Research Part A 46, 2012, pp. 614–625.

[9] J. Chodur, K. Ostrowski, and M. Tracz, "Impact of Saturation Flow Changes on Performance of Traffic Lanes at Signalised Intersections," Procedia - Social and Behavioral Sciences, vol. 16, 2011, pp. 600–611.

[10] M. Bauer, "Bus Running Time onto Sections with Designated Bus Lanes Modelling," Logistyka 2014, in press.

[11] V. R. Vuchic, "Urban Transit Systems and Technology," John Wiley & Sons, Inc., Hoboken, New Jersey 2007.

 ISBN: 978-1-61208-371-1