

# Simulation of the Influence of Curb-Parking on the Efficiency of Designated Curb Bus Lanes

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**Abstract**—This paper discusses the influence of curb parking on speeds of buses on designated bus lanes. This is a universal practical problem, its solution would aid the running of buses in many cities. This is also an important issue from the point of view of the construction of the simulation models used in the planning and design process, overly optimistic values of bus speeds are often adopted, and these can be very difficult to achieve after implementation of the planned solutions. The main tool in this discussion is the author's own probabilistic model of conflict between running buses and parking cars. This model states the part of comprehensive bus lane studies in Polish cities, leading to develop a scientific method of traffic organization within the right curb bus lanes. The model is based on the real measurement of the results of bus running times and parking facilities. The paper presents the results of the duration of parallel parking maneuvers by buses and cars within designated bus lane space and the time of occupying the potential conflict area in the separated lane. In this analysis, inter alia – bus driver's decision time and the time required for safe bus stopping are considered. The presented model can be used in simulations of the effects of curb-parking on bus speeds, in relation to different frequencies of parking maneuvers.

**Keywords**—urban transport; bus lane; curb-parking.

## I. INTRODUCTION

Designated lanes for bus public transport are an effective tool of transport policies, the objective of which is to increase the share of trips effected by public transport, as described in [1]. Thus, they form part of the group of highly relevant issues for managing mobility in cities. Dedicated lanes provide far more advantageous conditions for bus transit than lanes used by the generality of vehicles. They enable buses to reach high speed, contribute to an increasing punctuality and regularity of service. In Polish conditions (including Cracow), mostly right curb bus lanes have been introduced. Their greatest advantage is the ease of locating bus stops on the pavement, i.e., directly by the lane [2]. They are, however, susceptible to disturbances largely resulting from traffic signaling systems, the movement of vehicles turning right involving bus lane usage and due to maneuvers related to the service of buildings located in the immediate vicinity of the bus lane, including sidewalk parking [3]. These factors are characterized by substantial randomness of

impact and the impossibility of their mutual separation. An illustration of these problems is shown in Figure 1.

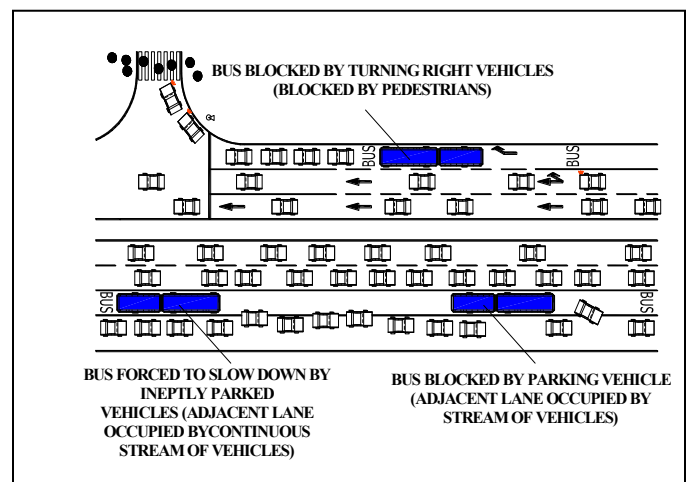


Figure 1. Disadvantages of right curb bus lanes (own work).

The negative impact of vehicles parking on the sidewalk results directly from the necessity for parking cars to use the bus lane, and also from bus drivers' apprehension to drive faster in conditions of limited visibility. In current research in Cracow (unpublished own research), it has been established that the average speed of buses on sections with bus lanes where sidewalk parking is permitted is on average 2.3-4.3 [km/h] (section lengths: 0.3 – 0.7 [km]) lower than where it is not allowed. This means a significant decrease in average speed, amounting to between 13 and even up to 22 [%]. Yet, the fact cannot be ignored that sidewalk parking is regarded as being particularly convenient for car users due to its relatively short parking operation time and quick access to journey destinations located in the immediate vicinity of the parking spaces. In this context, it is crucial to determine the scale of the difficulty of sidewalk parking for bus traffic. This is of even greater importance, because increasingly frequently paid parking areas are being introduced in Polish cities, which is an highly efficient method of restricting car traffic in central city districts.

In Section 2, the probability model of conflict between running bus and parking car is presented. Section 3 includes the results of the duration of parking maneuvers, whilst in

Section 4, the time of occupying the potential conflict area on a separated bus lane is analyzed. Section 5 presents a practical application of the model. Finally, Section 6 presents the conclusion of the paper.

## II. THE MODEL OF CONFLICT: RUNNING BUS VERSUS PARKING VEHICLE

Various possible solutions to the given problem, including the queueing theory, were taken into account. However, at the stage of the construction of the model, it was found that to describe the influence of sidewalk parking maneuvers on bus running time on a dedicated bus lane, reliability theory [4] is most useful. In this fully individual approach, the reliability structure of a system presents the manner of mutual connections of components, determining the dependency of system failures on failures of its elements. In the case of a section with sidewalk parking allowed right next to the bus lane, the system elements are the subsequent points on the bus lane, where a running bus and parking vehicle can meet [5]. This is an approach used in models of discrete events. However, the case here is not the probability of physical collision but specification of the probability of disturbances in bus running as a result of a parking vehicle [6]. This was defined as the probability of conflict between a running bus and a parking vehicle. The system will be unreliable if a bus driver, traveling along a dedicated bus lane is not be able to continue at the chosen speed as a result of a parking maneuver. When seeing a vehicle being parked (or a vehicle preparing for such a maneuver), the driver has three possibilities: he can slow down or change the lane or even stop the bus on the separated lane. All of these options are a waste time for passengers [7]. Since conventional parking spaces are located sequentially along the bus lane, it can be stated that the system has a serial reliability structure in which inefficiency of any component causes inefficiency of the entire system. In other words, a maneuver related to parking on one of the parking lots impacts on the reaction of a bus driver, even if the distance from the potential conflict place is significant. In general, the system unreliability function describing the probability of the conflict between a running bus and parking vehicle has the following form:

$$\Lambda_s(t) = \sum_{i=1}^n \lambda_i(t) \quad (1)$$

where:

$\Lambda_s(t)$  – function of failure intensity of the system, which is a function of intensity of potential disturbances of running time on the analyzed section (as a result of parking vehicles);  
 $\lambda_i(t)$  – function of failure intensity of  $i$ -th component of the system, as a result of a parking vehicle at parking position number  $i$ .

Most often, the peak hour (morning or afternoon) is adopted as the reference point, because of the increased number of parking maneuvers. The model can be simplified by applying average values of intensity of potential running time disturbances; i.e., the same for each parking space, regardless of its location on a section. Then, the average

intensity of disturbances in the bus lane area, right next to one parking space – can be multiplied by the number of parking positions:

$$\bar{\Lambda}_s = n \cdot P(C) \cdot P(A) \quad (2)$$

where:

$\bar{\Lambda}_s$  [No. of maneuvers/h] – average intensity of potential disturbances of running time on the analyzed section, during one hour of analysis;

$n$  [-] – number of effective parking positions at the analyzed section, assuming that in case of unspecified parking positions – one position is on average 6.0 [m] long;

$P(C)$  – probability that a parking car enters the bus lane (taking position or leaving parking position), right next to one parking space, during 1 hour;

$P(A)$  – probability of bus entries into the analyzed section, during 1 hour.

In the proposed approach, the intensity of section running time disturbances is modeled as the product of the probability of a meeting between a parking vehicle and an approaching bus, at the same time and place. These probabilities can be determined, including the time of occupying the separated lane by buses and maneuvering cars, attributable to one parking position.

The time of occupying the potential conflict area on the separated bus lane can be divided into two parts: the bus driver's decision time and the time required for eventual (if needed) safe bus stopping before a maneuvering vehicle. Decision time  $t_{A,d}$  is defined as the time when a bus driver, having diagnosed the possibility of a parking maneuver (taking or leaving a parking position), makes the decision to slow down, stop the bus or change the lane. While the time required for safe stopping  $t_{A,s}$  is defined as the time anticipated by the driver for potential slowing down at a deceleration acceptable for the passengers (Figure 2).

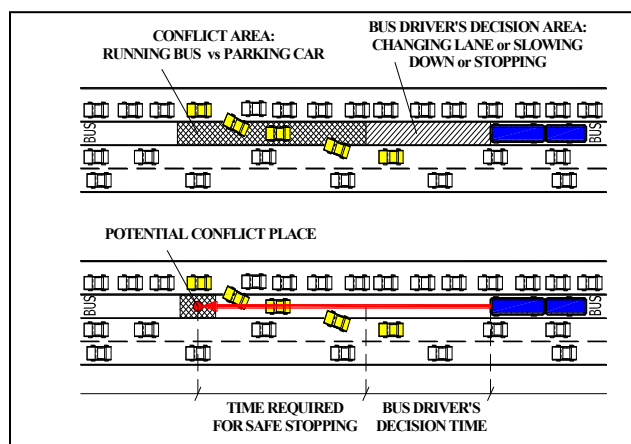


Figure 2. Bus driver's decision time and the time required for safe stopping before a maneuvering vehicle (own work).

Finally, the average intensity of section running time disturbances has the form:

$$\bar{\Lambda}_s = n \cdot \left( \frac{a \cdot \bar{\lambda}_{tp} \cdot \bar{t}_{C,tp}}{3600} + \frac{b \cdot \bar{\lambda}_{lp} \cdot \bar{t}_{C,lp}}{3600} \right) \cdot \left( \frac{c \cdot Q_A \cdot (\bar{t}_{A,d} + \bar{t}_{A,s})}{3600} \right) \quad (3)$$

where:

$\Lambda_{tp}, \Lambda_{lp}$  [veh/h] – average intensity of car maneuvers related to one typical parking position, in the case of – respectively: taking a parking position and leaving a parking position;

$t_{C,tp}, t_{C,lp}$  [s] – average time of typical parking maneuver – respectively: taking or leaving a parking position;

$Q_A$  [veh/h] – bus traffic volume;

$t_{A,d}$  [s] – average bus driver's decision time;

$t_{A,s}$  [s] – average time required for safe bus stopping;

$a, b$  [-] – disturbance factor for – respectively: taking a parking position and leaving a parking position by a single car – values can be estimated on the calibration stage;

$c$  [-] – coefficient of other traffic on bus lane;

all remaining variables – according to equation (2).

This is the classic approach used in traffic engineering, where calculations are often based on the average durations of the traffic processes. However, it should be noted that the choice of a mathematical formula and the choice of model variables are the result of the work of the author.

### III. THE DURATION OF PARKING MANEUVERS

The characteristics of parking maneuvers are similar in European cities. In Polish conditions, the duration of parallel parking maneuvers was measured by Gaca, Suchorzewski and Tracz [8]. They have established that the average full duration of typical parallel parking manoeuvre is 30 [s]. To confirm these values, my own measurements were carried out on one typical street section with a bus lane and parking places located at the sidewalk, right next to bus lane. During a 12-hour video registration, not only was the duration of maneuvers while taking or leaving parking positions taken into consideration, but also the time spent by the parking vehicle on the bus lane, looking for a free space as well as leaving bus lane and taking the general access lane was measured. In a situation when after leaving the parking space a vehicle continued driving on the bus lane, the moment of leaving the entire section was regarded as the time of leaving the lane. The duration of maneuvering only on the sidewalk area was not included, unless its effects could impact the bus traffic on the dedicated lane. Characteristics of maneuvers are shown in Table I.

TABLE I. CHARACTERISTICS OF PARALLEL PARKING MANEUVERS WITH BUS LANE USAGE

Kind of maneuver		Time [s]			
		Minimum	Maximum	Average	Standard deviation
Entry to the position	Time spent on the bus lane	2	19	8	4
	Taking parking position	7	59	20	13
Departure from the position	Leaving parking position	2	26	10	8
	Time spent on the bus lane	4	31	13	8

The results provide a good insight into the time of taking and leaving a parking position located on the sidewalk right next to a bus lane. The more important values are those concerning the time taken to park and then leave positions – these are on average 20 and 10 [s]. However, the additional time spent by a car on the bus lane is also significant. In the case of leaving a parking position – this is on average 13 [s].

The differences in times are caused by the differential characteristics of maneuvers. Drivers taking position are looking for a free space from a distance. In general, they continue driving along the general access lane and change lane only when they see a free parking place. These maneuvers are done under time pressure. In the case of leaving a parking position, drivers must wait for a gap on the bus lane. A maneuver without time pressure is easier to do. Total average time of taking position is 28 [s], but the time of leaving a parking position is 23 [s]. These results are very similar to the general findings from publications presented at the beginning of this Section. So, they can be used in further analysis. Of course, such research should be conducted on a much broader scale, in order to obtain more reliable variables for the conflict model.

On the basis of the above measurement results, it would be difficult to conduct a reliable analysis including the randomness of parking duration caused by different spaces between already parked vehicles and the sizes of vehicles being parked. This should be the next level of studies. Therefore, at the present stage of analysis it has been decided that the study will have a deterministic character. Cases of unlawful car movement on the bus lane were also recorded. These will not be considered in the current analysis.

### IV. TIME OF OCCUPYING THE POTENTIAL CONFLICT AREA ON THE SEPARATED LANE

The model presented in Section 2 can be applied to analyze the increase in probability of conflict between the buses driving on a dedicated bus lane and the cars performing maneuvers related to parking.

#### A. Bus driver's decision time

Firstly, the study focused on the period of time when a bus driver upon seeing a vehicle maneuvering can diagnose the situation and make a decision either to potentially slow down (or stop, or change the lane), or to continue driving at the current speed. The point here, however, is not emergency braking (which can also occur in exceptional situations), but any decrease in speed resulting in longer running time. In the case of a decision to continue driving, without visible danger, more time is required. This is the reason why values from the interval 3-7 [s] were taken into account. A comparison of distances covered during 3-7 [s] are presented in Figure 3.

For example, during 5 [s] a bus driving at a speed of 30 [km/h] covers the distance of 42 [m]. Due to the fact that buses on dedicated lanes often move at a speed of 40 [km/h] and faster, it was decided not to include longer decision times.

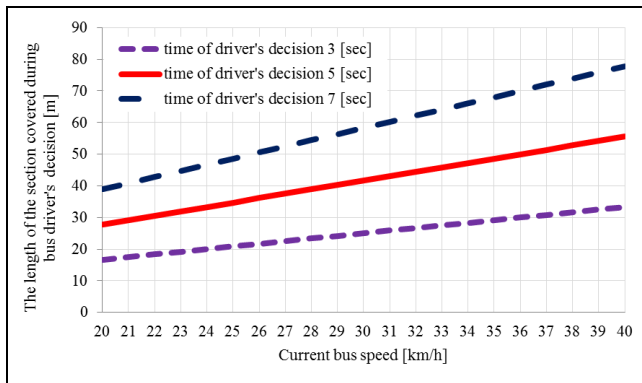


Figure 3. Comparison of distances covered by buses during bus drivers' decisions in relation to current speed of vehicle (own work).

**B. Time required for safe bus stopping**

Furthermore, the study also covered the time in which the bus reaches the potential conflict. Decelerations from 0.8 [m/s<sup>2</sup>] to as much as the exceptionally acceptable for passengers value of 1.6 [m/s<sup>2</sup>] were taken into account. Assuming that a bus running at a speed of 30 [km/h] brakes with a smooth deceleration of 0.8 [m/s<sup>2</sup>], the braking distance can be as long as 43 [m]. In the case of 1.6 [m/s<sup>2</sup>], which is generally inconvenient for passengers – this distance is only 22 [m]. Both cases seem unlikely, therefore in Figure 4, braking distances only for decelerations from 1.0 to 1.4 [m/s<sup>2</sup>], depending on the current bus speed, are presented.

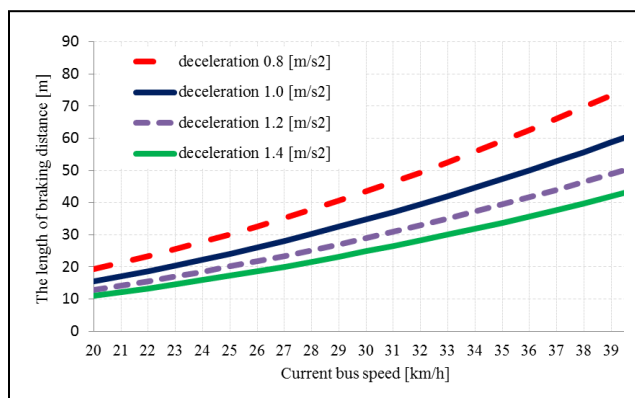


Figure 4. Comparison of distances covered by buses with time required for safe stopping (own work).

Current speed has a very significant influence on braking distances. Due to the fact that buses on dedicated lanes often move at a speed of 40 [km/h] and faster, even distant parking maneuvers can lead to bus (and passenger) time losses.

**C. Total time of occupying the potential conflict area**

On the basis of the length of the section covered during the driver's decision about potentially slowing down and of the length of the section covered during safe braking, the time in which the bus reaches the point of potential conflict

with a parking vehicle was established. These times are presented in Figure 5.

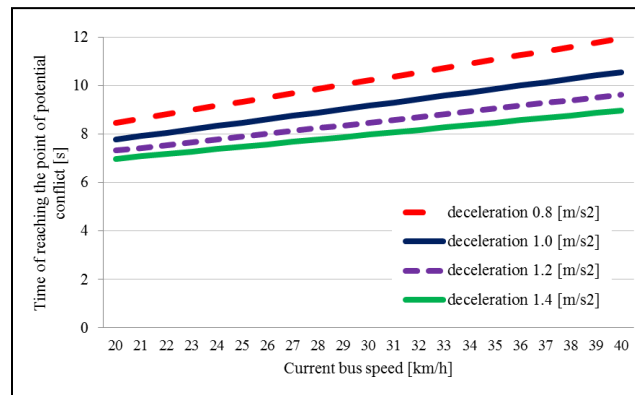


Figure 5. Comparison of times of reaching the point of potential conflict with a parking vehicle (own work).

**V. APPLICATION OF THE MODEL OF THE CONFLICT: RUNNING BUS VERSUS PARKING VEHICLE**

Analyses of potential conflicts on the designated bus lanes were conducted on the basis of results of measurements carried out along a section of Trzech Wieszców Avenue in Krakow (Figure 6).

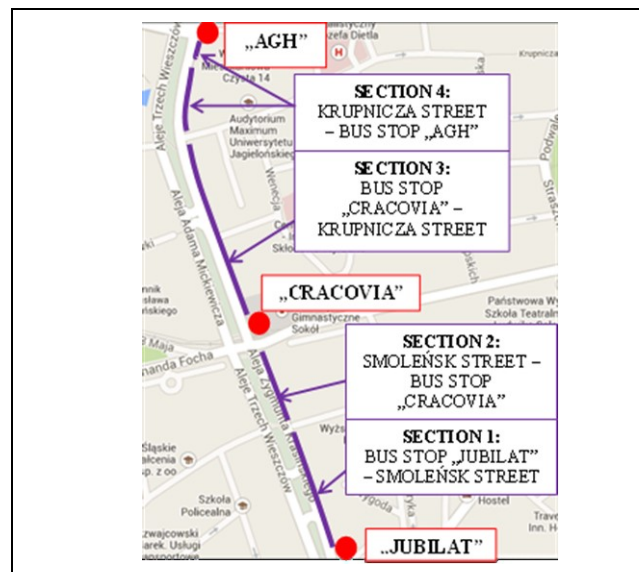


Figure 6. Analyzed sections along Trzech Wieszców Avenue in Cracow.

From a bus public transport perspective, this is one of the key transport corridors in the city. It has been provided with right curb bus lanes which can be used by all public transport vehicles, taxis and vehicles from municipal services (police and municipal guard) and additionally at intersection entries – by all vehicles, turning right. This part of the transport corridor has a typical urban character with intersections controlled by traffic signals, without priorities for buses. The

analysis covers a section starting from the “Jubilat” bus stop to the stop “AGH”. Taking into account distances between stops, the studied section amounts in total to 920 [m]. If one was to accept that parking takes place only in the allowed areas there would be 425 [m] at drivers’ disposal for parking.

As parking positions have not been designated, drivers occupy them according to their needs, habits and skills, not infrequently against the regulations. In order to determine the potential number of available parking spaces, it was assumed that the length of one parallel parking position is 6.0 [m]. Having assumed this, only 68 parking positions in total have been made available in the studied section. In practice, only intersection zones, pedestrian crossings and bus stop areas are free from parking. The numbers of parking positions are presented in Table II.

TABLE II. NUMBER OF PARKING POSTIONS AT THE ANALYZED SECTIONS

No.	Section	Total length of the section [m]	Length of the section (with legal and illegal) parking spaces [m]	Approximate number of parking positions [-]
1	“Jubilat” stop – Smoleńsk street	197	176	29
2	Smoleńsk street – „Cracovia” stop	203	108	18
3	„Cracovia” stop – Krupnicza street	261	236	39
4	Krupnicza street – „AGH” stop	259	75	12

#### A. The number and intensity of maneuvers related to parking on the sidewalk right next to the bus lane

From the perspective of potential conflicts between buses driving on a dedicated lane and the vehicles parking on a sidewalk and thus using the bus lane, the number of all maneuvers related to parking positions appears to be of great importance.

Studies were conducted using the patrol measurements method, by registration of vehicle numbers on individual positions. These were logged during subsequent measurement cycles – in morning (6:00 – 10:00) and afternoon (14:00 – 18:00) time periods. In order to describe the impact of parking vehicles on bus traffic, average intensities of entries and leavings were established for individual peak hours. Here it was assumed that in relatively homogenous peak periods the numbers of maneuvers can be divided evenly into single hours of study. It needs to be taken into account that the relatively long hourly measurement cycle could result in some maneuvers not being logged. Therefore, it can be acknowledged that the actual maneuver intensities will not be lower than those given in Table III.

In the current state, the number of maneuvers related to a single parking position in the analyzed section varies greatly – ranging between 0.028 and 0.291 maneuvers. In some cases, this ratio exceeds 0.2. Therefore, the number of parking positions at the analyzed sections will be crucial.

TABLE III. NUMBER OF PARKING MANEUVERS AT THE ANALYZED SECTIONS (PER 1H)

Section	Average intensity of entries per 1h [-]		Average intensity of leavings per 1h [-]	
	Morning peak hour	Afternoon peak hour	Morning peak hour	Afternoon peak hour
“Jubilat” stop – Smoleńsk street	<b>0.207</b>	0.126	0.057	<b>0.218</b>
Smoleńsk street – „Cracovia” stop	0.148	0.148	0.074	0.167
„Cracovia” stop – Krupnicza street	<b>0.291</b>	0.179	0.034	0.171
Krupnicza street – „AGH” stop	<b>0.222</b>	0.111	0.028	0.194

#### B. Running times of buses

There are 40 urban transport (municipal) buses and additionally 80 minibuses from private companies during each peak hour along Aleje Trzech Wieszców. The measurements of running time were conducted using GPS receivers in selected buses. These were collated after 37 (morning peak hour) and 40 (afternoon peak hour) running times of two analyzed stop-to-stop sections. Average values of running times and running speeds are shown in Table IV.

TABLE IV. AVERAGE BUS RUNNING TIMES AND SPEEDS

Section	Average running time [min]		Average running speed [km/h]	
	Morning peak hour	Afternoon peak hour	Morning peak hour	Afternoon peak hour
“Jubilat” stop – “Cracovia” stop	1.20	1.21	20.3	20.1
„Cracovia” stop – “AGH” stop	1.25	1.29	24.7	24.0

The running times of buses are very similar in both the peak periods. Unfortunately, in both sections, the running speeds of buses are not very high, which may be partly the result of curb-parking. Average time loss per bus is 15 [s], so in total, this is a significant problem for public transport passengers.

#### C. Probability of the conflict: running bus vs parking car

The impact of parking maneuvers on bus traffic, calculated using the model described in Section 2, is the greatest in the longest section where the number of potential conflicts is the lowest (Table V). On average, in existing situation, every fourth public transport bus is blocked by a parking vehicle. It should be noted that the process of taking and leaving a parking position includes the behavior of car drivers towards approaching buses. It was established that, in the case of entries, drivers generally do not take bus traffic into consideration as they need to occupy the bus lane earlier and when driving on the bus lane they need to find a free parking space. The situation in the case of leaving a parking position is different. In the majority of cases, drivers wait for the possibility to leave as long as there are no buses within a well seen distance. A problem arises when visibility is limited and a bus is running fast.

TABLE V. PROBABILITY OF CONFLICT BETWEEN RUNNING BUS AND PARKING VEHICLE IN CURRENT SITUATION

Section	Probability of conflict [-]	
	Morning peak hour	Afternoon peak hour
„Jubilat” stop – Smoleńsk street	0.038	0.032
Smoleńsk street – „Cracovia” stop	0.018	0.020
„Cracovia” stop – Krupnicza street	0.072	0.056
Krupnicza street – „AGH” stop	0.018	0.014

Therefore, after the model calibration process, it was proposed to adopt the following values of disturbance factors (equation (3)): 0.9 and 0.5 [-], for – respectively: taking and leaving a parking position by a single car.

#### D. Scenarios of increase of rotation on parking positions and the simulation results

In this analysis, the influence of the elimination of curb-parking and a potential increase in rotation at the parking positions along the bus lane is taken into account. There following four scenarios are included:

- Scenario S0: current state;
- Scenario S1: elimination of curb-parking along the bus lanes;
- Scenario S2: implementation of a paid parking zone, parking rotation rate = 0.50 [veh/h];
- Scenario S3: implementation of a paid parking zone, rotation rate = 1.00 [veh/h].

In the interest of simplification it was assumed that the rotation rates will remain the same at positions located in all four parts of the analyzed transport corridor. Simulation of probability of conflict between a running bus and a vehicle performing a parking maneuver was carried out for all scenarios using formula (3). The results of the simulation are presented in Table VI.

TABLE VI. PROBABILITY OF CONFLICT (ALL SCENARIOS, AFTERNOON PEAK HOUR)

Section	Probability of conflict [-]				Running time of buses [min]			
	S0	S1	S2	S3	S0	S1	S2	S3
„Jubilat” – Smoleńsk	0.016	0.000	0.017	0.032	1.21	1.18	1.21	1.24
Smoleńsk – „Cracovia”	0.010	0.000	0.010	0.019				
„Cracovia” – Krupnicza	0.028	0.000	0.035	0.068	1.29	1.26	1.30	1.34
Krupnicza – „AGH”	0.007	0.000	0.007	0.014				

Liquidation of parking along the bus lane will shorten running times of buses by an average of only 4 [s], while increasing the rotation to 1 [veh/h] will result in an extension of 3-6 [s], depending on the section. This is a relatively small effect, but it affects many passengers. If we assume that the section in the afternoon rush hour is traveled along by 3,000

passengers, this total can be achieved in close to 3.5 hours. However, one can conclude that the possible introduction of paid parking zones will not cause a serious loss of time for passengers. Another problem is a slower ride on buses resulting from reduced visibility - in this case, the profit would have been much larger.

## VI. CONCLUSIONS

Parking vehicles have a relatively slight influence on running speeds of buses along the designated bus lanes. Also, it will not be easy to find an efficient solution to the problem resulting from the growth of parking rotation on sidewalks located right next to bus lanes. One immediate solution, i.e., to create a maneuver lane between the bus lane and the sidewalk, cannot be applied in every case due to a lack of space. Therefore, it is worthwhile considering the removal of sidewalk parking from those transport corridors with separated bus lanes. This could have positive results, in the form of shortening the bus running times. This action could have yet another positive aspect. The area retrieved in this way could be used to improve conditions for pedestrian traffic, or it could be dedicated to the needs of bike traffic. It is true that even the least efficient bus lanes are better than general access lanes in increased traffic conditions, yet this should not be a reference point. Instead, the maximum functional possibilities, especially high speed of running, should be the reference. Studies on the efficiency of bus lanes, including the impact of sidewalk parking, will be continued, also with the use of stochastic methods.

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