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BUS LANE IMPLEMENTATION STRATEGY

Summary. This paper proposes a methodology for bus lane allocation including different strategies, dynamic bus lanes, and exclusive bus lanes. Choosing the right solution depends on many factors, such as traffic flow, passenger flow, and time losses. Analytical or simulation models can be used to evaluate the effectiveness of a separate bus lane. Analytical methods are simple to use and provide results in a short time. Simulation models, unlike analytical ones, require much more time and data to prepare but they are also much more detailed and accurate data. Therefore, analytical models may be particularly needed in the first stage of planning work during which potential sections for separated bus lanes are indicated. In this article, the author proposed an analytical model based on the 6th edition of the Highway Capacity Manual, which can be used to assess the implementation of separated bus lanes in different strategies. The final model developed was calibrated using traffic measurement results collected in a Polish city. As a result of the work, the author proposed the calculation procedure of the assumptions and diagrams, enabling the assessment of the selection of the appropriate solution.

1. INTRODUCTION

The constant growth of cities poses new challenges in developing the transport system. As part of the sustainable development policy, various solutions have been introduced to discourage residents from using their cars, especially in city centers. However, as the authors of many publications [1-2] have pointed out, limiting access to cars must be associated with an alternative in the form of efficient public transport. As the authors of other publications [3-4] pointed out that a well-functioning bus transit should be a component of the economic development strategy for communities for access to jobs and the benefits accruing to businesses. The high quality of public transport is related to frequent, fast, comfortable, and safe travel [5]. In many cities, bus networks are still inefficient. There are many solutions that could be employed to improve this situation. One of the most effective is separated bus lanes, which can be introduced as standard exclusive bus lanes (XBLs) or more modern dynamic bus lanes (DBLs). There are many factors that influence the success of this solution, including appropriate operational strategy, enforcement, and education [6-7]. The implementation of this solution requires appropriate analyzes using traffic models that could be used to:

- define the cases in which separated bus lanes may be used;
- specify the ultimate conditions which should trigger the activation of an XBL or DBL;
- compare the effectiveness of DBLs with other ways of prioritizing buses;
- assess the impact of DBL activation on other road users.

One popular tool to evaluate the effectiveness of XBLs (and DBLs) is the microsimulation model. In several studies [8-9], the authors built models that faithfully reproduce real conditions and provide the opportunity to test various scenarios and, often, detailed analyses. A great example is an article [10] in which the authors used the microsimulation model to evaluate the impact of the selected parameters of the bus lane (road lane marking and bus stop geometry) on delays in public and private transport.

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Another advantage of the microsimulation method is that it allows the development of a control strategy adapted to a specific section, taking into account the control logic [11-12].

However, the models mentioned above are complicated and time-consuming, especially when it is necessary to simulate DBL, which is not supported by modern software [13]. Therefore, analytical models are very popular in preliminary analyses. One example of this kind of analysis was presented by authors [14] who developed an economic and mathematical model to improve the efficiency of bus operation and service quality while adducing the implementation of the measures. Zu et al. [15] proposed an analytical model based on extended kinematic wave theory. The presented method allows the possibility of calculating changes in capacity and travel times in public and private transport in the case of implementing DBL. In other work [16], a cellular automation model was used to compare three strategies: no bus priority, XBL, and DBL. As a result of the numerical simulation, fundamental diagrams and the velocity-density profiles were presented. One of the limitations of this method is the assumption of the average number of passengers (in the bus and in the car) for which appropriate strategies have been proposed. The different numbers of passengers in public and private transport could have affected the results. In addition, there are many examples of studies in which the authors supported their work using analytical models presented in the Highway Capacity Manual (HCM). In one paper [17], HCM models were used to evaluate the regression models used to estimate the speed of the bus and non-bus travel under different conditions in CORSIM software. The aim of the work was to develop an operational and performance model for arterial bus lanes. Another example is the Transit Cooperative Research Program Report [18], which is based only on the analytical model presented in HCM. The report contains guidelines for estimating bus lane capacities and speeds and recommends the introduction of bus lanes in different traffic conditions. Calculations were made according to the standard procedure dedicated to the automotive and transit modes. An example of a study in which DBL was analyzed using HCM instructions couis presented in [19]. The HCM methodology was used to assess the impact of the DBL system on other vehicles, and simple linear regression models were constructed to predict the benefits of the DBL priority. The calibrated HCM model was used to predict the impact of the DBL system on other vehicles at each of the test intersections. This was done using 3.75 lanes instead of four lanes to account for the reduced number of lanes when the bus is present during the peak hour. While the assessment of the potential time savings for public transport was established very carefully, the impact on individual transport required a number of assumptions.

Traffic modeling methods should be selected appropriately, depending on the stage of the planning process. Based on the literature review, it may be noted that many authors use analytical models in the initial stage of planning, and because of this, it is possible to obtain satisfactory results over a short period. The use of analytical models is also associated with certain limitations and simplifications, which should be taken into account during the analysis. However, in the case of conceptual work, the results obtained would be sufficient.

The present study presents a new method based on the HCM [20] that takes into account the limitations of previous studies. The main objective of this study was to develop a methodology to evaluate the possibility of introducing bus lanes based on different strategies using basic road traffic parameters on a selected street. The proposed method makes it possible to calculate the changes in total travel time in public and private transport while taking into account the dwell time at the bus stop and the traffic conditions at the intersections of the analyzed section. The balance of time savings in public transport was used to assess the proposed strategies. The implementation of the new method required the introduction of an additional parameter related to the total activation time of the DBL.

2. MODEL STRUCTURE

This section presents the proposed automobile and transit methodologies based on the HCM 2020 manual. For both methods, the total travel time included time losses at the intersection and the segment running time. Time losses at the intersection were calculated according to the same scheme, whereas time losses related to travel time required the use of separate methods.

The analytical model presented in the HCM gives an opportunity to determine and compare the travel times of particular users, taking into account different traffic conditions in two different cases: travel time along the section without any bus lane (Option 1) and travel time along the section with a separate bus lane (Option 2). The travel time along the section with a dynamic bus lane (DBL) was estimated by calculating the travel time in private transport while taking into account the lane activation time per hour, whereas the travel time in public transport was the same as in the case of a separated bus lane. Details are described later in this article.

2.1. Time losses at intersections

The time losses at intersections included any delay incurred by a vehicle at the intersection, and it was computed by using Equation (1):

$$d = d_1 + d_2 \ \text{[s]} \tag{1}$$

where:
d_1 - uniform delay [s/veh];
d_2 - incremental delay [s/veh].

Uniform delay represents one way to compute delay when arrivals are assumed to be random throughout the cycle. It was calculated using Equation (2):

$$d_1 = \frac{0{,}5 * T - (1 - \frac{G_e}{T}^2)}{1 - (\min(1{,}X) * \frac{G_e}{T}} \ [s], \tag{2}$$

where:
X - volume to capacity ratio [-];
G_e- effective green signal [s];
T - cycle length [s].

In the next step, the incremental delay was computed based on Equation (3). This procedure modeled arrivals and departures as they occurred during the average cycle.

$$d_2 = 900 * t_a((X-1) + \sqrt{(X-1)^2 + \frac{7 * r_s * w_s * X^2}{C * t_a}} \ [s], \tag{3}$$

where:
t_a - duration of the analysis period (-);
rs - correction factor related to intersection control type [-], (1);
w_s - incremental delay adjustment for the filtering or metering by upstream signals;
C - capacity of the lane group (veh/hr).

2.2. Automobile mode

According to HCM 2020, segment running times are calculated separately for buses and other vehicles. For an automobile mode segment, the running time is based on free-flow speed, vehicle proximity, and various midsegment delay sources:

$$t = \frac{6 - l_1}{0{,}0082 \cdot L} \cdot rs + \frac{3{,}6 \cdot L}{S_f} \cdot f_v + \sum_{i=1}^{N_{ap}} d_{ap} + d_{other} \ , \tag{4}$$

where:
t – private vehicle travel time [s];
l_1 - time loss at the segment beginning [s];
L - segment length [m];
S_f - free flow speed [km/h];
f_v - factor related to traffic volume, cross-section, and free flow speed [-];
N_{ap} - number of access points along the segment [-];
d_{ap} - delay due to left and right turns from the street into access point [s];
d_{other} - delay due to other sources (e.g., curb parking) (s/veh) [s].

The free flow speed was calculated using Equation (5) and provided an estimate of the base free flow speed and the single spacing adjustment:

$$S_f = S_{fo} * f_L \left[\frac{km}{h}\right] \ , \tag{5}$$

where: S_{fo} - base free flow speed; f_L - signal spacing factor.

For the analyzed case, the base free-flow speed ($S_{fo} = 55{,}97\ km/h$) was calculated using Equation (6), and it took into account a constant speed (S_o =60,31 km/h) and adjustment for the cross-section - two traffic lanes, curb in all lengths ($f_{cs} = -4{,}34\ km/h$) and no access points ($f_A = 0$).

$$S_{fo} = S_o + f_{cs} + f_A \left[\frac{km}{h}\right] \ , \tag{6}$$

where:
S_o- Speed constant for the speed limit;
f_{cs}- adjustment for cross-section;
f_A- adjustment for access points.

The adjustment signal spacing factor was used to account for the impact of slower free-flow speed on shorter segments. This factor was calculated using Equation (7):

$$f_L = 1{,}02 - 4{,}7 * \frac{S_{fo} - 19{,}5}{\max(L, 400)} \ [-]. \tag{7}$$

The proximity adjustment factor adjusted the free-flow running time to account for the effect of traffic density based on Equation (8):

$$f_v = \frac{2}{1 + (1 - \frac{q}{52{,}8 * N_{th} * S_f})^{0{,}21}} \ [-] \ . \tag{8}$$

All variables were considered as previously defined. The difference in average private vehicle travel times was calculated according to Equation (9):

$$\Delta t_{TI} = (t + d) - (t_{bus} + d_{XBL}) \ [\mathrm{s}] \tag{9}$$

2.3. Transit mode

The transit mode methodology in HCM 2020 is applicable to public transit vehicles operating in mixed traffic or exclusive lanes and stopping along the street. There are major components of transit travel time: segment running time and delay incurred at transit stops. The delays associated with entering and leaving the bus bay depend on many factors, including the location of the stop along the section, the slope of the road, and the presence of heavy vehicles.

Transit vehicle running time was computed by Equation (10):

$$t_{Rt} = \frac{3{,}6 \cdot L}{S_{Rt}} + \sum_{i=1}^{N_{ts}} d_{ts} \ \ [s] \ , \tag{10}$$

where:
t_{Rt} – segment running time [s];
S_{Rt} – average bus travel speed [km/h];
N_{ts} – number of all delays;
$d_{ts,I}$ - delay due to dwell time [s].

$$S_{Rt} = \min\left(\frac{3{,}6 * L}{t}, \frac{98{,}15}{1 + e^{-1 + (\frac{361{,}19 * N_{stops}}{L})}}\right) \ [\mathrm{km/h}] \tag{11}$$

As in the case of automobile mode, two cases were analyzed: Option 1 (assuming no bus lane) and Option 2 (assuming the introduction of an XBL).

3. CASE STUDIES

3.1. Assumptions for analysis

The model assumed a roadway section with two lanes in each direction and intersections with traffic lights at both ends. In this methodology, the road sections were divided into a few segments. The results and analysis presented in this article are concerned with a single segment. The length of the segment was constant (500 m). It was assumed that there was a bus stop on the segment, generating total delays equal to 21 s. When determining the time loss at the intersection, it was assumed that the left and right turns had dedicated lanes and did not block movement. In the calculations, traffic volumes varying from 300 to 1000 P/h were taken into account. For intersections located at the beginning and at the end of sections, it was assumed that the cycle length was 90 s. Measures of Rzeszow saturation flows were used to perform calculations for capacity in the case with no bus lane and vehicles were allowed to use all traffic lanes and in the case with an XBL.

3.2. Traffic measurements

In the development of the analytical model, a series of additional measurements were carried out to calibrate key elements of the model. For this purpose, additional measurements included specifying the saturation flow associated with an unusual street cross-section that consists of two lanes—one for buses and the second for other users—and tests of public transport travel times.

The saturation flow was measured according to the manual [20] (Volume 4, Chapter 31). The purpose of this measurement was to determine the time intervals between vehicles leaving the queue, measured on the stop line. The initial value of the saturation flow was determined by considering the specificity of each lane at a particular intersection entrance (i.e., the share of heavy vehicles, the width of the lane, and slope). The results of the measurements are presented in Table 1.

Table 1

Results of the saturation flow measurements in Rzeszów

	Street without a bus lane				Street with a bus lane			
Street	Krakowska		Podkarpacka		Warszawska		Lis-Kula	
Traffic line	Left	Right	Left	Right	Left	Right	Left	Right
No. of measurements	26	24	18	17	22	20	25	10
Saturation flow [E/h]	1824	1852	1844	1823	1814	1603	1852	1546
Avg. time interval $\Delta\bar{t}$ [s]	2.05	2.02	1.95	1.97	1.98	2.24	2.11	2.57
Standard deviation [s]	0.26	0.24	0.27	0.24	0.22	0.29	0.14	0.21
Standard error [s]	0.048	0.041	0.054	0.048	0.046	0.72	0.053	0.082
Saturation volume flow for cross-section [E/h]	3672				3408			

The calculated standard error for the open access traffic lane did not exceed 3%. In the case of separate bus lanes, the error in estimating the average value was 7% for Warszawska Street and 8% for Lis-Kula Street. The saturation flow calculated in this way for the cross-section was 3672 [E/h] without XBL and 3408 [E/h] with XBL.

3.3. Travel time results

On the basis of the assumption, and HCM model analytical calculations were performed. Time losses for each option were calculated using Equation (1). The saturation flow volumes for each type of cross-section are presented in Table 2. The capacity for each cross-section was calculated using Equation (12):

$$C = S * \frac{Ge}{T} \text{ [P/h].} \tag{12}$$

The volume to capacity ratio was calculated for all ranges of traffic flow assumed in the analysis according to Equation (13):

$$X = \frac{q}{c} \text{ [-]}. \tag{13}$$

The incremental delay was also calculated for all ranges of parameters. In this case, the parameter corresponding to the time analysis 'ta' was assumed to be one hour (ta=1). The delay due to left and right turns from the street into the impact point of the access point was omitted. According to HCM, manual time loss at the beginning of the segment for the signalized intersection is 2 s and the correction factor related to the intersection control type is rs = 1. The selected results are presented in Table 2.

Table 2

Delay results

Traffic flow	No bus lane			Exclusive bus lane		
Q	d_1	d_2	d	d_{1XBL}	d_{2XBL}	d_{XBL}
300	4.41	0.00	4.41	4.44	0.01	4.45
400	4.55	0.01	4.55	4.59	0.01	4.60
500	4.69	0.01	4.70	4.75	0.02	4.76
600	4.84	0.02	4.86	4.92	0.03	4.94
700	5.00	0.03	5.03	5.10	0.04	5.13
800	5.18	0.04	5.22	5.29	0.05	5.34
900	5.36	0.05	5.42	5.50	0.07	5.57
1000	5.57	0.07	5.64	5.73	0.09	5.82
1100	5.76	0.09	5.85	6.01	0.10	6.11
1200	5.95	0.10	6.05	6.24	0.11	6.35

For all options analyzed, the main factor that influenced the time loss was uniformity. In Option 1 (no bus lane), the increase in traffic from 300 to 1000 vehicles resulted in an increase in time losses by almost 27% per vehicle. In Option 2, the increase in time losses was 30% per vehicle.

Travel times for private vehicles were computed using Equation (6) for the option where there was no bus lane (t) and vehicles were allowed to use all traffic lanes, as well as for the option with only one traffic lane and one XBL (t_{bus}). Calculations were performed for all traffic flow ranges. The selected results of vehicle travel time are presented in Table 3. In the case of travel time, the time losses per vehicle related to the introduction of the bus lane were not noticeable. For the adopted traffic range (over 1100 vehicles), the travel time increased by more than 6% per vehicle.

The transit vehicle running time was calculated using Equation (11). For public transport, time losses related to passenger service were taken into account, including dwell time, as well as departure and reentry delays. Based on the survey carried out in Rzeszów, this — simplify the calculation methodology. In further calculation, it was assumed that there was only one bus stop (N_{stops}).

When calculating the saved travel time in public transport related to the introduction of an XBL, it was assumed that the bus would move along a separate lane with minimal traffic (q^{300}=300 veh/h), which would allow the bus to pass efficiently along the section. This assumption was justified by the fact that different users can use the bus lanes (municipal vehicles, carpool vehicles, or taxis). There was also a group of private drivers who illegally used the bus lanes to drive on. Savings in public transport were calculated according to Equation (14):

$$\Delta t_{TP} = (d + t_{Rt}) - (d^{300} + t_{Rt}^{q300}) \text{ [s]} . \tag{14}$$

The selected results for vehicle travel time are presented in Table 3.

As expected, time savings increased as traffic volume increased. This time, for 1200 veh/h, the calculated time savings was 2% per bus.

4. BENEFIT ANALYSIS

At the initial stage, the calculations allowed the travel time of private and public transport with and without a bus lane to be compared. It can be assumed that the implementation of bus lanes will be justified when the total time losses for all passengers in private transport is lower than or equal to the time savings in public transport. The balance of this approach can be determined using the following equation.

Table 3

Travel time results

	Private Transport			Public transport		
Traffic flow [veh/h]	Travel time (no bus lane), t [s/veh]	Travel time (bus lane), t_{bus} [s/veh]	Time loss, Δt_{TI} [s]	Bus travel time (no bus lane), t_{Rt} [s/veh]	Bus travel time (XBL), t_{Rt}^{q300} [s/veh]	Time savings, Δt_{TP} [s]
300	34.55	34.22	-0.36	55.22	55.22	0.00
400	34.79	34.33	-0.51	55.33	55.22	0.25
500	35.05	34.44	-0.67	55.44	55.22	0.50
600	35.33	34.55	-0.85	55.55	55.22	0.78
700	35.63	34.67	-1.06	55.67	55.22	1.07
800	35.96	34.79	-1.29	55.79	55.22	1.37
900	36.32	34.92	-1.56	55.92	55.22	1.70
1000	36.73	35.05	-1.87	56.05	55.22	2.05
1100	37.20	35.18	-2.24	56.18	55.22	2.42
1200	37.73	35.33	-2.68	56.33	55.22	2.82

$$\Delta TP \geq \Delta TI \tag{15}$$

where:

ΔTP - total change (saving) of time in bus transport [h];

ΔTI - total change (loss) of time in private transport [h].

$$\Delta TP = \frac{|\Delta t_{TP}| \cdot Q_{TP} \cdot N_{TP}}{3600} \tag{16}$$

where:

Δt_{TP} – difference in average bus travel times in compared Options 1 and 2 [s];

Q_{TP} – number of buses during the peak hour [bus/h];

N_{TP} – average bus occupancy [person/bus].

For the purposes of further analyses, the number of buses (Q_{TP}) and the average number of passengers (N_{TP}) in Equation (16) were replaced by passenger flows (q_{TP}), which varied from 300 to 1,200:

$$q_{TP} = Q_{TP} * N_{TP} \tag{17}$$

$$\Delta \mathrm{TI} = \frac{|\Delta \mathrm{t_{TI}}| \cdot \mathrm{Q_{TI}} \cdot \mathrm{N_{TI}}}{3600} \tag{18}$$

where:

Δt_{TI} – difference in average private vehicle travel times in Options 1 and 2 [s]

q_{TI} – private traffic volume during the peak hour [veh/h]

N_{TI} – average private vehicle (car) [person / vehicle]

The time losses resulting from DBL operation were estimated assuming that, during the active lane, the time loss values generated by private vehicle users would be the same as those calculated for Option 2 with a classically separated bus lane. On the other hand, when the DBL system was inactive, it was assumed that vehicles traveling the entire section would have the same time losses as in Option 1. Therefore, the estimation of the total time difference in private transport was determined using the following formula:

$$\Delta TI^{DPA} = \frac{U_{DPA}}{100} \cdot \Delta TI, \tag{19}$$

where:
ΔTI^{DPA} - total time change (loss) in private transport while the DBL is active [h];
U_{DPA} – share of active time in an hour [%];
ΔTI - total change (loss) of time in individual transport [h].

Implementing a dynamic bus lane required calculating a parameter related to the total activation time of the lane in an hour, which depended on the number of buses per hour and the traffic conditions in the section. In the calculations, the least favorable case was assumed, in which the activation of the lane allowed only one bus to travel. The system activation time can be determined using the formula:

$$U_{DPA} = \frac{T_c \cdot Q_{TP}}{3600} \cdot 100 \tag{20}$$

where:
U_{DPA} – share of lane activation time in an hour [%];
T_c – total lane activation time required for a single bus [s];
Q_{TP} – number of buses per hour [bus/h].

Equation (21) was used to determine the time at which the bus lane should be separated for a single bus:

$$T_c = t_{op} + t_{Rt} + t_z, \tag{21}$$

where:
t_{op} – time needed to remove cars from the traffic lane[s];
t_{Rt} – bus travel time [s];
t_z – waiting time for the next notification (if the activation of the system is assumed for a single bus trip, the coefficient value is 0) [s].

The average time needed to remove cars from the traffic lane was determined using Equation (22). It is related to the traffic light program, the length of the queue, and the number of vehicles that can cross the stop line during the effective green light signal.

$$\mathrm{t_{op}} = \frac{\mathrm{K*T}}{\mathrm{S*G_e}}\,[\mathrm{s}] \tag{22}$$

where:
K - queue length [P];
T – cycle time [s];
G_e – effective green light signal [s];
S - saturation volume [P/h].

Prepared analytical models can also be used to analyze the operation of the bus lane outside rush hours or to assess the possibility of introducing bus lanes to other sections where traffic light settings are similar. For this purpose, an additional parameter was introduced into the model to easily determine the final traffic conditions for the functioning of the DBL:

$$U_{DPA}^{max} = min\left\{ 100\,; \quad 100 * \frac{\Delta TP}{\Delta TI} \right\}, \tag{23}$$

where:
U_{DPA}^{max} – maximum DBL activation time (in an hour) [%];
ΔTP - total change (saving) of time in public transport [h];
ΔTI - total time change (loss) in private transport [h].

5. RESULTS

A Matlab script was developed to analyze the final conditions of DPA activation. It allowed the calculation process to be automated and the results to be presented in a graphic form. It was decided to analyze three options of the coefficient λ equal to 0.3, 0.5, and 0.7, reflecting the relationship between the effective duration of the green light signal and the length of the cycle time. In this way, it was possible to analyze the strategy of the bus lane in different traffic conditions. In the next step, the time losses in private transport and the time savings in public transport per vehicle were compared when the bus lane was introduced. Determining the maximum share of activation time, as determined using Equation (23), allowed for a quick assessment of the possibility of introducing separate bus lanes in the analyzed sections. If the value of U_{DPA}^{max} was greater than (or equal to) the share of the active DBL lane in an hour (U_{DPA}), it meant that this form of priority was justified in the considered section. The XBL strategy was justified if the calculated maximum activation time was greater than 100%. The selected results are presented in Table 4.

Table 4

Selected benefit analysis results

q / q_{TP}	N_{TI}	Time loses, Δt_{TI} [s]	Time savings,Δt_{TP} [s]	ΔTI	ΔTP	U_{DPA}^{max} [%]
300	1.2	-0.36	0	-0.04	0.00	0
400	1.2	-0.51	0.25	-0.07	0.03	41
500	1.2	-0.67	0.5	-0.11	0.07	62
600	1.2	-0.85	0.78	-0.17	0.13	76
700	1.2	-1.06	1.07	-0.25	0.21	84
800	1.2	-1.29	1.37	-0.34	0.30	89
900	1.2	-1.56	1.7	-0.47	0.43	91
1000	1.2	-1.87	2.05	-0.62	0.57	91
1100	1.2	-2.24	2.42	-0.82	0.74	90
1200	1.2	-2.68	2.82	-1.07	0.94	88

As expected, when traffic and passenger flows were increased, the bus lane became more justified. This can be seen by analyzing the maximum activation time of the bus lane in an hour U_{DPA}^{max}. As the analysis shows, with the intensity of 1000 vehicles per hour and 1000 passengers in public transport, the bus lane could operate 90% of the time in an hour (i.e., 54 minutes). All cases are illustrated in a Matlab surface graph that was generated to assess the maximum activation time of the DBL for various values of passenger and vehicle flows. The maximum value (expressed in %) refers to the share of total DBL activation time in an hour. If a given section of the activation time of the lane was equal to or less than the maximum value shown in Fig. 1, it means that, in a given section, this form of priority can be considered.

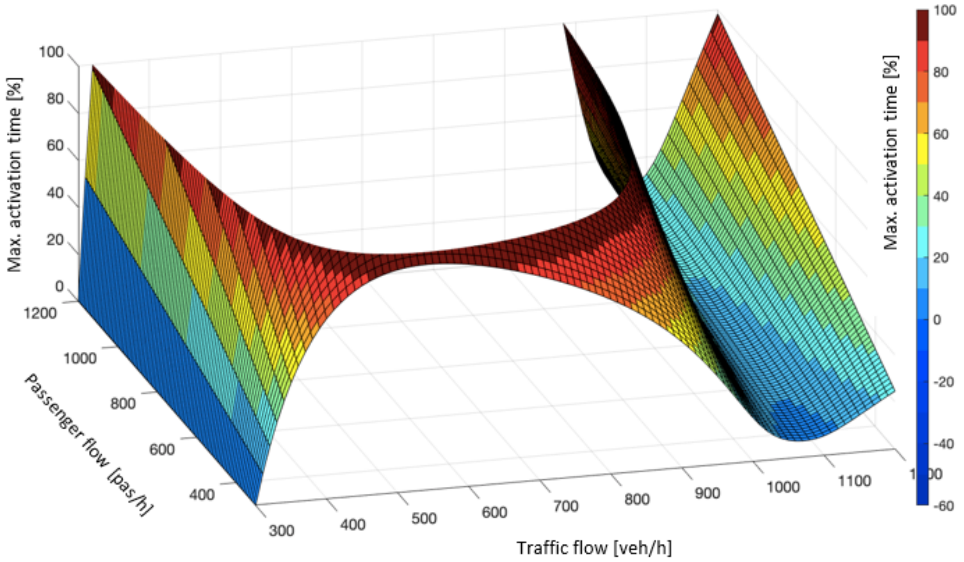

Fig. 1. 3D graph of the selection of the maximum share of the activation time of a dynamic bus lane (λ = 0.3)

In the first case, in which λ = 0.3, the classic form of the bus lane can be justified in two ranges of 330-970 [P/h] and 1200 [P/h]. In fact, the first range does not require this form of priority due to the low volume of traffic. The DBL system can operate in the rest of the area, that is, from 700 [p/h] to 1200 [p/h], even for a relatively small passenger flow. In this case, an XBL can be considered for the maximum values assumed (-1200 veh/h and 1200 pas/h) or more. An increase in the λ coefficient to 0.5 changes the surface layout, in which there is only one minimum with low values of traffic flow (Fig. 2).

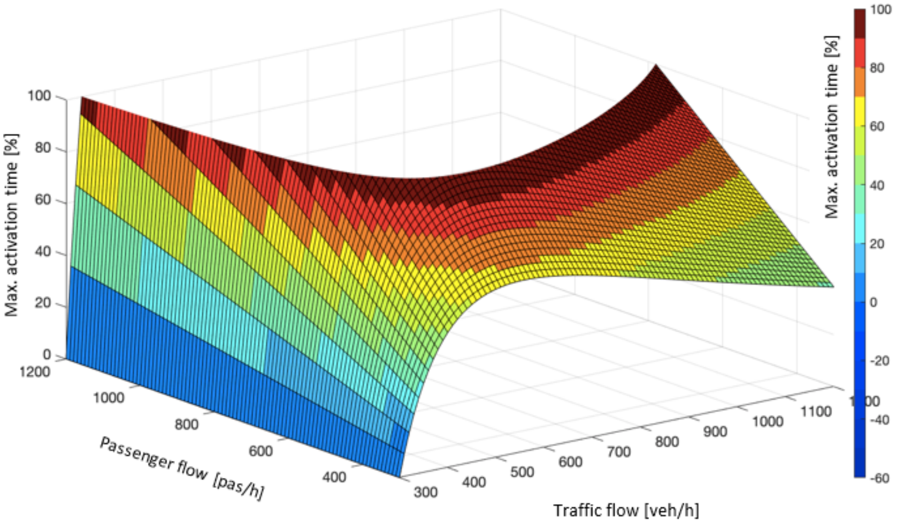

Fig. 2. 3D diagram of the selection of the maximum share of the activation time of a dynamic bus lane (λ = 0.5)

In this case, the XBL can be justified even for relatively small passenger flows starting from the range of 450 [pas/h], with a minimum traffic flow of 600 [veh/h]. The dynamic bus lane does not have such restrictions, assuming that the time needed to activate the DBL system is less than the maximum value shown in the graph.

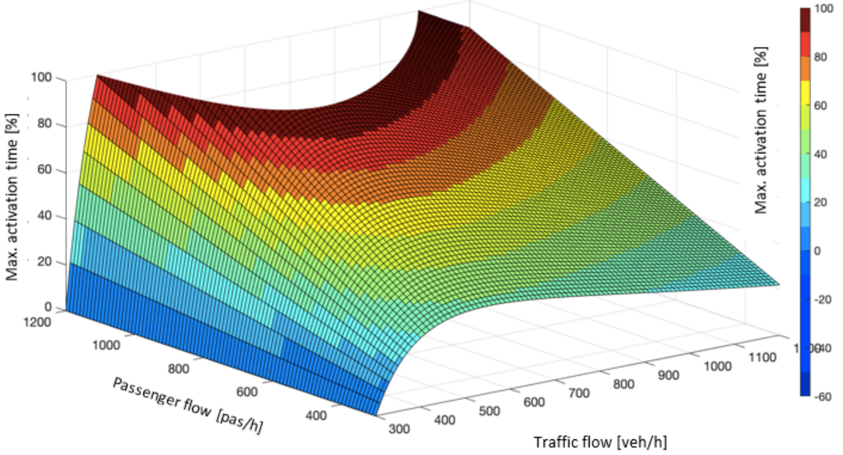

Fig. 3. 3D graph of the selection of the maximum share of the activation time of a dynamic bus lane (λ = 0.7)

In the last case, the dynamic bus lane can operate in a much wider range. In this case, the implementation of the standard solution (XBL) was justified only at the maximum value of passenger flow, while the DBL could operate in the time range of 18 min to over 45 min (Fig. 3).

6. SUMMARY AND CONCLUSIONS

The paper presented the assumptions for the analysis, as well as the method for determining time losses and savings for the analyses while assuming the use of dynamically separated bus lanes. The research resulted in the development of a script in the Matlab program, enabling the generation of graphical models of the evaluated section in terms of the possibility of introducing separate bus lanes.

The DBL system may be an alternative to the classic approach in certain traffic conditions, significantly reducing time losses in private transport. As a result, it could allow for more favorable balance and time-saving results.

In the analysis of the introduction of DBL, the least favorable case of using the active lane was taken into account. It will be possible to increase the benefits of this solution if the number of buses traveling within the same bus lane activation period or bus occupancy increases. Another important factor allowing the optimization of the DBL system is the activation time of the lane, which can be reduced by taking into account additional priorities in traffic lights for public transport.

The graphs developed for the benefit analysis showed that the DBL can be used in situations where passenger flows do not justify the introduction of the classic bus lane. When λ is greater than or equal to 0.5, the dynamic bus lane can operate, assuming that the maximum activation time is not exceeded.

The models developed in the Matlab program allowed the authors to significantly accelerate the section evaluation process, determine the balance of time loss and savings, and determine the maximum activation time of the bus lane in an hour, at which time losses and savings will be balanced. In order to use these models, it is necessary to determine the volume of traffic in private transport and the flow of passengers in public transport.

7. DISCUSSION

The proposed model can provide guidance on the first stage of planning work. The main limitations related to the use of the proposed model concern the section geometry and the selected elements used to calibrate the model (especially the saturation flow). Future work should allow assessments of the impact of the DBL system on streets with different lane geometries (three or four lanes). A universal model can be developed by carrying out more saturation flow measurements on bus lanes in other cities in the country (currently, measurements have been taken only in Rzeszów). In relation to other studies, the impact of undisciplined drivers should be considered in the future.

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