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DETAILED ANALYSIS OF PUBLIC BUS VEHICLE RIDE ON URBAN ROADS

Summary. Public transport priority is still a big issue in many cities. Priority measures for street public transport are the key tool to increasing the attractiveness and reliability of public transport systems. This paper contributes to this problem by introducing a detailed analysis of street public transport vehicle ride on urban roads. The ride will be divided into segments with a definition of the potential reason for possible delays. This view is the first step for a future objective decision-making tool for assessing the quality of operation of public transport on a defined urban road section.

ANALYSE DÉTAILLÉE DE LA CIRCULATION DES BUS EN VOIES URBAINES

Abstract. La préférence dans le domaine du transport public est encore un grand sujet dans beaucoup de villes. Les mesures de préférence qui concernent le transport public urbain représentent l´instrument primordial pour réussir à avoir un système du transport public plus attractif et plus sûr. Cet écrit contribue à trouver la solution du problème en présentant une analyse détaillée de la circulation/ du trajet les véhicules du transport public en voies urbaines. Le trajet des bus sera décomposé en éléments avec la définition des raisons potentielles qui peuvent causer un retard du bus. Ce point de vue est le premier pas pour établir un instrument décisif à prendre à fin d´augmenter la qualité de la circulation du transport public.

1. INTRODUCTION

During a continuous competitive battle between individual car traffic and public transport, the quality of public transport systems plays a very important role. The meaning of "quality" would be slightly different for anybody, but there are key characteristics that most passengers identify as crucial in terms of the quality of public transport – reliability and travel speed. It simply means that passengers expect to be transported in an adequately attractive amount of time and expect to be at their destination on time. In a situation where key factors in the perception of the quality are reliability and travel speed, transportation engineers must focus on solutions designed to achieve a required level of quality of public transport.

This article is dedicated to the issue of preferential measures for public buses because, generally speaking, bus services are usually the most negatively affected part of public transport system by car traffic.

2. MODERN VIEW ON PUBLIC BUS PRIORITY MEASURES

Public transport priority measures are most often perceived as a basic tool to reduce the negative impact of car traffic on public transport operation on those sections of the road network where traffic congestions appear regularly. This means they are seen as a tool for eliminating the delays of public transport services arising in sections of the urban road network with high intensity of car traffic. That is, let say, the traditional point of view on public transport priority measures.

However, there is a potential to make bus services even faster than in the original state of traffic without congestion. Public transport priority measures are no longer just bus lanes or priority on traffic lights at busy intersections. Global and complex views on public bus rides through urban road networks have to be initiated with the subsequent proposal of a combination of measures maximizing fluency, reliability and travel speed of public bus services along the entire length of the line. That is the main principle of the concept of public transport priority axis.

We can demonstrate the effects of this new point of view on a theoretical example: the initial scenario without any public transport priority arrangements (a common situation in many cities in the past) means that public buses are operated in traffic flow with other car traffic and there are traffic lights with fixed signal plan at intersections. The travel speed of public bus services in free traffic flow is marked as $u_{(free,0)}$. When a traffic congestion appears, travel speed of buses drops down, marked as $u_{(cong,0)}$:

$$u_{(free,0)} \gg u_{(cong,0)}$$

The problem here is not only low travel speed of bus services during the congestion, but also significant differences between a state of normal traffic flow and a state of congestion.

When traffic lights with a dynamic signal plan and priority of public transport were not invented yet, the usual approach was to apply spatial preferential arrangements (bus lanes), at least, where the spatial conditions of the road were sufficient, which provided at least partial improvements. If we mark travel speed of public buses in free traffic flow as $u_{(free,1)}$ and travel speed of public buses in congestions as $u_{(cong,1)}$, we can compare this and the original situation:

$$u_{(free,0)} = u_{(free,1)}$$

$$u_{(cong,0)} < u_{(cong,1)}$$

Theoretically, if there are bus lanes in every section between intersections, a congestion or tailback of cars has no influence on bus services, and the level of their travel speed is the same as travel speed in free traffic flow in the previous scenario:

$$u_{(cong,1)} = u_{(free,1)} = u_{(free,0)}$$

The invention of traffic lights with a dynamic signal plan enabled the possibility of giving priority to public buses at intersections with traffic lights. When public buses pass the intersection with priority, the travel speed increases in case of free traffic flow [marked as $u_{(free,2)}$] but the effect of priority on traffic light is quite small in case of traffic congestion [marked as $u_{(cong,2)}$] without spatial priority measures in a section before the intersection:

$$u_{(free,1)} < u_{(free,2)}$$

$$u_{(cong,2)} < u_{(free,2)}$$

$$u_{(cong,2)} < u_{(cong,1)}$$

The modern approach to public transport priority is based on a combination of many types of measures, including bus lanes, priority at intersections and other changes in arrangements of the road, making the bus ride easier. Thanks to this approach the travel speed in case of congestion [marked as $u\_(\mathrm{cong}, 3)$] is higher than in two previous cases, even the travel speed in case of free traffic flow [marked as $u\_(\mathrm{free}, 3)$] could be higher than travel speed in normal traffic flow in an initial situation:

$$u\_(\mathrm{cong}, 2) < u\_(cong, 3)$$

$$u\_(\mathrm{free}, 0) < u\_(free, 3)$$

The ideal solution can be seen in the combination of bus lane in the entire section between an intersection and a high priority at an intersection (similar conditions as segregated rail system) known as linear priority or bus rapid transit system. In that case, the traffic congestion has absolutely no influence on bus services and their travel speed is higher than in the initial situation described above:

$$u\_(\mathrm{free}, 4) = u\_(\mathrm{cong}, 4)$$

$$u\_(\mathrm{cong}, 4) > u\_(free, 0)$$

The following table provides a comparison of different levels of public buses priority on urban roads.

3. FACTORS INFLUENCING PUBLIC TRANSPORT VEHICLES' RIDE ON URBAN ROAD AS A BACKGROUND OF ITS DETAILED ANALYSIS

The detailed analysis of a bus ride and its manoeuvres has to be an indivisible part of the modern point of view on public transport priority measures. A ride in public transport vehicles (thus also level of quality and reliability of public bus services) is influenced by three main factors:

- car traffic volume (in relation to road capacity)
- traffic lights at intersections, respectively parameters of their signal plan and level of priority of public transport
- road and street space layout, arrangement of lanes, right of way etc.

3.1. Factor of car traffic volume

Between car traffic volume (in relation to road capacity) and bus service delays, there is usually quite clear dependence. In the case of road congestion when traffic volume hits the level of the road capacity, the speed of traffic flow sharply decreases and public buses riding in that traffic flow are delayed. This situation leads to unreliability of bus services over the entire length of bus lines and to a decrease in their travel speed. This factor is decisive mainly in sections between intersections, but traffic volume can also overload an intersection.

3.2. Factor of traffic lights at intersections

Traffic lights without public transport priority (or even without dynamic control - with fixed cycles) may delay the bus service, even if the road is completely empty. Buses can be delayed completely independently of the current oncoming traffic but just by the occurrence of the red signals. This also applies to intersections with a dynamic signal plan but without public transport priority (controller detects vehicle is coming, but cannot distinguish whether it is a public bus or not).

Table 1

A comparison of different levels of public buses priority on urban roads

Level of priority	Characteristics	Travel speed of bus services
Initial situation (0)	No priority measures	Travel speed in case of free traffic flow: $u\_(\text{free}, 0)$ Travel speed in case of congestion: $u\_(\text{cong}, 0)$ $\mathbf{u\_(free, 0) \gg u\_(cong, 0)}$
Spatial priority measures (1)	Only bus lanes if possible in congested area	Travel speed in case of free traffic flow: $u\_(\text{free}, 1)$ Travel speed in case of congestion: $u\_(\text{cong}, 1)$ $\mathbf{u\_(free, 0) = u\_(free, 1)}$ $\mathbf{u\_(cong, 0)} < u\_(cong, 1)$
Priority at intersection (traffic light) (2)	Buses ride in traffic flow with other car traffic, they have priority at intersections	Travel speed in case of free traffic flow: $u\_(\text{free}, 2)$ Travel speed in case of congestion: $u\_(\text{cong}, 2)$ $\mathbf{u\_(free, 1)} < u\_(free, 2)$ $\mathbf{u\_(cong, 2)} < u\_(free, 2)$ $\mathbf{u\_(cong, 2)} < u\_(cong, 1)$
Modern approach (3)	Progressive combination of measures including bus lanes, priority at intersections and other changes in arrangements of road making the bus ride easier	Travel speed in case of free traffic flow: $u\_(\text{free}, 3)$ Travel speed in case of congestion: $u\_(\text{cong}, 3)$ $\mathbf{u\_(cong, 2)} < u\_(cong, 3)$ $\mathbf{u\_(free, 0)} < u\_(free, 3)$
Modern approach - Linear priority or bus rapid transit system (4)	Buses in segregated corridor, high level of priority at intersection	Travel speed in case of free traffic flow: $u\_(\text{free}, 4)$ Travel speed in case of congestion: $u\_(\text{cong}, 4)$ $\mathbf{u\_(free, 4) = u\_(cong, 4)}$ $\mathbf{u\_(cong, 4)} > u\_(free, 0)$

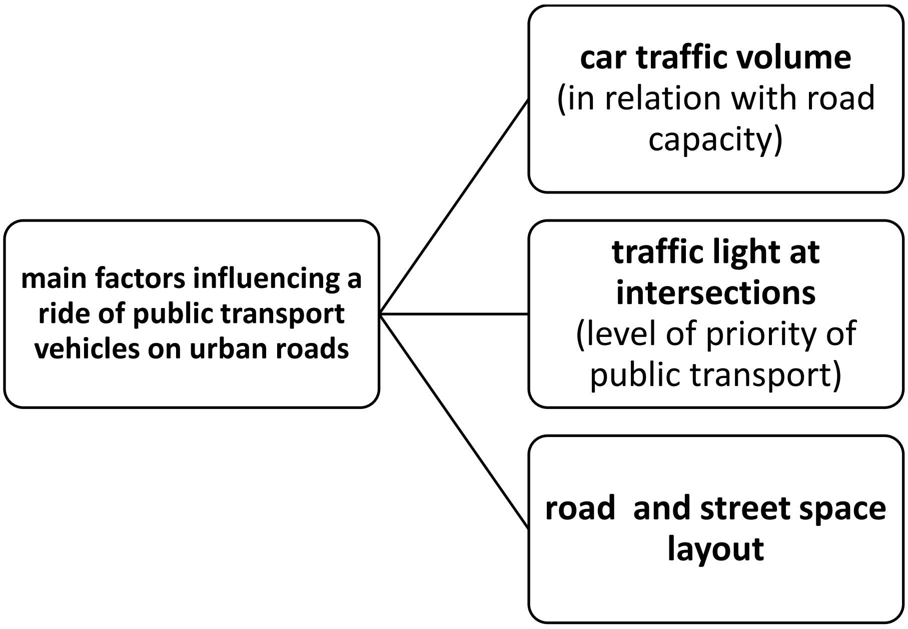

Fig. 1. Main factors influencing a ride of public transport vehicles on urban roads
Fig. 1. Les facteurs principaux influençant un tour de véhicules de transport en commun sur les routes urbaines

Another issue is the level of public transport priority on traffic lights. We distinguish two types of priority:

- absolute priority (when the bus passes through an intersection without stopping or slowing)
- conditional priority (when the priority for the bus depends not only on coming bus but also on global conditions and the state of traffic at the area of intersection)

Degree of public transport priority in traffic lights usually depends on the type of intersection, directions of bus lines and if there is an exclusive bus approach lane or not.

3.3. Factor of road and street space layout

The actual layout of street space can provide a higher quality of public transport and make a ride of public transport vehicles easier and faster even when traffic flow is relatively free. The public transport-friendly layout of street space could come together with other traffic calming measures. This makes public transport priority natural in street space.

4. A DETAILED ANALYSIS OF BUS PUBLIC TRANSPORT VEHICLE RIDE ON AN URBAN ROAD

One of the bases for the assessment of a bus ride before a proposal for a comprehensive solution of public transport priority is a detailed analysis of the bus ride and its manoeuvres on an urban road and definition of potential reasons for delays, respectively which factor is relevant. This definition is important for two reasons. Firstly, there are delays due to the state of traffic on the road (traffic volume, acceptable time headway for entering the lane etc.) but, secondly, there are delays that are caused by the very arrangement of the road. Without this analysis, the progressive and complex priority solution is not possible.

The following part of this paper divides a bus ride on an urban road, respectively in street space, to basic parts and manoeuvres as the basis for the detailed analysis mentioned.

4.1. Bus ride between intersections

When riding in a lane, a bus can be regularly delayed by traffic congestion, whether the congestion has a local character (for example resulting from an overloaded intersection) or it is a “global” congestion, that is, when the whole network is overloaded (for example, during a rush hour). If tailbacks or congestions occur regularly, setting up a bus lane is often the only solution.

When changing lanes, a potentional delay depends on headway between vehicles in the target lane. But could the road be adjusted so that the bus did not have to change lane?

Lane merging is obviously a place where the capacity of the road drops which is accompanied by a decrease of traffic flow speed so there is always a strong potential to create of tailback or congestion. It generally depends on actual traffic volume in relation to the capacity of the merging place.

Exiting a bus stop bay is a similar situation as “changing lanes” manoeuvre, but it is complicated by the fact that the initial speed of a bus is 0 km/h, so the acceptable headway in the target lane has to be much larger. It, of course, depends on the speed and volume of traffic flow in the target lane.

The following table shows situations or manoeuvres, potential reasons for delay and relevant factors.

Table 2

Situations or manoeuvres, potential reasons for delay and relevant factors

Situation/manoeuvre	Potential reason for delay	Factor of traffic volume	Factor of traffic lights at intersection	Factor of road and street space layout
Ride in a lane	Traffic congestion	**Yes**	**Only in specific circumstances**	**No**
Changing lanes	Traffic volume, acceptable distance headway	**Yes**	**No**	**Yes**
Passage through lane merging	Traffic volume (capacity)	**Yes**	**No**	**Yes**
Exiting bus stop bay	Traffic volume, acceptable distance or time headway	**Yes**	**No**	**Yes**

4.2. Passage through intersection without traffic lights (entering on a major road)

When a public bus enters an intersection on a major road, a right turn and passage ahead are quite smooth. The only possible reason for a delay is vehicles blocking the lane when typically waiting for their left turn. This situation can occur when there is no exclusive left turn lane or when that lane is too short.

A left turn is more problematic because all vehicles, including public buses, have to give way for vehicles riding on major roads in the opposite direction. This can be a reason for significant delays for a public bus, especially in cases of high volume of traffic flow to cross.

The following table shows directions, potential reasons for delay and relevant factors.

4.3. Passage through intersection without traffic lights (not entering on a major road)

When a public bus does not enter an intersection on a major road, it has to give way from 1 to 3 traffic flows, which is inadequate in terms of reliability of bus services because there is a strong potential for unpredictable delays. A right turn is less complicated with only 1 traffic flow to give way. On the other hand, left turn is the most complicated with 3 traffic flows to give way, leading almost always to delay of bus service.

The following table shows directions, potential reasons for delay and relevant factors.

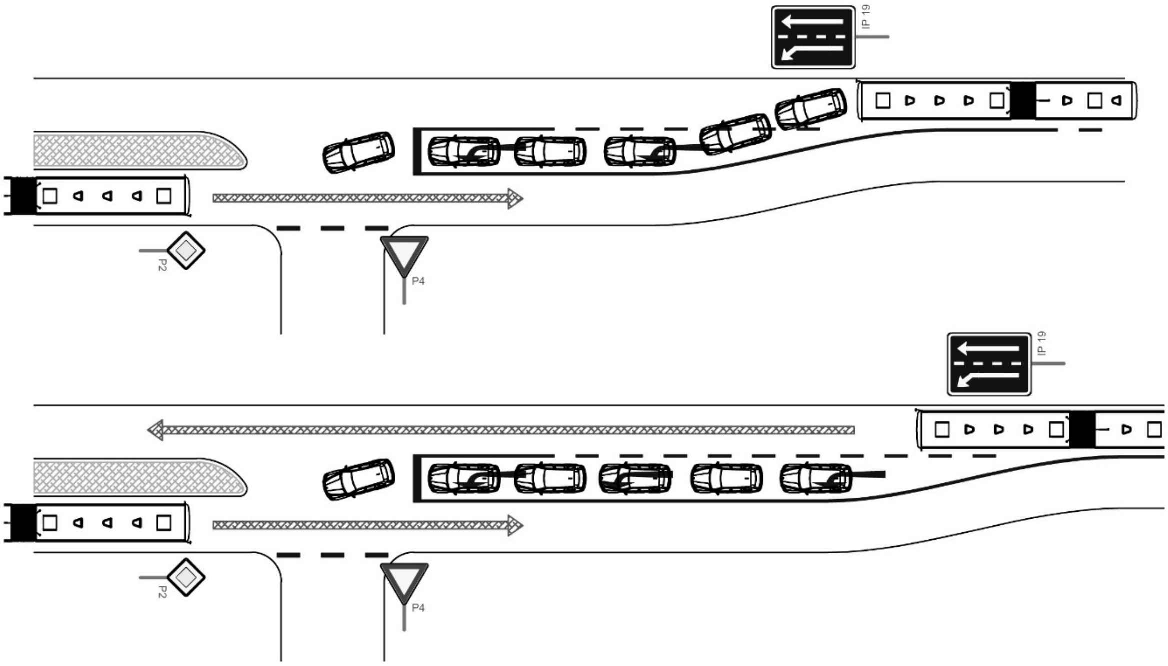

Fig. 2. Example of a short and sufficient length of exclusive left turn lane and its possible influence on public transport [2]
Fig. 2. Exemple d'une courte longueur de la voie de virage à gauche suffisante et exclusive et son influence possible sur les transports en commun [2]

Table 3

Directions, potential reasons for delay and relevant factors

Direction of passage	Number of traffic flows to give way	Potential reason for delay	Factor of traffic volume	Factor of traffic lights at intersec.	Factor of road and street space layout
Ahead	0	*(Ride ahead is blocked by vehicles waiting to turn left when intersection without exclusive approach lanes)*	**Partially**	**No**	**Yes**
Right turn	0	*(Ride ahead is blocked by vehicles waiting to turn left when intersection without exclusive approach lanes)*	**Partially**	**No**	**Yes**
Left turn	1	Waiting for acceptable time headway in crossed traffic flow	**Yes**	**No**	**Yes**

Table 4

Directions, potential reasons for delay and relevant factors

Direction of passage	Number of traffic flows to give way	Potential reason for delay	Factor of traffic volume	Factor of traffic lights at intersec.	Factor of road and street space layout
Ahead	2	Waiting for acceptable headway in 2 crossed traffic flows	**Yes**	**No**	**Partially**
Right turn	1	Waiting for acceptable headway in target traffic flow	**Yes**	**No**	**Partially**
Left turn	3	Waiting for acceptable headway in 3 crossed traffic flows	**Yes**	**No**	**Partially**

4.4. Passage through a signal-controlled intersection (intersection controlled by traffic lights)

At a signal-controlled intersection, the difference between whether a bus arrives on a major road or not blurs and the key parameter is signal plan, respectively level of public transport priority at traffic lights.

Public transport priority solutions are quite easier when bus services are operated through an intersection in one direction. Public transport lines crossing each other at an intersection make the solution of the priority more complicated because the controller of traffic light has to deal with conflicting demands of passage through an intersection.

The only really effective way of reducing the delay of public transport vehicles in signal-controlled intersections is a combination of a dynamic signal plan with a high level of public transport priority and the optimal structural layout of the intersection.

The following table shows directions, potential reasons for delay and relevant factors.

Table 5

Directions, potential reasons for delay and relevant factors

Direction of passage	Number of traffic flows to give way	Potential reason for delay	Factor of traffic volume	Factor of traffic lights at intersec.	Factor of road and street space layout
Ahead	0	Absence of public transport priority on traffic lights	**Partially**	**Yes**	**Partially**
Right turn	0	Absence of public transport priority on traffic lights	**Partially**	**Yes**	**Partially**
Right turn on exclusive turn signal	0	Absence of public transport priority on traffic lights	**Partially**	**Yes**	**Partially**

Left turn	1	Waiting for acceptable headway in 3 crossed traffic flow Absence of public transport priority on traffic lights	**Yes**	**No**	**Partially**
Left turn on exclusive turn signal	0	Absence of public transport priority on traffic lights	**Partially**	**Yes**	**Partially**

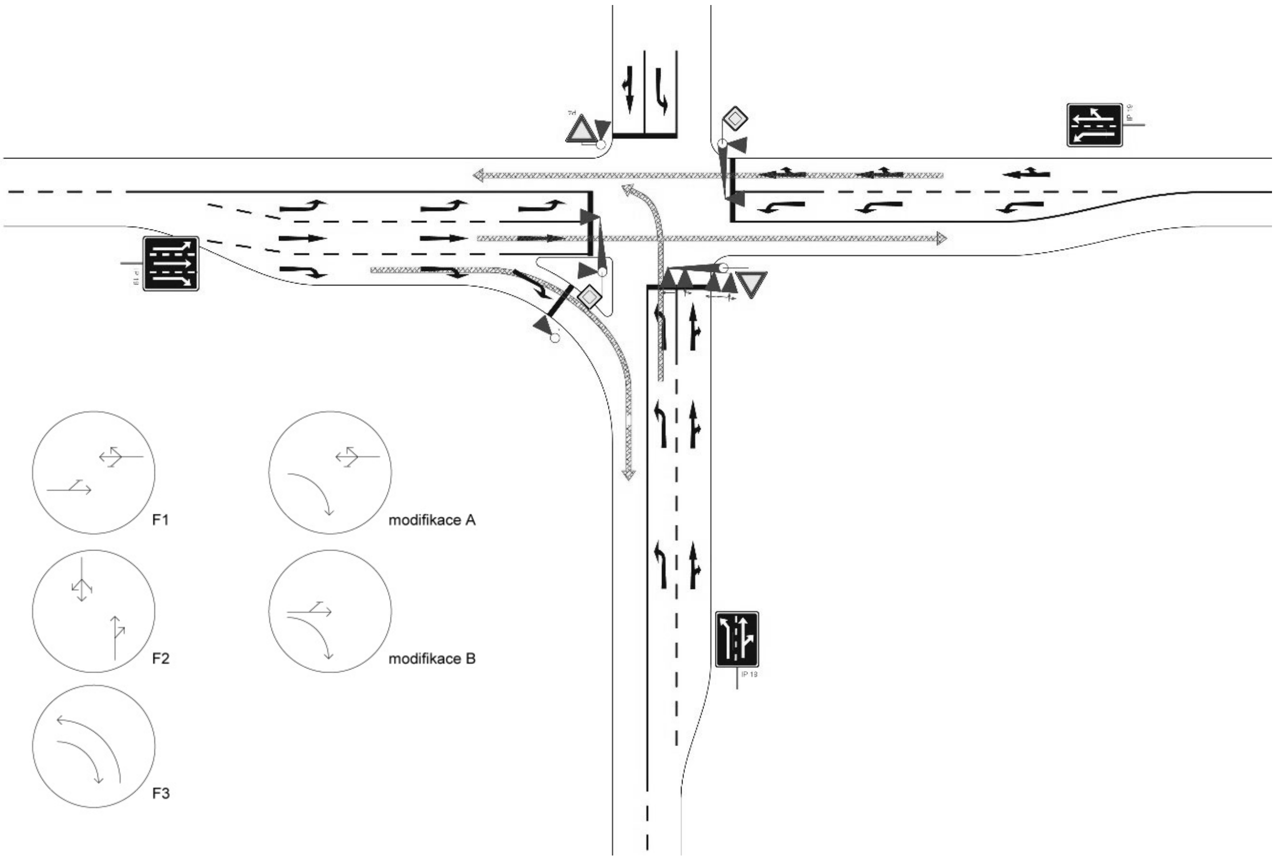

Fig. 3. Example of optimal layout of an intersection in relation to phase diagram of signal plan in case public transport lines cross each other at an intersection [2]

Fig. 3. Un exemple d'un arrangement d'intersection par rapport au diagramme de phase du plan de signal dans le cas les lignes de transport public se croisent à l' intersection [2]

4.5. Passage through roundabout

Passage through roundabout consists of entering a roundabout and ride on its ring. The only potential reason for delay is a local tailback or congestion in the area ahead of a roundabout. Entering the roundabout is an analogical situation as a right turn from a minor road.

Table 6

Passage through roundabout

Direction of passage	Number of traffic flows to give way	Potential reason for delay	Factor of traffic volume	Factor of traffic lights at intersec.	Factor of road and street space layout
Enter a roundabout	1	Waiting for acceptable headway in target traffic flow	**Yes**	**No**	**No**

5. REVIEW OF RELEVANCE OF THREE MAIN FACTORS ON DEFINED BUS RIDE SEGMENTS

As said at the beginning (see chapter 3), the level of reliability and travel speed of public transport depends also on the actual layout of the urban road, respectively whole street space. While the factor of traffic volume is obviously included in all of defined bus ride segments (62.5% “yes”, 37.5% “partially”), the factor of road and street space layout is somehow included in 87,5% of defined bus ride segments (37.5% “yes”, 50.0% “partially”). That means the road and street space layout has to be arranged to be “bus-friendly” when having the ambition to speed up the public bus services.

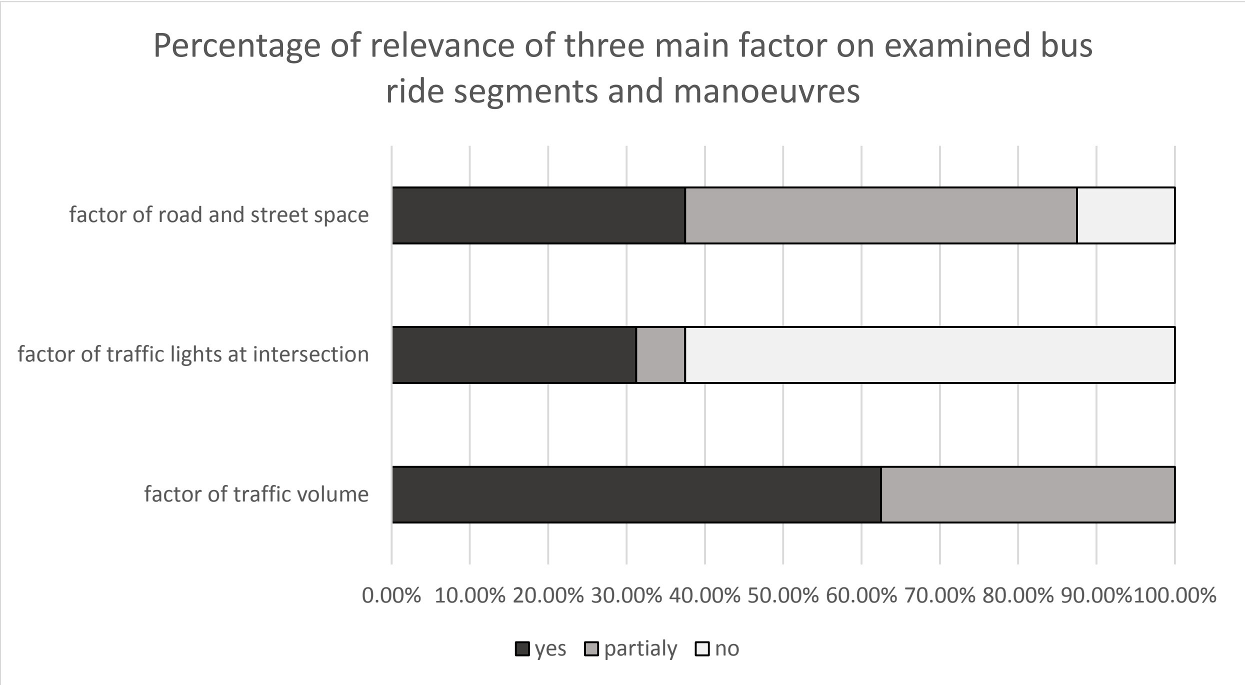

Fig. 4. Review of relevance of three main factors on examined bus ride segment and manoeuvres
Fig. 4. L'examen de la pertinence des trois principaux facteurs en segments de trajet en bus et manoeuvres

6. EXAMPLE – BUS EXITING A BUS STOP BAY

Exiting a bus stop bay is a classic example of how road and street space layout can delay a bus operation. When boarding of passengers is finished and the bus is about to exit a bus stop bay, it is a situation similar to change of lane. The bus has to join a traffic flow in a target lane. But there is a significant difference. While changing lane, initial and target traffic flows often have similar speeds, while exiting a bus stop bay, the initial speed of a bus is 0 km/h.

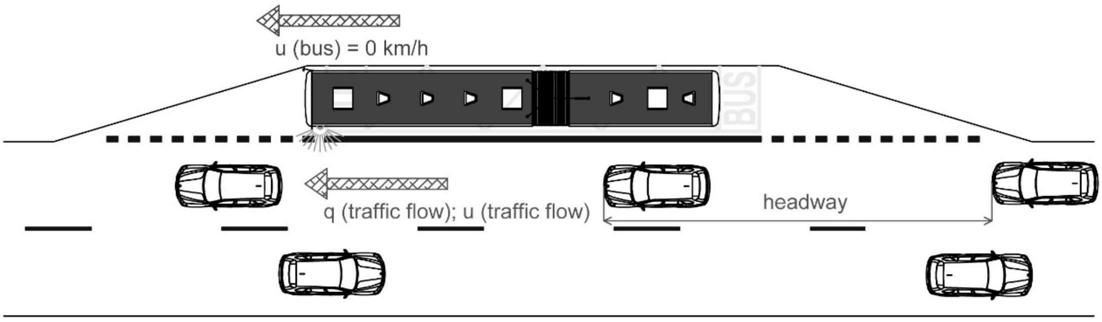

Fig. 5. Analysis of the situation when a bus is exiting a bus stop bay
Fig. 5. L'analyse de la situation lors la un bus sort d'une baie de l'arrêt de bus

At the time of writing this article, results of measurements at the bus stop "Na Kovárně" in Prague were available (6th of May, 2015). The aim of the measurements was to determine the level of delays caused by exiting the bay in relation to traffic volume and state of traffic flow. Traffic volume was measured in 5-minutes profiles and during each exit of a bus from the bay, the time between closing doors and leaving the bay was also measured.

From previous measurements, it can be stated that the time between closing doors and leaving the bay when target lane is absolutely free is about 7 s. This helps to calculate the delay generated by the bay because of the state of traffic flow.

The following figure shows the development of traffic volume and the time required to exit the bus stop bay. In the figure is also shown the level of 7 s (average time for exiting the bay when target lane is free) and time interval when the traffic flow was becoming congested.

As Fig. 6 shows, the delays become higher when traffic flow is becoming saturated and congested. The traffic volume is lower in time of congested character of traffic flow because of decrease of speed. The average delay of the bus is much higher within the saturated and congested character of traffic flow – about 10 s delay. This delay does not seem dramatic, but if there are 12 stops on the bus line, it means a delay of 2 minutes – just because a bus stop is situated in bus stop bay. This delay is not insignificant.

7. CONCLUSION

The detailed analysis of a bus ride on an urban road, respectively in street space, appears to be a potentially useful tool for assessing the present level of quality of the bus ride, and in further research this instrument will be further developed. The aim of the research is also setting of an integrated tool for identifying those sections on an urban road network in which public transport priority measures are most needed and will be most effective.

Together with classic analysis of punctuality of bus services and analysis of traffic flow, the detailed analysis of bus ride will be a cornerstone of a prepared concept of public transport priority axis. This concept will combine various attitudes and views on public transport priority in order to define those sections of an urban road network, where complex solution of public transport priority will be the most effective.

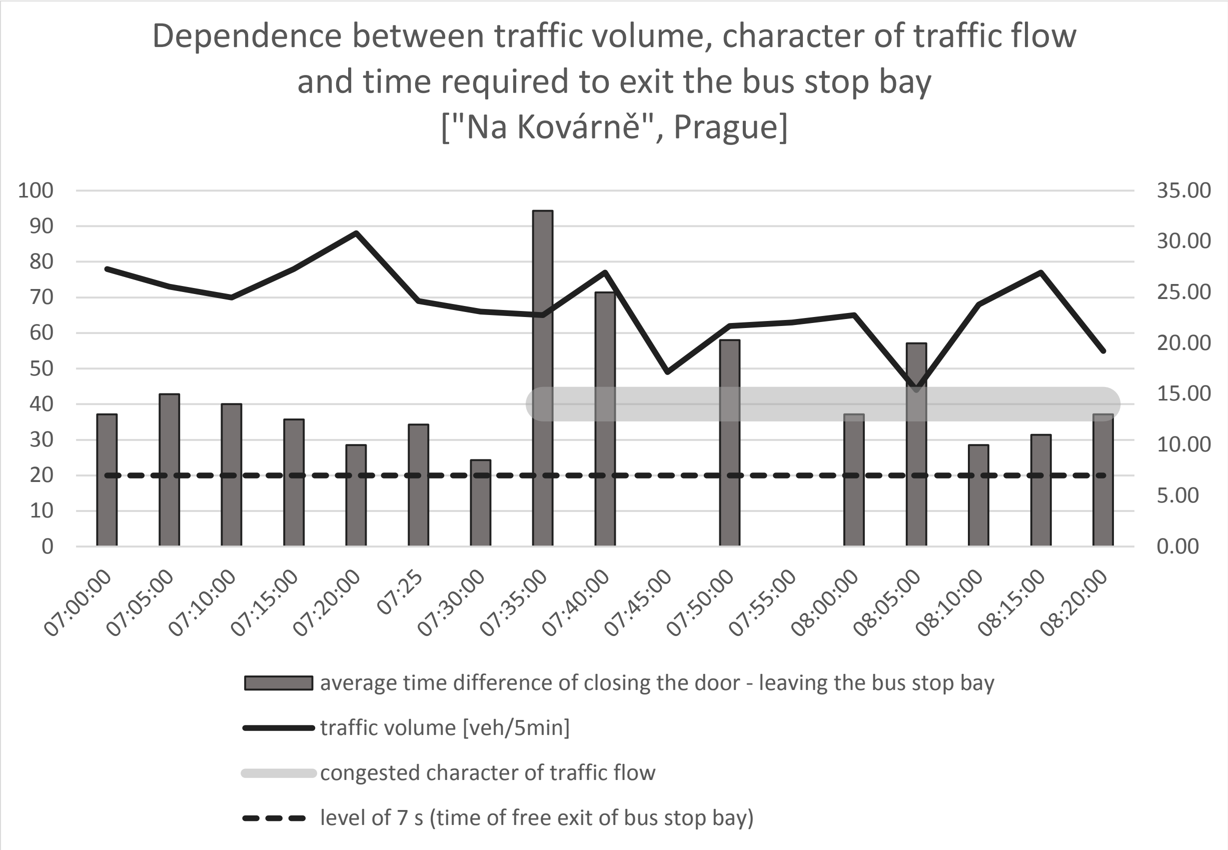

Fig. 6. Analysis of the situation when a bus exits a bus stop bay
Fig. 6. Dépendance entre le volume de trafic, le caractère de la circulation et le temps requis pour quitter la baie de l'arrêt de bus

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