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Quantitative Assessment of the Bus Rapid Transit Efficiency in Solving the Problems of Motorization of Modern Cities

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In this situation, the possibilities of public transport look very attractive. Vukan R. Vuchic, the wellknown American scientist, underlines that city governments recognize urban public transport as the critical element in achieving a balanced transportation system. In this case, “the support for urban transit provided by federal/national and other levels of government have played a major role in its upgrading through research and development, financing of a new system, new modes, and applied research for solving technical, operational and planning problems” [8].

The possibilities of urban passenger transport in improving the transport situation of large cities are highly appreciated not only by specialists in this field but also by prominent organizations, such as American Public Transport Association (APTA). According to APTA technology for big cities public transit is Bus Rapid Transit (BRT) enhanced with modern elements of ITS. In 2010 APTA issued a document «Implementing BRT Intelligent Transportation Systems». It established recommended practices for incorporating Intelligent Transportation Systems into Bus Rapid Transit Services and Infrastructure [7].

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Veniamin Bogumil

I. Introduction

The cause of congestions of traffic flow is its oversaturation with private cars. The fraction of private cars within traffic flow exceeds 80% [1]. Another reason is the low utilization of private vehicles. In Moscow, according to statistic, the average number of passengers in a car during rush hours is about 1.5 [1].

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The possibilities of urban passenger transport in improving the transport situation of large cities are highly appreciated not only by specialists in this field but also by prominent organizations, such as American Public Transport Association (APTA). According to APTA technology for big cities public transit is Bus Rapid Transit (BRT) enhanced with modern elements of ITS. In 2010 APTA issued a document «Implementing BRT Intelligent Transportation Systems». It established recommended practices for incorporating Intelligent Transportation Systems into Bus Rapid Transit Services and Infrastructure [7]. The document includes a very helpful recommendation in general. But decision-makers need to calculated any planned activity in any particular case and answer questions such as:

- What are the problems to be overtaken?
- What is the goal of this activity?
- What is the result to be achieved?
- What is another benefit?
- How much does it cost?

The nature of the answers for such questions needs to be not qualitative but quantitative.

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The problem is that the highway is overload regularly during morning or evening rush hours and thousands of people are stucked in traffic losing their time.

Here we consider BRT as a problem-solving tool. Our goal is to get a quantitative assessment of the Bus Rapid Transit lane implementation efficiency considering a specific use case.

In this article, we'll try to discuss a situation with suburban service which occurs every morning and evening on main highways between downtown and outlying suburban area. To be concrete, we assume that highway length (L) connecting suburban area and downtown is15 kilometers and it has eight lanes (l): i.e., four lanes in each direction. Therefore, four lanes of highway from suburb to downtown are overloaded during morning rush hours, and another four lanes from downtown to suburb overloaded during evening rush hours.

1. Estimation of traffic flow parameters

To obtain quantitative estimates, we will use the relations between the average speed and the average density of the traffic flow, determined by the fundamental diagram. American scientists created the "following the leader" theory and found out that in dense traffic flow conditions the relationship between the average speed (V) and average traffic density (ρ) on a highway lane is expressed by the formula [5,6]:

$$V = C_1 e^{-c_2 \rho} \qquad (1)$$

We have conducted studies of Moscow highways to obtain parameters C_1 and c_2 in (1) expression for dense traffic flow. We estimated that for traffic density ρ: $50 < \rho < 160$, the relationship between the average speed (V) and average traffic density (ρ) one can express by the formula [2]:

$$V = 86e^{-0.02\rho} \text{ km/h} \qquad (2)$$

According to equation (2), the density of the traffic flow one can express as follows:

$$\rho = 50(ln86 - lnV) \text{veh/km} \qquad (3)$$

Let's assume that the average speed of dense traffic flow is 10 km/h. So our commuters spend 1.5 hours to reach downtown in the morning and another 1.5 hours to return home in the evening. Three hours in total for transport every working day are unacceptable.

The density of dense traffic flow, according to equation (3) is:

$$\rho = 50(ln86 - ln10) = 108 \text{ cars/km} \quad (4)$$

The number of cars, moved in dense traffic (N_c), one can estimate as follows:

$$N_c = T_r V l \rho \text{ cars/hour}, \quad (5)$$

where,

Tr –Rush hours;

V – Average speed of traffic flow in congested mode;

ρ – Density of dense traffic flow;

l – Number of lanes of the congested side of the road;

Let's estimate the intensity of traffic flow during one rush hour. In our case, according to (5)N_c value one can estimate as follows:

$$N_c = 1*10*4*108 = 4320 \text{ cars/hour} \quad (6)$$

From equation (6) we can calculate N_c^1=1080 cars/hour – the number of cars, moved in dense traffic flow in our case during one hour. And number of cars remain in dense traffic flow Nc^r= 4320 -1080=3240 cars/hour.

To solve the problem, we propose to organize dedicated BRT lane, eliminating part of cars from traffic flow and carry passengers of eliminating cars by BRT buses. Therefore, for this purpose one lane of the highway in each direction need to be dedicated to BRT buses. In new conditions, only three lanes in each direction will be available for private cars.

2. Replacement possibilities of separated BRT lane

Let's introduce an "elimination coefficient" k as follows:

$$k = \frac{C_{bus}}{C_0} \quad (7)$$

where:

C_o – Average number of private car passengers during rush hour period, passengers/vehicle

C_{bus}–Capacity of BRT bus.

The sense of the k coefficient is an average number of private cars, which one can eliminate by one BRT bus. It depends on the average occupancy of a private car during the rush hour period. The mandatory condition is that BRT bus not be overloaded during the trip. So, let's assume that during rush hours the bus passenger load is not excided established normative value [3, 4]. Then the total number of private cars (N_e), eliminated during one hour period by dedicated BRT lane can be estimated as follows:

$$N_e = kf \quad (8)$$

where:

k – Eliminating coefficient

f – Frequency of BRT bus movement, vehicle per hour.

Let's estimate the value of *k* coefficient for different types of buses and value of average occupancy of a private car. Let's consider two types of city bus:

1) A regular bus with normative capacity (C_{bus}) equal to 100 passengers.
2) An articulated bus with normative capacity (C_{bus}) equal to 140 passengers.

Let's suppose that the value of average occupancy of a private car during rush hour period (C_o) lays in the limits: 1.1 $\le C_o \le$ 1.5 passengers per vehicle. With this assumption in mind, according to (8) we have:

1) For regular bus: 100/1.5 ≤k≤ 100/1.1, so 67 ≤k≤ 91 private cars per bus;
2) For articulated bus: 140/1.5 ≤k≤ 140/1.1, so 93≤k≤127 private cars per bus.

Let's estimate "status quo" situation, when BRT lane replaces regular highway lane as 1:1, In this case, BRT buses need to carry passengers of 1080 cars replaced every rush hour.

For frequency of BRT bus movement from equation (9) we have:

$$f = \frac{N_e}{k} \quad (9)$$

Denote f_0 –frequency of BRT buses, needed to eliminated 1080 cars per hour for BRT lane to replace regular highway lane as 1:1.

So, we have:

1) For regular buses: 1080/91$\le f_0 \le$ 1080/67, so 12$\le f_0 \le$ 16BRT buses per hour. In this case the headway (h_0=60minutes/f_0) is estimated as follows: 60/16 $\le h_0 \le$ 60/12, so 3.75 $\le h_0 \le$ 5.0 minutes.
2) For articulated buses: 1080/127$\le f_0 \le$ 1080/93, so 9$\le f_0 \le$12 BRT buses per hour. In this case the headway (h=60minutes/f_0) is estimated as follows: 60/12$\le h_0 \le$ 60/8, so 5.0$\le h_0 \le$7.5 minutes.

To be attractive, BRT buses must have Right of Way (ROW) Category (B) [8] that are longitudinally physically separated lane by carbs. In this case, BRT buses movement not depend on traffic parameters. We suppose that BRT bus maximum speed along the separated lane is 60 km/h. We suppose that to keep maximum speed value 60 km/h for the separated lane, headway for BRT buses must not be less than 2 minutes for safety and organizational reasons which correspond to maximum frequency f_{max}=30 buses per hour. So, we have the reserve of capacity of BRT lane, which can be used to eliminate additional vehicles from another three lanes and to raise the average speed of dense traffic flow on regular lanes.

Let's denote $\Delta f = f - f_0$, additional frequency of BTR buses movement that one can spend to eliminate additional vehicles from congested lanes to rise average speed. Using equations (2), (4) and (8) we can express the dependence of average speed (V=f(Δf,k,l)as follows:

$$V = 86e^{-0,02(108-\frac{k\Delta f}{Ll})} \text{ km/h,} \quad (10)$$

where,

Δf – additional frequency of BTR buses movement that one can spend to eliminate vehicles from regular lanes to rise average speed;

l – The number of regular lanes;

k – The eliminating coefficient,

L – The length of highway, kilometers.

The fraction $\frac{\Delta fk}{Ll}$ reflects the possibility of BRT lane to eliminate additional vehicles from congested lanes and to rise the average speed on regular lanes.

Let's see a numeric example.

In our case the number of regular lanes equal to 3. As was shown before, f_0 value belongs to a numeric interval (12, 16) and the numeric interval range depends on the average number of passengers of private cars.

We suppose that maximum frequency value equal to 30 buses per hour. So, if the average number of passengers of private cars equal to 1, 5 then coefficient k=67 and Δ f can vary from 0 to (30-16) or inside the interval (0,14).

If the average number of passengers of private vehicles equal to 1,1 then coefficient k=91 and Δ f can vary from 0 to (30-12) or inside the interval (0,18). If values of parameters "l" and "k" are fixed, we can consider V value as a function of Δ f with numeric parameters "l" and "k". For k=67 and l=3 equation (10) is shown as:

$$V = 86e^{-0,02(108-\frac{67\Delta f}{15*3})} \text{ km/h,} \quad (11)$$

For k=91 and l=3 equation (10) is shown as:

$$V = 86e^{-0,02(108-\frac{91\Delta f}{15*3})} \text{ km/h,} \quad (12)$$

Function graphs for this case is shown in Figure 1a and 1 b. As we can see, if the frequency of BRT buses raise to a prescribed maximum value equal to 30 buses per hour and carry addition number of passengers, and eliminate private cars from traffic, average speed value rises to approximately to 16 kilometers per hour.

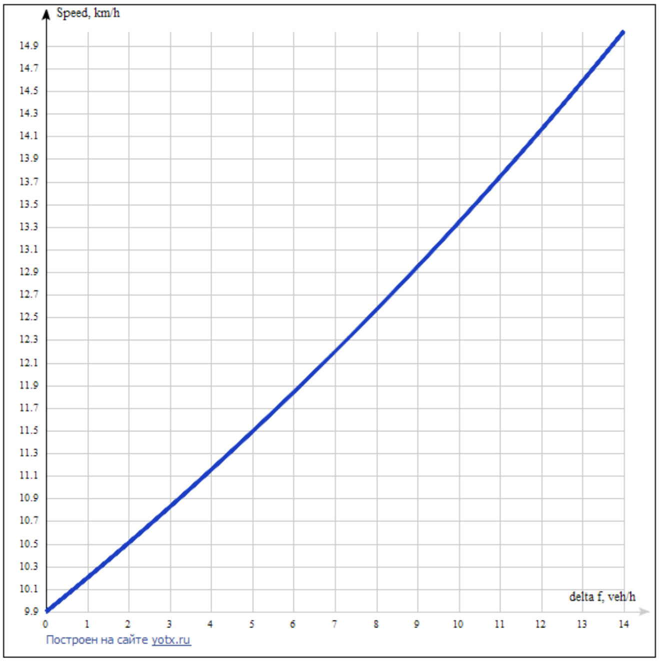
In case of the articulated bus, if the average number of passengers of private care equal to 1.5 then k=93, f_o=12, Δ f can range from 0 to 18 buses per hour. The average speed of traffic flow one can estimate as follows:

$$V = 86e^{-0,02(108-\frac{93\Delta f}{15*3})} \text{ km/h,} \quad (13)$$

If the average number of passengers of private care equal to 1.1 then k=127, f_o=8, Δ f can range from 0 to 22 buses per hour. Average speed of traffic flow can be estimated as follows:

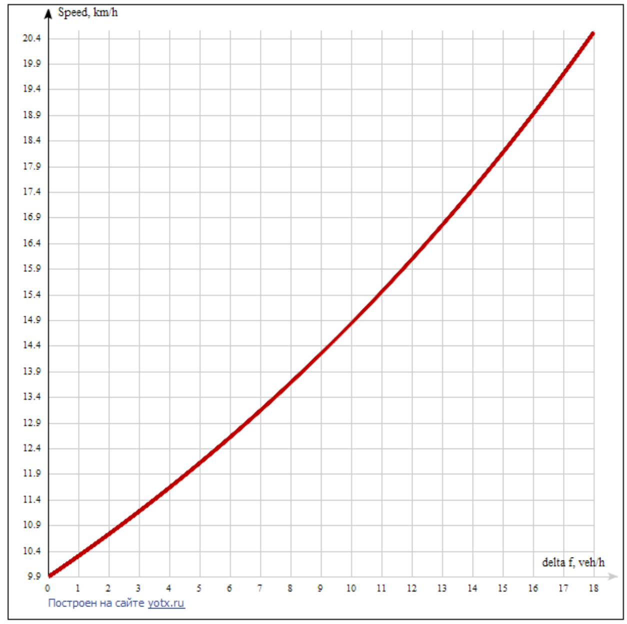
$$V = 86e^{-0,02(108-\frac{127\Delta f}{15*3})} \text{ km/h,} \quad (14)$$

Function graphs for this case are shown in Figure 2a and 2 b.



1a

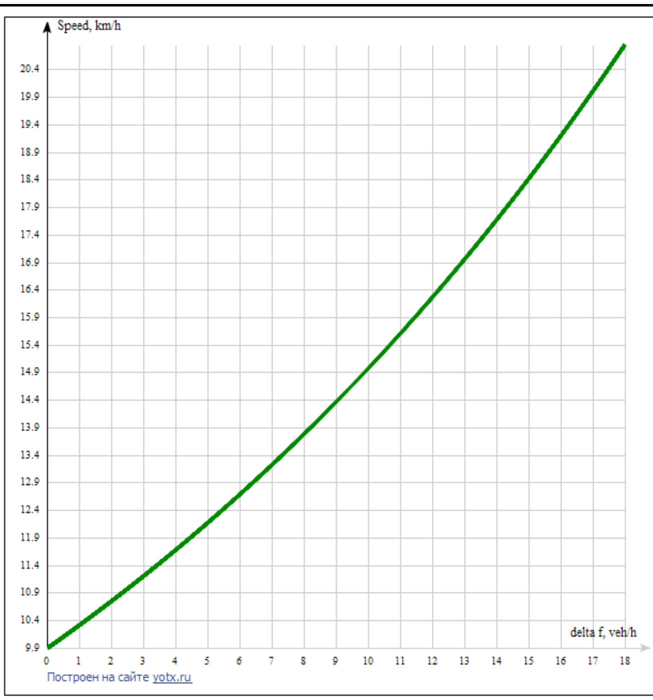
BRT Bus Capacity equal to 100 passengers, the average number of passengers in private car equal to 1.5



1b

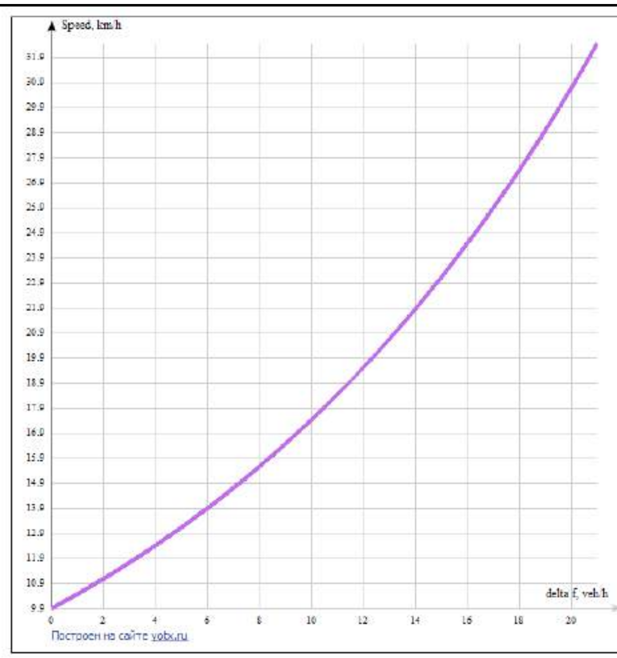
BRT Bus Capacity equal to 100 passengers, the average number of passengers in private car equal to 1.1

Figure 1: Dependence of the average speed of the traffic flow on the movement frequency of regular BRT buses and the average number of passengers in private cars.



1a

BRT Bus Capacity equal to 140 passengers, the average number of passengers in private car equal to 1.5



1b

BRT Bus Capacity equal to 140 passengers, the average number of passengers in private car equal to 1.1

Figure 2: Dependence of the average speed of the traffic flow on the movement frequency of BRT buses and average number of passengers in private cars.

3. Operating speed and travel time estimation

Travel time depends not only maximum speed but on the number of stops. Let's estimate, how much time we need to spend for stops. The components of spending time are:

- Passenger's boarding time;
- Passengers alighting time;
- Bus accelerating time;
- Bus decelerating time;

We assume that 1)During transportation from suburb to downtown, passengers only boarding buses in suburb area and alighting buses in the downtown area.2) During rush hours bus passengers load equal to bus capacity. 3) Quality of transfer process is rather high, so buses are not overloaded. Therefore, time for boarding/alighting process during the trip (T_{ba}) can be estimated as follows:

$$T_{ba} = \frac{C_{bus}}{N_d \lambda} + \frac{C_{bus}}{N_d \mu}\text{, seconds} \qquad (15)$$

where:

C_{bus} – The capacity of BRT bus;

N_d – Numbers of bus doors for boarding/alighting;

λ –Boarding rate, second per passenger per door;

μ – Accelerating rate, second per passenger per door.

Another time spend on accelerating/ decelerating bus (T_{ad}) at each stop. This time can be estimated as follows:

$$T_{ad} = (N_{st} - 1)\left(\frac{V_{max}}{3.6a} + \frac{V_{max}}{3.6d}\right)\text{, seconds} \qquad (16)$$

where:

N_{st} – Number of stops on the route;

V_{max} – Maximal speed on the route, km/h;

a –bus acceleration rate, m/sec^2;

d – bus deceleration rate, m/sec^2.

The third component of time spend on running along the route with maximum speed (T_{msp}). This time with the same notation one can estimate as follows:

$$T_{msp} = \frac{3.6[1000L - 0.5(N_{st} - 1)(at_a^2 + dt_d^2)]}{V_{max}}\text{, seconds} \qquad (17)$$

where L – Length of the route lane, km.

Operating time (T_o) can be estimated as follows:

$$T_o = \frac{T_{ba} + T_{ad} + T_{msp}}{60}\text{, minutes} \qquad (18)$$

Operating speed (V_0) for a line one can estimate as follows:

$$V_o = \frac{3600L}{T_{ba} + T_{ad} + T_{msp}}\text{, km/h} \qquad (19)$$

Let's estimate the dependence of operating speed on numbers of bus stops on the route in our case for regular and articulated buses.

We assume that regular and articulated buses typical dynamic characteristic are: approximately acceleration rate a=1.6 m/sec^2. Therefore, acceleration time to reach maximum speed 60 km/h t_a=10 seconds; deceleration rate d=1 m/sec^2.Therefore, deceleration time to decelerate from 60 to 0 km/ht_d=16 seconds.

Let's calculate length of acceleration/ deceleration way (S). In total S= 0.5[a(t_a)^2 + a(t_a)^2]= 0.5[1.6*100 + 1.0*256]=0.5[160+256]=208 meters. Time spent for acceleration/deceleration equal to 10 +16= 26 seconds.

According to statistics, we have boarding/ alighting rate from for low floor buses estimated from 2.0 to 2.5 second per passenger per door when fare collection organized before boarding []. We assume that boarding rate λ=2.0 second per passenger per door, alighting rate μ=2.0 second per passenger per door.

Using equations (15),(16),(17),(19) we can for regular bus write out the equation as follows:

$$V_o = \frac{3600L}{\left[\frac{C_{bus}}{N_d \lambda} + \frac{C_{bus}}{N_d \mu}\right] + \left[(N_{st} - 1)\left(\frac{V_{max}}{3.6a} + \frac{V_{max}}{3.6d}\right)\right] + \left[\frac{3.6[1000L - 0.5(N_{st} - 1)(at_a^2 + dt_d^2)]}{V_{max}}\right]}\text{,km/h} \qquad (19)$$

After substitution we have for the regular bus:

$$V_o = \frac{3600*15}{[\frac{90}{2*2}+\frac{90}{2*2}]+[(N_{st}-1)\,(\frac{60}{3.6*1.6}+\frac{60}{3.6*1.0})\,]+[\frac{3.6[1000*15-0.5(N_{st}-1)(1.610.0^2+1.0*16^2)\,]}{60}]} \quad (20)$$

After simplification we have:

$$V_o = \frac{54000}{[45]+[(N_{st}-1)(27.12)\,]+[\frac{3.6[15000-0.5(N_{st}-1)(416)\,]}{60}]} = \frac{54000}{930.36-14.64N_{st}}\text{, km/h} \quad (21)$$

For articulated buses we have:

$$V_o = \frac{3600*15}{[\frac{140}{3*2}+\frac{140}{3*2}]+[(N_{st}-1)\,(\frac{60}{3.6*1.6}+\frac{60}{3.6*1.0})\,]+[\frac{3.6[1000*15-0.5(N_{st}-1)\,(1.610.0^2+1.0*16^2)\,]}{60}]} \quad (22)$$

After simplification we have:

$$V_o = \frac{54000}{[46{,}7]+[(N_{st}-1)(27.12)\,]+[\frac{3.6[15000-0.5(N_{st}-1)(416)\,]}{60}]} = \frac{54000}{931.96-14.64N_{st}}\text{, km/h} \quad (23)$$

We can see, that dependence of operating speed on numbers of bus stops almost identical for regular and articulated buses(see equations (21) and (23)).

The graph for operating speed for the regular bus (equation 21) is shown in figure 3.

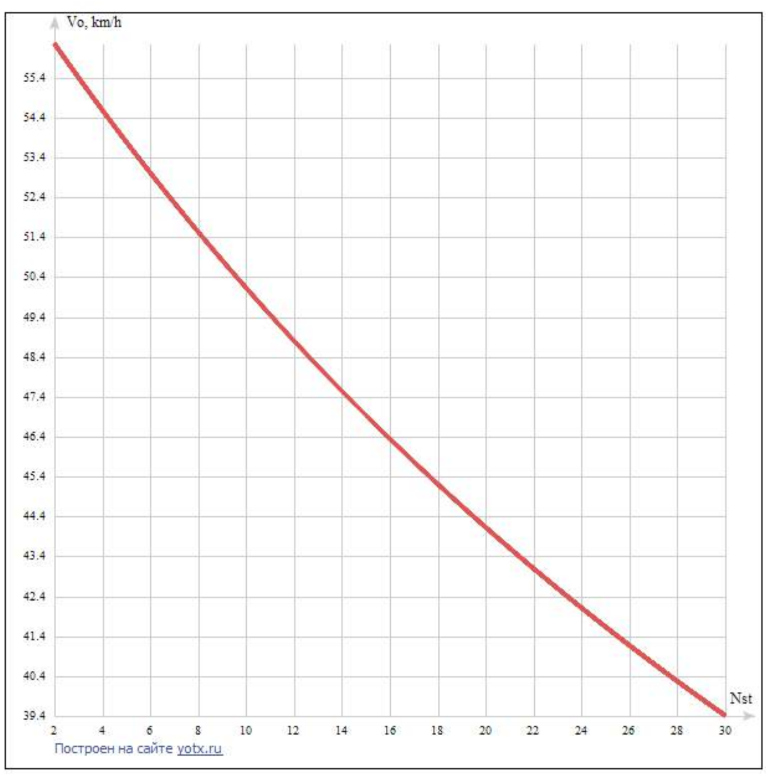


Figure 3: Dependence of bus operating speed on numbers of bus stops on the route for regular buses.

The number of stops varies from 2 to 30. Two stops on the route are terminals only. 30 stops mean two bus stops per kilometer in average. If the number of stops rises then operating speed drops significantly.

II. Conclusion

During rush hours travel time from suburb to downtown significantly less than for private vehicles congested in a regular lane. Buses can move along separated BRT lane with maximum speed 60 km/h. The Capacity of BRT bus lane and the operational speed depend on the number of bus stops. The best attraction of BRT lane is buses high speed during rush hours. If the number of stops on the route is not big, then operating speed value is close to maximum speed. Therefore, the number of bus stops of BRT route must be limited to ensure BRT passengers speed advantage over private cars passengers during rush hours.

Annotation

The article deals with public transport. It discusses the possibilities of this transport in solving complex problems that rizrd as a result of uncontrolled motorization. The article focuses on the case study of commuter's movement from suburb to downtown of the city and back along a highway during rush hours when chronic congestions occur.

Quantitative estimations of the Bus Rapid Transit efficiency developed and its prospect to eliminate traffic flow congestions discussed. The effects one could reach if (and only if) part of the passengers using private cars will agree to change the mode of transportation and use buses on BRT route. The goal could be reached if the BRT transportation process will be comfortable, buses will not overloaded during rush hours, and operating speed will be much more than the average of dense traffic[7,8].

Calculations of the operating speed, travel time, number of BRT buses, needed to eliminate traffic jam, are presented. The calculations made by Fundamental Diagram. Parameters of analytical expressions used were estimated by the author with statistical data, gathered during traffic flow observation on the highways of Moscow and its suburb.

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