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OPTIMIZATION OF STREET LANE USAGE

1. Introduction

With increasing deficit of road space in urban areas, making use of road space efficiently remains the only comprehensive solution. The number of lanes cannot be freely increased in accordance to the varying demand constraints i.e. spatial, maintenance, functional, environmental and economical as this will only encourage further traffic growth. The objective of urban traffic is to move passenger - an individual travelling by either private car or public transport (microbus, bus, tramway etc). One of the aims of transportation policy is to ensure convenient trip conditions for a given number of individuals. This however is not consistent with the aim put up by traffic engineers, where maximisation of lanes/intersections traffic flow is the main goal. The most preferred mode of transport in most urban areas is still the private car. However this mode disclose its biggest disadvantage in urban traffic - very high unit space seizure (with reference to number of passenger per vehicle) when it comes to utilisation of road space and parking. If no restrictive measures are taken, the car flow will increase toward road capacity causing the average stream speed to decrease from the free flow speed to the speed at maximum traffic flow. Beyond this point the internal friction between vehicles in the stream becomes severe, the traffic conditions worsen and severe shock waves and slow-moving platoons develop. Making a trip by use of cars only would mean time dissipation, rapid deterioration in the link flow conditions and in consequence limiting the mobility of the community. This can be controlled and managed by raising the standard of the public transport services (and in consequence high share of public transport in urban trips), which is characterised by an average of 10 times more efficient in utilisation of road space in urban areas than private car. Therefore, the proportion of vehicles composition in traffic - used here for the purpose of this paper to mean the share of buses and private cars in road traffic, can have a dominating effect to the efficiency of lane utilisation. The problem of optimum utilisation of traffic lanes had been the subject of extensive research for several decades. Exhaustive analyses of the state of the art of the models (and general methods) for simultaneous network assignment and modal split modelling are presented (e.g. in [2], [3] and [6]). The main task is to determine an optimum point of bus volume in congested conditions at which an exclusive bus lane should be introduced. This is important because a bus lane shouldn't be implemented without first undertaking a comparative evaluation of the expected benefits to bus passengers against any estimated disbenefits to car passengers. The introduced recommendation, as a starting point is taken to determine the flow of passengers in mixed traffic, i.e. the modal split is determined. The optimisation models with consideration of feedback evaluation between trip production, trip distribution, model split and trip assignment have been considered in [4] without specific cases and elaborated methodology. Lack of such solution seems to be a "hard task" - i.e. how optimally to carry trip-makers with consideration of passenger flow, their preferred mode of transport as well as given traffic conditions. Such an attempt has been taken up in this paper.

2. Assumptions and essence of the model

The objective of the study is to analyse the effect of modal split in servicing trips by individual transport (private car) and public transport (bus) on efficiency of street sections utilisation with different numbers of lanes. Mode choice is a travel choice in itself and can vary for different journeys where performance or level-of-service attributes have considerable influence. The choice of mode in general conditions, depending on mode availability is influenced by many factors. The share of different modes in trips is the sum of individual decision utility. A typical urban trip of a given length will be considered, which is made along the corridor of a multilane street as well as a bus line (or bus lines). The accessibility to the defined arterial for public transport passengers will be access to the bus stop and waiting for the bus. For private car, this will be the access to and egress from parking which has been assumed to be located adjacent to the arterial. It is assumed on addition that the arterial functions as a typical urban transport facility i.e. the traffic at intersections is controlled by traffic signals. The inlets to the intersections are wide enough in such a way that, it will be possible to maximally use the practical capacity between two intersections. The considered range of traffic volume changeability wouldn't exceed two times the value of practical capacity. A simplified traffic composition of a section is then assumed: only private cars and buses of public transport will use the road section. Heavy good vehicles are omitted, which can be partly justified by low share of these types of vehicles in urban traffic. A uniform street section of a given length will be considered (equivalent to the average trip distance covered in most cities) with the following numbers of traffic lanes and their utilisation as shown in Fig 1.

- a four lane street
  - without exclusive lane for buses
  - with exclusive lane for buses
- A six lane street
  - without exclusive lane for buses
  - with exclusive lane for buses

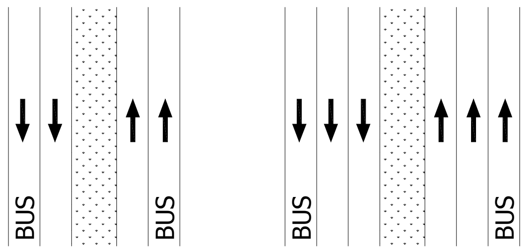

Fig.1. a four lane street and a six lane street

The model input parameters are:
- trip distance (corridor length),
- sum of access time and egress time to and from the bus stop or parking in relation to origin and destination of the trip,
- practical capacity ,
- free flow speeds of buses and private cars,
- speed of buses on exclusive lane (it's assumed that there won't be auto-congestion i.e. the speed doesn't depend on traffic volume in exclusive lane),
- average occupancy rate of passenger car in urban traffic,
- maximum acceptable average number of passengers per bus,
- average unit operational cost for buses and private car (in relation to unit travel length).

The model variables (dependent on link performance) are:
- the required service frequency of buses (dependent on the number of passengers),
- average waiting time for buses (expressed as a function of the bus frequency),
- real travel speed of buses and private cars on lanes designated for all types of vehicles (dependent on traffic volume),
- modal split (the share of buses and private cars in motorised trips dependent on the ratio of travel time by these modes).

A feedback is obtained from the above values. The control variable is the number of passenger flow along the corridor. The final function which will be taken will be of a given traffic volume and lanes utilisation which ensure the maximum passenger flow in consideration to:

- minimum time lost while making a trip,
- minimum operational cost,

On addition, the general aim will be the degree of conformity with transportation policy in urban areas which recommends maximum share of public transport in urban trips.
The basic dependants used are:

- modal split - a binary logit model calibrated for a Polish city,
- a function for predicting travel speed - a link-capacity function model calibrated for different street categories in Polish cities. It assumes that, the degree of speed reduction due to the increasing traffic volume is the same for cars as well as buses, taking into account the free flow speed diversity of these vehicles.

In the initial step, a fixed demand is assumed, whereby the demand flows are independent of variations due to road network congestion. The total travel demand (number person trips) carried depend on supply (link) capability. However, by use of binary logit model an elastic demand between public transport and private cars is obtained due to the facility performance. This elastic demand (flow) is a function of travel time resulting from congestion. Obviously, from a practical viewpoint, demand elasticity is relevant only for congested networks where cost (in our case travel time) depends on flow. The effect of varying congestion in streets due to operational cost is not taken into account. Its inclusion e.g. in form of generalised cost would give a better solution for link performance.

3. The basic dependants used in the model

The adjusted (real) travel time t_r can be estimated by use of capacity restraint function:

$$t_r = t_o \left[1 + c \left(\frac{q}{q_p} \right)^3 \right] = t_o \cdot f(q) \qquad (1)$$

t_o - free flow travel time,
c - constant for a given category and street section,
q - traffic volume,
q_p - practical capacity for the street section (critical traffic volume),
$f(q)$ - link performance function relating the physical and functional street characteristics to the degree of capacity usage.

A binary logit model is used to estimate the share of public transport in motorised trips:

$$U_z = \frac{1}{1 + a\, e^{-bS_t}} \qquad (2)$$

a,b - parameters calibrated for a given city,
S_t - the ratio of trip travel times t_i/t_z where,
t_i - trip travel time by individual transport (private car),
t_z - trip travel time public transport (bus).

For private cars t_i is defined by

$$t_i = t_{di} + t_{ri} \tag{3}$$

t_{di} - access and egress time to and from the parking,
t_{ri} -real in-vehicle travel time by private car.

The in-vehicle travel time by private car can then be calculated using eq. (4)

$$t_{ri} = \frac{l_p}{v_i} \tag{4}$$

l_p - travel distance (equivalent to the corridor length),
v_i - average travel speed by private car.

Analogically, the trip travel time by public transport can be defined as

$$t_z = t_{dz} + t_{cz} + t_{rz} \tag{5}$$

t_{dz} - access and egress time to and from the bus stop,
t_{cz} - waiting time at the bus stop,
t_{rz} - real in-vehicle travel time by bus.

$$t_{rz} = \frac{l_p}{v_z} \tag{6}$$

l_p - travel distance (equivalent to the corridor length),
v_z - average travel speed by bus.

Using eq. (2) the share of trips by private car is:

$$U_i = 1 - U_z \tag{7}$$

If we denote the number of trips (passenger flow) by private cars as N_i and buses N_z, then the total number of trips along the corridor will be:

$$N = N_i + N_z \tag{8}$$

The traffic volume of private cars q_i will be

$$q_i = \frac{N_i}{n_i} = \frac{N}{n_i} \cdot U_i = \frac{N}{n_i} \cdot \frac{a \cdot e^{-bS_t}}{1 + a \cdot e^{-bS_t}} \tag{9}$$

n_i - average occupancy rate of a passenger car.

While the traffic volume of buses q_z:

$$q_z = \frac{N_z}{n_z} = \frac{N}{n_z} \cdot U_z = \frac{N}{n_z} \cdot \frac{1}{1 + a \cdot e^{-bS_t}} \tag{10}$$

n_z - design capacity of a bus (a constant dependent on bus type).

Using eq. (10), the average waiting time at the bus stop for a perfectly regular line, i.e. the headways between successive bus arrivals will be constant and can be given by:

$$t_{cz} = \frac{1}{2q_z} \tag{11}$$

In the case of the street section with separated lane for buses, the ratio of trip travel time by both modes of transport will be:

$$S_t = \frac{t_{di} + t_{oi}\left[1 + c\cdot\left(\frac{q_i}{q_{pi}}\right)^3\right]}{t_{dz} + \frac{1}{2q_z} + t_{oz}\left[1 + c\cdot\left(\frac{q_z}{q_{pz}}\right)^3\right]} \tag{12}$$

Where indices i and z are related to private car traffic and bus traffic consecutively.
q_{pi} means the practical capacity of lanes used by private cars while q_{pz} is the capacity of separated lane used by buses. Using eq. (9), (10) and (11), the S_t can be calculated iteratively using eq. (12) which can then be substituted to eq. (2) to calculate U_z as well as U_i in eq. (7). Once this is known, the parameters q_i, q_z, t_i, t_z, can then be calculated using the formulas above.

In the case of mixed traffic i.e. without separated lane for buses one can use eq. (13)

$$q = q_i + q_z = \frac{N}{n_i \cdot n_z}\left[n_i + \frac{(n_z - n_i)\cdot ae^{-bS_t}}{1 + ae^{-bS_t}}\right] \tag{13}$$

Where,

$$S_t = -\frac{1}{b}\ln\left[\frac{1}{a}\left(\frac{q\cdot n_i \cdot n_z - N\cdot n_i}{N\cdot n_z - q\cdot n_i \cdot n_z}\right)\right] = g_1(q) \tag{14}$$

Or expressing it analogically to eq. (12),

$$S_t = \frac{t_{di} + t_{oi}\left[1 + c\cdot\left(\frac{q}{q_p}\right)^3\right]}{t_{dz} + \frac{1}{2q_z} + t_{oz}\left[1 + c\cdot\left(\frac{q}{q_p}\right)^3\right]} = g_2(q) \tag{15}$$

Where $q = q_i + q_z$ and q_p is capacity of all lanes in mixed traffic.
Using eq. (14) or (15), q can be calculated interactively. If q is known we calculate S_t by use of eq. (14), q_i by eq. (9), q_z by eq. (10) and t_i, t_z, U_i, U_z by the formulas given above.
It is easy to see that for the various cases of total number of trips N, different length of corridors in the city l_p, different average occupancy rate of a private car n_i and buses n_z, transportation planners can make a decision on whether to introduce the exclusive lane for buses or not.

In order to compare the effectiveness of street usage (with or without the exclusive lane for buses), the average travel time lost by all passengers can be used as a criterion and can be calculated as follows:

$$\overline{T} = \frac{1}{N}(t_i \cdot N_i + t_z \cdot N_z) \tag{16}$$

or the total operation costs criterion expressed as:

$$\overline{K} = \alpha \cdot l \cdot q_i + \beta \cdot l \cdot q_z \tag{17}$$

Where, α is the cost per kilometre for private cars, β the costs per kilometre for buses and l is the length of the corridor. For initial approximations one can assume that the constants $\alpha = 0.6$ [EURO/km] and $\beta = 0.2$ [EURO/km]. These values are suitable for Polish conditions.

4. Obtained results

For numerical calculations the MATLAB software was used for searching of the optimal solution. The following parameter values were taken for the above formulae

t_{oi}	t_{oz}	c	q_p	a	b	t_{di}	l_p	v_i	v_z	n_i	n_z
[min]	[min]	-	[pcu/lane/h]	-	-	[min]	[km]	[km/h]	[km/h]	[pers]	[pers]
8	15	0.97[1)]	1000[1)]	2.50[2)]	1.63[2)]	3	3;10	35	20	1.2	70;120

1) value calibrated by Brzeziński and Wartz [1] for main arterials in Poland.

2) values calibrated by Wainaina [7] for Krakow city.

In Fig. 1a. – 3b., the relationship between traffic volume of buses and private cars, average unit of trip travel time and operational cost as well as share of public transport to the number of people to be carried for different street sections of varying types and length is presented.

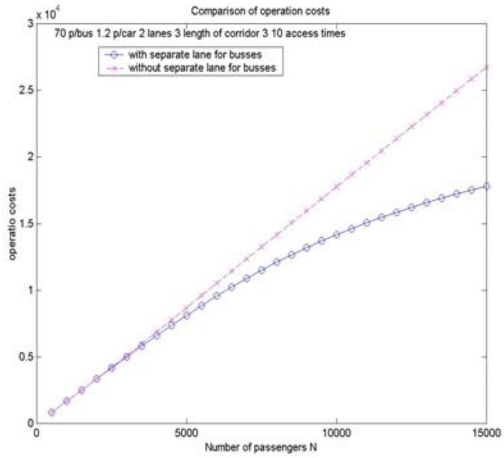

Fig. 1a. Operation costs for the case of 2 lanes, 3 km corridor and bus capacity of 70 passengers.

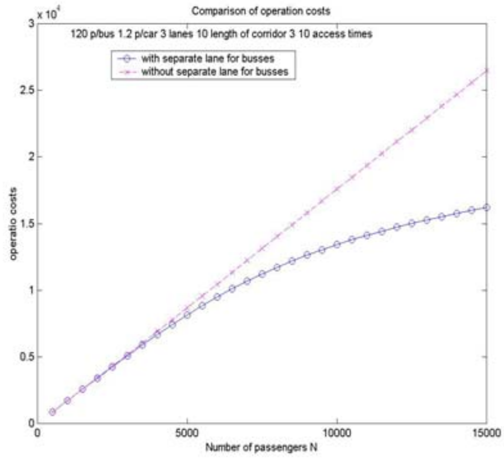

Fig 1b. Operation costs for the case of 3 lanes, 10 km corridor and bus capacity of 120 passengers.

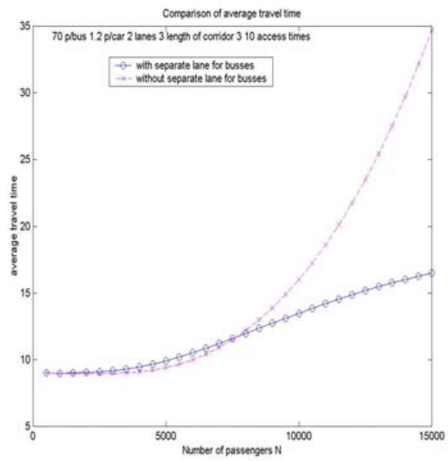

Fig. 2a. Average travel time for the case of 2 lanes, 3 km corridor and bus capacity of 70 passengers.

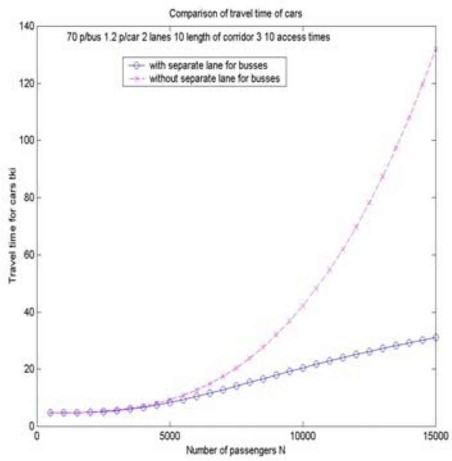

Fig. 2b. Travel time of cars for the case of 2 lanes, 10 km corridor and bus capacity of 70 passengers.

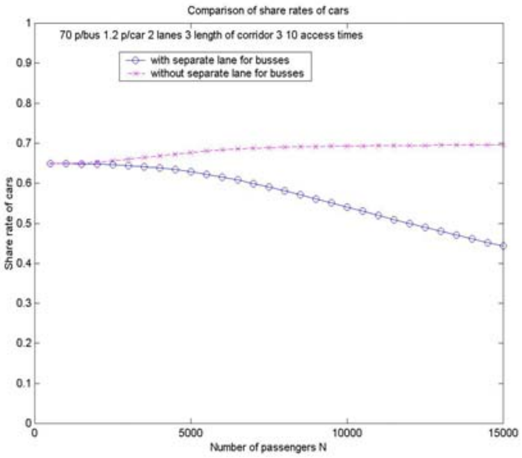

Fig. 3a. Share rates of cars for the case of 2 lanes, 3 km corridor and bus capacity of 70 passengers.

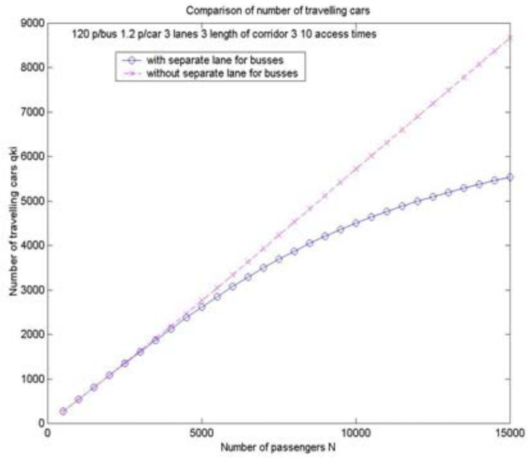

Fig. 3b. Number of travelling cars for the case of 3 lanes, 3 km corridor and bus capacity of 120 passengers.

Based on such figures, the marginal parameter values can be estimated for which introduction of exclusive lane for buses is fully justified. Table 1 shows the marginal values for the street section 2/3 got by use of EXCEL software and using the parameters l_p =5 km, n_i = 1.5 and n_z = 70 taking into consideration the unit average travel time lost and operational cost criteria.

Optimisation criterion	Travel time		Operational cost	
Ways of using street lanes	Street without separated lane for buses only	Street with separated lane for buses only	Street without separated lane for buses only	Street with separated lane for buses only
Marginal values (minimum) for number of people carried at which separated lane for buses is most effective	15 500		8250	
Marginal traffic volume for private cars [veh./h]	5150	3700	2780	2790
Marginal traffic volume for buses [veh./h]	112	143	59	59
Share of public transport in trips [%]	50	64	49	49

5. Comments of obtained results

1. Due to the complicated formulation of the relationship between the share of public transport in motorised trips to traffic volume as well as to average travel speed, the use of analytical methods e.g. differential equations for optimisation, proved to be time consuming and inefficient.
2. The criterion of minimising average travel time gives higher traffic flow values for buses and private cars on the shared street lanes than the criterion of unit operational cost, for which the obtained parameter values recommend to implement exclusive lane at a bus volume of more than 20 buses per hour for a 4-lane street and above 60 buses per hour for 6-lane street. There exists a wide range of sub optimisation when operation cost criterion is used for evaluation.

3. The effective share of trips by public transport along the analysed transport network section should be at least 50%. This is in accordance with frequently used marginal criterion of the modal split between public transport and private cars for binary logit model.
4. The estimated marginal values by use of travel time criterion, gives a higher bus volumes than given in studies conducted elsewhere (e.g. recommendation of the board of public transport in Ottawa [2]). It follows that there is a balance between the benefits and losses perceived by passengers for public transport passengers and individual transport passengers in the analysed section. However, the presented model is wholly dependent on travel time and in this way makes the private car a better mode of transport than public transport (relatively a lot of time lost during its accessibility which include access and egress time as well as waiting time).
5. The effect of diurnal (time of day) distribution of travel demand to the efficiency of exclusive bus lanes suggests the separation of such lanes during the period of increased passenger's conveyance i.e. peak hours, when capacity limitations are very critical.
6. The estimated results are relative to locally calibrated parameter values used in the model as well as functional link parameters and that’s why they can’t have a universal application. However, the used parameter values for estimation don’t deviate from average values of big European cities and that’s why the results give a general outlook for the extent to which an exclusive lane for buses can be optimised in a multilane street.
7. It would be recommended for further research the sensitivity analyses of functional parameters (such as practical capacity, free flow speed, average vehicle occupancy, trip distance, access time to the vehicle) to the formation of optimum range as well as sub-optimum range of the necessity to separate the lane. Due to the effect of city specificity to modal split, it would be necessary in addition to try different values of binary logit model calibrated elsewhere or eventually a different form of modal split model e.g. a multinomial (MNL) logit model.

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