TRANSPORT
ISSN 1648-4142 print / ISSN 1648-3480 online
2014 Volume 29(1): 59–68
doi:10.3846/16484142.2014.897645

SUPPORT OF DECISION-MAKING ON ECONOMIC AND SOCIAL SUSTAINABILITY OF PUBLIC TRANSPORT

Jan Černý[1], Anna Černá[2], Bohdan Linda[3]

[1,2]*Dept of Exact Methods, University of Economics in Prague, Czech Republic*
[3]*Institute of Mathematics and Quantitative Methods, University of Pardubice, Czech Republic*

Submitted 29 May 2012; accepted 4 October 2012

Abstract. The main purpose of the paper is to present theoretical findings suitable as a support of decision-making on economic sustainability and accessibility of public transport. Czech experience with solving this problem is taken into account. The paper focuses on the relationship between two of three pillars of public transport sustainability – social and economic. Accessibility of public transport service for the clients is considered the main feature of the social pillar. Three types of accessibility are taken into account: spatial, time and economic. Indicators of all three types are presented and their role is studied in details. The main factors influencing the indicators are described. It is shown that, usually, strengthening the social pillar is then weakening the economic one. Further, the public transport accessibility issues are discussed in the most complicated case – in the weak demand areas. Demand Responsible Transport (DRT) is presented as an efficient and effective tool in maintaining the public transport sustainable in these areas. Different types of DRT are outlined and evaluated for the purpose of deciding which one to choose.

Keywords: public transport, accessibility, economic sustainability, decision-making, weak demand, demand responsive transport.

Reference to this paper should be made as follows: Černý, J.; Černá, A.; Linda, B. 2014. Support of decision-making on economic and social sustainability of public transport, *Transport* 29(1): 59–68.
http://dx.doi.org/10.3846/16484142.2014.897645

Introduction

This article is a result of research whose aim was to find exact models and methods, supporting managers of public administration and transport companies in their decision-making, concerning the balance between economic and social sustainability of public transport.

When these managers make their decisions, they have to consider them in a broader context. They have to realize that, at the beginning of the 21st century, one of the most important questions is whether the development of the human society is sustainable. As described in Tunčikienė *et al.* (2010), such strategic decisions in public institutions should be supported by a Decision Support System (DSS). The authors hope that the models and methods of solutions supporting these decisions may cooperate with such DSS's or may become an integral part of these systems.

There are three basic pillars of sustainability:
- ecological – humankind will have no future when the environment is not kept fit for life;
- social – only satisfied, not frustrated people can form the basis of a permanently developing society;
- economic – humankind needs sufficient funding for the previous two pillars.

It is necessary to note that this terminology is not universally accepted, e.g. Kennedy *et al.* (2005) call this triplet a 'classic triangle of sustainability' and by 'pillars' they mean four components of moving to sustainable transportation.

Economic efficiency is highlighted as a prerequisite for sustainable development in Bojnec and Papler (2011). Especially, for transport it is emphasized in Hensher (2007).

Finally, it is necessary to emphasize that the harmonization of the ecological and social requirements with the possibilities of the third pillar is a political issue.

This general scheme can also be applied to transport. Its negative environmental impacts such as emissions, noise and appropriation of land are among the

Corresponding author: Jan Černý
E-mail: *cerny@fm.vse.cz*

most serious. On the other hand, transport ensures mobility of the population, which is a highly important social requirement. Also the fact that transport on the one hand consumes but on the other hand produces a huge value, illustrates its role in the third pillar. In this context, it is necessary to change the paradigm of mobility, as shown in Banister (2008).

Public transport has a specific position. It provides a service enabling mobility of people and it also provides a substitute to individual movement of passenger cars which can be regarded as significant polluters of the environment.

The ecological pillar of public transport thus evokes two views. The first observes the direct (negative) impact on the environment. The second conversely sees a positive indirect effect by reducing environmental consequences of individual motorized traffic as public transport takes its place in the mobility of the population.

The economic pillar of public transport is extremely important for the public authorities since they have limited resources created almost entirely by taxpayers, see e.g. Hensher (2007). With the exception of air transport and some lucrative ground transportation, revenues from passengers do not cover the costs of the carriers and this difference has to be met from subsidies from public authorities.

In the sequel, the major attention will be devoted to the social pillar of public transport. Its basic characteristic is accessibility. It expresses the extent to which the service capabilities meet the transport needs of the population. It has the following components:

- spatial accessibility, which can be expressed by the average distance from the starting point to the nearest public transport stop;
- time accessibility, i.e. the average time lag between the time when transportation is required and the time of the nearest usable (bus, etc.) service;
- price (economic) accessibility, which can be expressed either as an absolute amount, for example, the price per person-kilometre (this term will be further abbreviated as pkm), or as a relative amount, in relation to the cost of individual transport.

It is important to emphasize that the paper studies the accessibility issue in general, concerning the major part of 'ordinary' passengers, taking into account that some particular passengers require special care, e.g. seniors, as described in Cao *et al.* (2010) or disabled persons, see Peško (2003). However, these groups of passengers are not the aim of this study.

1. Spatial Accessibility of Public Transport

1.1. Indicators of Spatial Accessibility

The indicator of the average distance to the bus stop can be mathematically expressed as follows:

$$d_a = \frac{1}{2|C|} \sum_{c \in C} \left(d\left(v_c, Z\right) + d\left(k_c, Z\right) \right), \quad (1)$$

where: C is the set of all individual passenger trips during the given period; $|C|$ is the number of trips in C (those who travel more than once appear the same number of times in C); v_c is the starting point of the trip c (e.g. the entrance to the house); k_c is its destination (e.g. the factory entrance); Z is the set of all stops; $d(v_c, Z)$ or $d(k_c, Z)$ are the distances respectively between v_c or k_c and the nearest stop. Public authorities may set a target for this indicator not to exceed an acceptable limit, e.g. 500 m, etc.

This indicator may be replaced by the indicator of 'percentile' type:

$$d_p = \min\left\{ d \geq 0 : \frac{\left|\left\{ c \in C : \left(d\left(v_c, Z\right) \leq d\right) \wedge \left(d\left(k_c, Z\right) \leq d\right)\right\}\right|}{|C|} \geq \frac{p}{100} \right\}, \quad (2)$$

where p is the given percentage; d_p is the smallest number d for which at least p% trips $c \in C$ have both distances $d(v_c, Z)$ and $d(k_c, Z)$ not exceeding d. Public authorities may require that for, say, p% = 95% of trips both distances $d(v_c, Z)$ and $d(k_c, Z)$ do not exceed 500 m.

If public authorities decided to work with the parameter $p = 100$, i.e. if they require everybody to have the closest stop within $d_p = 500$ m, it would not be very appropriate. People, living or working in outlying locations, would increase significantly the cost of the transport service.

1.2. Factors Influencing the Spatial Availability of Public Transport

As one can see from (1) or (2), whether one chooses the indicator d_a, or d_p, in both cases it is an aggregation of individual distances $d(v_c, Z)$ or $d(k_c, Z)$, respectively. They are mainly influenced by the following two factors:

- network density, which is inversely proportional to the average distance $d(V, G)$ or $d(K, G)$ of the locations v_c or k_c, respectively, from the nearest route operated by a public transport network G;
- the average distance of adjacent stops $d(Z/G)$ on the routes of the network G.

If the passenger first walks by the shortest route from a starting location v_c to the nearest public transportation route and then walks to the nearest stop, it is possible to estimate the average length of the total path by the expression $d(V, G) + 0.5\ d(Z/G)$. Similarly, the path from the alighting stop to the location k_c can be estimated by $0.5\ d(Z/G) + d(K, G)$, which leads to the estimation of d_a:

$$d_a \approx d\left(V, G\right) + d\left(K, G\right) + d\left(Z / G\right). \quad (3)$$

This estimate will be the more accurate, the more the sidewalk network is close to rectangular. In fact, the value of d_a is a bit smaller than the right side of equation (3), but the difference is usually less than 10%.

However, it is important that for any change of the size of a summand in (3) there is a corresponding change in the size of the indicator d_a. The same can be expected also for the indicator d_p, though for that no direct estimate of the type (3) is available. It can be derived from (2). If the global indicator $d(V, G)$ increases, the same almost certainly applies to $d(K, G)$ and, therefore, a major part of the individual distances $d(v_c, Z)$ and $d(k_c, Z)$ will increase as well. Consequently, the value d_p can be expected to increase.

From what was said above, it follows that spatial accessibility of public transport is affected by the decisions of public authorities on network density and average distance of adjacent stops. The smaller the distances, the greater the accessibility, but, as it is easy to show (see e.g. 2.2), the greater will be the costs as well. Strengthening the social pillar is then weakening the economic one.

However, the development of public transport can be sustainable only when there is some harmony between these pillars. Therefore there needs to be a balance between the requirements of the two pillars. The solution might be:

– to minimize costs subject to meeting a given limit on accessibility;
– to maximize accessibility subject to meeting a given limit on costs.

As concerns the second approach, Černá *et al.* (2011) presented exact and heuristic methods for the solution to the following problem: Given a limit $\lambda > 0$, minimize the length of the bus route connecting the stops from the set Z meeting the condition $d_a = d_a(Z) \le \lambda$, where d_a is defined by (1).

2. Time Accessibility of Public Transport and its Relation to Spatial Accessibility

2.1. Indicators of Time Accessibility

In contrast to spatial accessibility, time accessibility is not so easy to define and to express. It is obvious that the time accessibility of public transport should be expressed using the time lost while not actually travelling, since travelling is necessary but waiting is not. Similarly, it is not necessary to lose time during an unnecessarily long walk to the bus stop, which will be discussed later.

Formulas of type (1) or (2) could be used if the resulting loss of time t_c of waiting for (e.g. bus) service were known for each path $c \in C$. Analogous to formula (1), the average passenger time loss would then be:

$$w_a = \frac{1}{|C|}\sum_{c \in C} t_c. \quad (4)$$

However, the value of t_c can be determined only for certain types of passengers, such as:

– those who have well-defined times of arrival/departure to/from their target (ride to work, school, etc.);
– those who use routes with a time interval between the (e.g. bus) services of up to 20 minutes. Their average time loss can be estimated as a half of this interval;
– those who can adapt their program (jaunt, shopping, etc.) to fit in with the transport timetable. The time loss in this case is zero.

Other passengers (visit to a doctor, public office, etc.) have their time losses between zero and a half of the interval. If their share is minor and their loss is estimated at a quarter of the interval, then the result calculated by formula (4) will not be far from the truth.

2.2. Discrepancy between Spatial and Time Accessibility, Economic Impact

Suppose that one or more bus operators deploy together n buses to provide public transport in a medium size city. It is clear that if the passenger demand remains unchanged, then the total number of services offered to satisfy this demand will remain unchanged as well and therefore the number n will be more or less stable.

Suppose further that a street network with $2m$ parallel streets $k_1, k_2, ..., k_{2m}$ can be used for bus routes and that the distance between each pair of neighbouring streets is about h = 400 m (Fig. 1, only schematic, the dimensions are distorted). Suppose, moreover, that each street can be serviced by a 5 km long bus route with a round journey time of 30 min, including idle times at the terminuses. Finally, suppose that the bus fleet size $n = 2m$.

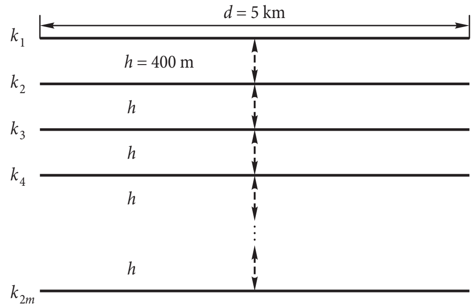

Fig. 1. Diagram of a parallel network

Two variants of the decision on the use of the network are compared in the next text.

V1: The municipal authority wants to achieve that:

p = 100 (%) of passengers fulfil the constraints;
$watl$ = 5 min is the walking time upper bound;
$awalkt$ = 2.5 min is the average walking time;
d_{100} = 333 m is the corresponding walking distance upper bound;
h = 400 m is the (unique possible) distance between parallel streets with the bus service and, therefore, one bus operates on each street;
I = 30 min is the interval between two successive buses;
$awaitt$ = 15 min is the average waiting time at stops;
$alostt$ = 17.5 min is the total average time loss of a passenger.

V2: The municipal authority wants to achieve that:

p = 100 (%) of passengers fulfil the constraints;
$watl$ = 10 min is the walking time upper bound;
$awalkt$ = 5 min is the average walking time;
d_{100} = 667 m is the corresponding walking distance upper bound;

h = 800 m is the distance between parallel streets with the bus service and, therefore, two buses operate on each street (= every second street has a bus service);

I = 15 min is the interval between two successive buses;

awaitt = 7.5 min is the average waiting time at stops;

alostt = 12.5 min is the total average time loss of a passenger.

Remark: 17.5 is by 40% more than 12.5. However, the advantage of the latter compared with the former is actually much higher.

In the case of variant V1, the spatial accessibility d_{100} = 333 m would be achieved if the distance of adjacent stops was less than 267 m since 333 m consists of 200 m to get (perpendicularly) to the route and 133 m is then the distance to the nearest bus stop. The optimal distance of adjacent stops is usually calculated between 350÷450 m (Černá, Černý 2004). Therefore, the value 267 m needs by 50% more stops than in the optimal case having the corresponding increase of costs.

On the contrary, in the case of V2 a passenger would walk at most 400 m perpendicularly to get to a route and at most 267 m along it, which corresponds to the distance of adjacent stops 534 m. Since this distance is too long, in fact, it will be reduced to, say 400 m. Therefore the average walking distance 267 m is reduced to 200 m, which represents saving about 1 min of walking. Then the value *alostt* decreases to 11.5 min and 17.5 is by 52% higher!

Variant V2 may be regarded as an example of supply intensification and a concentration of the bus service on fewer routes. An insignificant reduction in spatial accessibility is compensated for by a considerable improvement in time accessibility. Note that time is a precious asset for passengers.

In the previous text there have been compared the benefits of variants V1 and V2 in terms of their impact on accessibility, i.e. the social pillar of sustainable development.

Variant V2 is much better also in terms of the economic pillar of sustainable development. In variant V1, public transport is operated on the double number of routes and each route contains the double number of stops. That means it is necessary to build and maintain four times more bus shelters compared to variant V2 at least at four times the cost. It should not be forgotten the fact that the interval is double in variant V1 and that passengers spend twice as much time at the stop. Therefore, they should be better protected against the weather, which means building better and more expensive shelters.

Moreover, one should not forget the Mohring effect as described e.g. by Van Reeven (2008). When the interval is shorter, the number of passengers increases together with revenue from fares and consequently the economic pillar is strengthened in this sense as well.

In summary, political decisions on space accessibility (333 m or 667 m) have a direct impact on time accessibility (17.5 and 12 min respectively) i.e. on the social pillar. Moreover, it impacts also the economic pillar of sustainability through cost of building stops and revenue from fares.

3. Price Accessibility of Public Transport

Price accessibility can be expressed:

- in an absolute form, as the price of one pkm;
- in a relative form, as the ratio of the price of 1 pkm to the cost per 1 pkm of individual transport.

Public authorities have these data available when making decisions. It is much more difficult to estimate the behaviour of possible users of public transport, especially as they choose between:

- individual and collective (public) transport;
- purchasing season tickets for unlimited journeys, or tickets for one journey.

Larsen and Rekdal (2010) presented a relatively complex model for choosing between these two alternatives.

Even assuming that there was only one type of ticket, it is not enough just to know its value for the sake of estimating the extent of interest in a public transport service. To do this, it is necessary to know the price elasticity of demand for public transport, or at least its credible estimate. Without this information, one can not foresee the consequences of fare changes on the demand for public transport. However, as seen from the article by Pojkarová and Ježek (2009), this elasticity can be locally very different. It is theoretically possible and maybe even feasible to get elasticity for a particular town or region by the way of an experiment run in a small but representative district where one could change the tariff and observe the development of demand.

Here, the Scandinavian view on demand elasticity presented in Holmgren (2007) ought to be added. It is shown there that a wide variation in elasticity estimates was obtained in their studies and the author presents an explanation of it.

Since individual transport is an easily available substitute of public transport, this elasticity is fairly high. Therefore, the dependence of the total revenue r on the fare p can be expressed by a function $r = f(p)$. It is clear that at public transport fares at the price $p = 0$ CZK (Czech Koruna) per pkm the total revenue r will be zero and also at exorbitant fares, e.g. 10 CZK per pkm it will again be zero (1 USD ≈ 20 CZK). Of course, if the fares are 'reasonable' then $r > 0$ and the graph of the function f will be of the type shown in Fig. 2. It is slightly similar to the well-known Laffer curve described e.g. by Wanniski (1978) expressing the dependence of total tax revenue on the tax rate.

Obviously, f is a continuous function and therefore there exists a price p_{opt} giving the maximum total revenue.

It is necessary to add that the maximum revenue leads to the minimum subsidies from public authorities.

Unfortunately, no formula is known for the value p_{opt}. It will be influenced by alternatives to public transport.

The most important alternative to public transport is traveling by car. The price of fuel consumed per 1 km by the most common passenger cars is around 2 CZK. Since the mean occupancy of a car in the Czech Republic is about 1.5, one can expect $p_{opt} < 1.4$. Consequently, a fare increase significantly over 1.5 CZK per pkm can cause a significant drop in total revenue!

This implies that the consolidation of this part of the social pillar is actually in line with the consolidation of the economic pillar of sustainability.

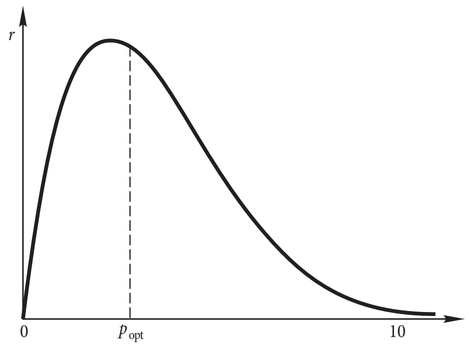

Fig. 2. Dependence of the total revenue *r* on the price *p* of 1 pkm

Finally, it is possible to hope that, even in the competition between public transport and individual car use, a new paradigm of 'sustainable competitiveness', described by Balkytė and Tvaronavičienė (2010), will be taken into account.

4. Sustainability of Public Transport in Areas of Weak Demand

The need for harmonization of the social and economic pillars of public transport sustainability is particularly acute in areas with weak demand. Those are the areas where the operation of 'traditional' public transport gives extremely small revenue in comparison to the costs (e.g. below 20%). There, any increase in the space or time accessibility for passengers makes only a small increase in revenue, but a big jump upwards in the cost.

An effort to achieve economic sustainability of public transport then leads inevitably to the effort to omit some of the paradigms of 'traditional' (conventional) public transport. For example, one of them is that any bus journey has a fixed schedule with a fixed route consisting of a sequence of mandatory (compulsory) stops.

4.1. Demand Responsive Transport as a Replacement for Conventional Public Transport Systems

Demand Responsive Transport (DRT) waives these requirements. A bus journey calls at some stop only when it is requested by a passenger. Such a stop is called optional.

The most common way of expressing demand is a telephone call to the operator. That is why such a system is called a Dial-a-Bus System (in Germany Rufbus system, or also R-bus). From these names, one can deduce that this transport operates on roads using multi-seat vehicles, usually buses. Since the transport demand is small, the 'classic' big buses are not convenient for DRT service. Midibuses, minibuses or microbuses are more suitable.

DRT systems are found in many countries all over the world. They differ in the type of stops and in the way of deciding the vehicle routing. The paper by Mageean and Nelson (2003) compares DRT systems in Belgium, Finland, Great Britain, Ireland, Italy and Sweden. A complex overview is presented by Nelson *et al.* (2010). In the Czech Republic, however, only the simplest and the least effective ones are in use.

4.2. Hail-and-Ride Systems, Systems with Request Stops

These two systems are very similar one to another. However, they have two important common features with the conventional ones:

– fixed routes that each vehicle must go along;
– fixed timetables.

Hail-and-Ride (or Hail-a-Ride) systems operate on sections of a route where the passenger can request, by 'hailing', to board or to alight from the bus at any place where it is safe to do so.

The system with request stops has normally marked bus stops where a bus is not obliged to stop unless a passenger indicates a wish to board or to alight from the bus.

A compromise between these systems is that all the safe places are marked in a simple but clear way.

The cost saving compared to a traditional system is not large. For example, for a normal type of bus for about 80 passengers, passing one stop saves about 1 CZK. Passing 3 stops during a 5 km journey decreases the cost from about 200 to 197 CZK, i.e. minus 1.5%. It is certainly not negligible, but some other variants of DRT bring significantly higher savings.

4.3. System with Journeys Based on Demand

In the timetable, some journeys have a footnote: 'The connection runs in the case of the interest of at least *n* passengers paying the adult fare'. Such a solution is usually seen in mountain cable-cars, but the authors know of two examples in the case of public transport in the Czech Republic:

– in the past, the evening train Konstantinovy Lázně – Bezdružice ran if the full fare for 40 passengers was paid. Now (2011), the service is extended to the segment Bezdružice – Konstantinovy Lázně – Cebiv and back. It is of the 'train-taxi' form based on telephone request to the railway station at Pňovany;
– the urban bus transport timetable of the town Rychnov nad Kněžnou contains several request journeys running only in the case of a telephone

order from at least one passenger. Passengers pay a supplementary charge of 4 CZK in addition to the standard fare for this service. This system is described in detail and analysed in the thesis by Končická (2010).

One can say that this type of system has no impact on the spatial accessibility of public transport. On the other hand, it can improve the time accessibility for a small segment of passengers. However, it leads to a not negligible increase in costs, paid partially by passengers, but mainly by public authorities. Therefore, such a system can hardly serve to the strengthening of the economic pillar of the public transport sustainable development in weak demand areas.

4.4. DRT Systems with Compulsory and Optional Stops (DRT–COS)

This system seems very promising to serve areas with weak demand, both in terms of availability and economy. Therefore it will be presented in detail.

DRT–COS systems have routes and schedules similar to the classic 'non-interactive' systems. Timetables indicate journeys and their compulsory stops. Moreover, between a pair of adjacent compulsory stops some stops can be denoted as optional. These are visited only on request confirmed by a dispatcher.

The departure times (from compulsory stops), which are shown in the timetable, indicate the earliest possible departure time. The vehicle may be late, but the delay is limited to e.g. $\varepsilon = 5$ or $\varepsilon = 8$ minutes.

Such a system has been successfully operated for example in suburbs of Genoa (Italy) for many years.

4.4.1. Implementation of DRT–COS Systems

The challenges facing the introduction of such systems touch both its preparation and planning, as well as its operation. The second of these issues was explored in detail by experts Carraresi *et al.* (1995) or Crainic *et al.* (2005). Therefore, attention will be paid to decisions in the planning phase, which, moreover, mainly affect the economic performance of the system. Basically, bus transportation will be examined due to the fact that the weak demand area services are totally dominated by buses.

The first question, a public authority should ask, is: where and when to introduce a DRT–COS system?

The authors' experience indicates two possible answers:

- in the area where due to the small demand no public transport operates but pressures on its implementation are growing, or it is needed for some other reason;
- in the area where a classic 'non-interactive' public transport system already operates, however, it is very inefficient, because weak demand causes low occupancy of vehicles.

4.4.2. Fares in DRT–COS Systems

If a public authority decides to implement this system, it must determine some of its important parameters. The first is the fare. It is possible to recommend the following structure, used for example in Genoa in Italy:

- passengers pay the normal fare as in the traditional system, if they board at a compulsory stop and alight at any stop where the vehicle stops and do not request the driver (personally) or the dispatcher (by telephone) to do anything different;
- they pay a supplement, if they have requested to use an optional stop.

4.4.3. Location of Compulsory Stops and Route Design

Areas of weak demand are usually in a range of a few square kilometres. Therefore, it can be assumed that only one line will be designed to serve it. It is then necessary to answer three interconnected questions:

- which locations to choose for the placement of stops?
- which of them will be compulsory?
- what will be the route connecting these stops?

The solution is derived from a given set of points V which represent (possible) locations of stops, origins and destinations respectively of passengers (entrances to businesses, public offices, apartment buildings, schools, hospitals, stadiums, shopping centres, etc.). For each such point $v \in V$, $q(v)$ represents the total in-flow plus out-flow of passengers.

The set V represents the vertices of a network $G1 = (V, E1, d)$, where the edges represent pedestrians' movement on foot and $d(e)$ is the length of the edge $e \in E1$.

A subset $S \subset V$ represents all possible places for stops. It is a vertex set of a network $G2 = (S, E2, \delta)$ where these edges represent the movement of buses and $\delta(e)$ is the length of the edge $e \in E2$.

It is necessary to choose two subsets of the set S:

- $Z \subset S$ as the places for compulsory stops;
- $O \subset S$ as the places for optional stops.

Obviously $Z \cap O = \emptyset$, but it is not necessary that $Z \cup O = S$.

The requirement that the delay caused by detours to optional stops does not exceed a given threshold, e.g. $\varepsilon =$ 8 minutes, partially determines the selection of the set of compulsory stops Z. It is based on the fact that sometimes a passenger's demand for boarding or alighting at some optional stop is not possible to meet because of the threat that the time limit is exceeded. Then the passenger will have to walk to another stop and, therefore, some passengers will not be served at the closest stop, if it is optional.

Therefore, it is not possible to rewrite the formula (1) simply into the form:

$$d_a(Z \cup O) = \frac{1}{\sum_{v \in V} q(v)} \sum_{v \in V} q(v) d(v, Z \cup O) \le \lambda \quad (5)$$

and to minimize the total length of the route passing the set Z using the methods of Černá *et al.* (2011). The results could be inexact.

However, one would probably commit a larger inaccuracy using these methods for $d_a(Z) \le \lambda$ only, i.e. completely omitting the optional stops.

It seems that an iterative heuristic procedure is hopeful in this case. It consists of three steps which are recursively repeated, changing auxiliary parameters $\gamma \geq 1$ (expected about 2) and $\beta \leq 1$ (expected about 0.8).

The choice of the set Z of compulsory stops is the goal of the first step taking the parameter $\gamma = 2$. Let, for the moment, the demand $q(v)$, $v \in V$ expresses the mean number of passengers during one time interval between two successive journeys on the route.

1st Step: Let the set $Z \subset S$ fulfil the constraint $d_a(Z) \leq \gamma\lambda$ and minimize the length of the shortest route passing through all vertices from the set Z. The methods from Černá *et al.* (2011) can be used.

4.4.4. Choice of Optional Stops

It represents the second step of the iterative procedure using the notation $w(v, Z)$ for the nearest vertex of the set Z to the given vertex $v \in O$. In the beginning, the value $\beta = 0.8$ is chosen.

2nd Step: Let the set $O \subset S - Z$ fulfil the constraint $d_a(Z \cup O) \leq \beta\lambda$ and minimize the objective function:

$$h\left(O,Z,\beta,\gamma\right) = \sum_{v \in O} d\left(v, w\left(v,Z\right)\right) \rightarrow \text{min.} \tag{6}$$

The set of compulsory stops Z and the set of optional stops O are initial solutions of the iterative procedure. They can be used also as the final solution, but their accuracy is smaller than any of the results of the iterative procedure.

3rd Step: Let us simulate the random demand corresponding to the mean values $q(v)$, $v \in V$. Let us simulate the bus journey, covering the demand and not exceeding the delay limit ε. Let d' be the mean value of the walking distance of the passengers served by this journey. Repeat the 3rd Step until the arithmetic mean d_a of the values d' is stabilized:

- if $d_a \leq \lambda$ and $\lambda - d_a$ is sufficiently small, the procedure is over and Z, O is the final solution;
- if $d_a < \lambda$ and $\lambda - d_a$ is not sufficiently small then increase slightly β or γ or both and return to the 1st Step;
- if $d_a > \lambda$ then decrease slightly β or γ or both and return to the 1st Step.

4.4.5. Economic Benefits of Implementing the DRT–COS System

Since the journeys need not pass through all stops this system saves usually 20÷30% of costs compared with conventional systems. On the other hand, a significant increase in sales cannot be expected since the supplements are usually paid by a small minority of passengers only.

4.5. DRT-OS Systems without Compulsory Stops and Timetables

The systems described in 4.4 were actually just modifications of conventional public transport systems towards a taxi service. In this section, on the other hand, possible modifications of taxis towards public transport will be observed.

These are fully demand responsive systems where there are no compulsory stops and theoretically each point of the transport network can become an optional stop. The bus moves through the network according to immediate needs (i.e. in 'on-line' mode), or according to pre-specified requirements for transportation. In the second case, operators usually require an order to be put in several hours in advance. Quite often it is necessary to order the transport a day in advance.

Operating in an 'on-line' mode requires development of a new methodology for producing a timetable. The most complicated aspect is designing the passenger route through the network.

4.5.1. Designing the route

Except for the case where the vehicle is occupied by one person only and no other transport request is received before arriving at the destination point, it is clear that the bus will not always take the shortest route between the getting on point and the destination point with regard to any one request. On the route, the vehicle will pick up further passengers including those for whom the pick-up point and destination are off the route of the first passenger, and so on as further passengers get on. This means that the bus route changes dynamically during the course of a journey. The driver will get information on the nearest destination from the control centre (the source of transport requests). For this decision to be the best, it must be taken using some optimising algorithm. Every such algorithm is based on some model. Therefore in designing the route it is important first to develop a suitable model. On that basis a particular Telematics Sub-System (TSS) will then operate in practice ensuring the operation of the whole system.

The TSS must register all current transport requests and all available vehicles at the same time so that the optimal vehicle can be allocated to each newly arising request. This is an example of a large combinatorial problem which can be solved only using a computer and optimization methods. It is known that companies such as Dornier, MBB and so on are involved in the development of such models, but most of their results are usually considered to be 'trade secrets'.

At present the authors do not know of any model and algorithm which would always find an optimal solution for any given large problem. For this reason it makes sense to develop new models and algorithms. Given the extent of the task it will mainly be a matter of developing heuristic algorithms.

4.5.2. Development of a Model

The model must take into account the fact that the passenger will not be willing:

- to walk too far before getting on point;
- to wait too long for a vehicle;
- to spend too much time in a vehicle.

In the model, the following symbols are used:

- T_j – journey time, that is the period from getting on until getting off the vehicle;
- T_c – complete journey time (i.e. the time needed to get to the destination from the point where the request for the transport originated). It is made up of the walking time to the boarding point, the travelling time in the vehicle and the walking time from the alighting point to the destination of the journey;
- T_w – waiting time until the arrival of the vehicle;
- $T_{w\max}(d)$ – the maximum time someone is prepared to wait when travelling a distance d;
- T_{vp}, T_{cp} – walking time from the point where the transport request originated to the vehicle boarding point and from the alighting point to the destination of the journey respectively;
- $T_{vp\max}$, $T_{cp\max}$ – the maximum times that a passenger is prepared to accept;
- T_p – time needed to walk to the destination of the journey from the point where the transport request originated;
- $k_p(d)$ – for a given distance d from the starting point to the destination of the journey, it represents the ratio of the walking time T_p to the time T_c, above which the value of T_c becomes interesting for the passenger;
- T_i – travel time if an individual vehicle is used;
- k_i – the ratio of T_i to T_c above which the value of T_c becomes interesting for a passenger;
- Z – the excess of the actual travel time above the time originally notified to the passenger by the system;
- $Z_{\max}(d)$ – the maximum delay acceptable to a passenger whose destination is distant d from his or her starting point.

The TSS system will decide after receiving the passenger's request if it is at all possible to fulfil it and if so which vehicle to allocate to the passenger and how to modify its route. To do this it will use an optimization model and algorithm starting from the required limiting conditions to minimise some decision function expressing particular (usually general) expenses. Different operators will, based on their own views, have different expenses and will include different expense items in them.

Before the formal description of the model it is necessary to realize that the number of possibilities from which the TSS will choose the best is relatively small. On the one hand it is limited by a small number of passengers which a given vehicle will plan to service, which implies that the number of modifications to this plan is correspondingly small, and on the other hand there will be only one, or a small single-figure number of vehicles which will be sufficiently close in both time and distance to the point of demand for travel. The algorithm will therefore choose the best octad from those few available. So there will not be any problem in terms of the number of possibilities. Nor in fact will there be in the calculation of the individual parameters, as they are standard values calculated using computers for many years in 'classical' public transport systems.

The formal model will take the following form:

$$\text{minimize } f\left(T_i, T_c, T_w, T_{vp}, T_{cp}, T_p, T_i, Z\right) \quad (7)$$

given

$$T_w \le T_{w\max}\left(d\right); \quad (8)$$

$$T_{vp} \le T_{vp\max}; \quad (9)$$

$$T_{cp} \le T_{cp\max}; \quad (10)$$

$$\frac{T_p}{T_c} \ge k_p\left(d\right); \quad (11)$$

$$\frac{T_i}{T_c} \ge k_c; \quad (12)$$

$$Z \le Z_{\max}\left(d\right). \quad (13)$$

There (7) is the decision function. (8) expresses the fact that a passenger is only willing to wait for a vehicle for a certain time. This time is of course dependent on the distance between the destination and starting point of the overall journey. (9) and (10) express the distances that the passenger is prepared to walk to the vehicle boarding point and from the vehicle alighting point to the journey's destination. The condition (11) expresses how walking and travel time may be related to each other (what is the time saving). It is reasonable to consider this only up to some distance h which one can assume the average person is compliant to walk.

Similarly the condition (12) indicates that passengers are prepared to use DRT only in case that the total travel time is not excessively increased as compared with using individual transport. The condition (13) guarantees that each passenger will get to the alighting stop subject to a maximum delay as compared with the notified travel time.

The model can be simplified or complicated by deleting or adding further conditions. Thus, for example in case of an ideal route network, i.e. the one where a vehicle will access every point where there might be a demand for transport, one can omit the quantities T_{vp} and T_{cp}, see for example Linda, Kubanová (2008). On the contrary, a requirement to minimize transfers or the number of vehicles can significantly complicate the model.

4.5.3. Tariffs in DRT–OS Systems

A classical taxi service using a car will usually convey one to three people from point A to point B within one journey. Having dropped these people the taxi is then available for further clients. A modification of this is a DRT–OS system which uses larger cars or microbuses for seven to ten passengers and at the same time fulfils a number of orders. The vehicle may convey passengers with various boarding and alighting points (request stops).

Let us compare, at least as a benchmark, the expenses per 1 pkm for Classical Public Transport (CPT), for DRT–COS and DRT–OS systems and for 'classical' taxi services provided they served the same area of a weak demand, subject to both variants having equal access to stops and equal gaps between vehicles. An accurate comparison is not possible as bus operators do not want to make the necessary data available (they consider them to be 'trade secrets').

In the case of CPT the authors' experience indicates that the possible cost in areas of usual demand is about 2 CZK per pkm and in areas of weak demand about 4÷5 CZK per pkm. A well designed DRT–COS system may have costs about 1÷2 CZK less, as the number of vehicle kilometres is much lower. To a large extent of outlying stops where a CPT vehicle would go on every journey, a DRT–COS will only go on demand.

As opposed to bus operators, one can find a model calculation for classical taxi services on the Internet, provided by the Vehicle Calculator of Prague Taxi Federation. One can deduce from this that the total annual costs per vehicle including a 6% profit margin are 724000 CZK in respect of 9700 client vehicle kilometres, which works out at about 75 CZK per vehicle kilometre and for an average occupancy of 1.25 passengers about 60 CZK per pkm.

For a DRT–OS system, one can possibly estimate that the annual costs per vehicle will be about 50000 CZK higher than those for a taxi service to cover higher taxes depreciation, about 40000 CZK higher in respect of fuel costs and about 200000 CZK higher for dispatcher costs, whilst other costs will be about the same as for a classical taxi service. So, it is possible to finish up with annual expenses of 1015000 CZK. On the other hand the number of passenger kilometres will be at least double and the vehicle occupancy possibly up to 3÷4 times, giving a possible estimate of the costs per vehicle kilometre of 52 CZK and per pkm of 10÷13 CZK. This is about a fifth of the costs of a classical taxi service and three times the cost of a DRT–COS system.

These last results in particular reduce the attractiveness of a DRT–OS system, as it would either enormously increase the subsidy needed from public authorities or would be unable to compete with personal car transport. In the next section, the possibility of reduction of these costs will be presented.

4.5.4. Travel Band Systems (DRT–TB)

This is an intermediate step between DRT–COS and DRT–OS systems. A travel band is formed from a series of smaller localities (zones) of weak demand. The vehicle (almost always a microbus) visits these zones in a fixed order. Within these localities it moves freely according to the immediate demand for transport. A journey between localities is usually treated as one stop. For such a system, an estimation possible costs is about 6÷9 CZK per pkm. An extreme form of DRT–TB is the route taxi system (in Russian speaking countries known as 'marshtrutnoe taksi').

4.6. An Untraditional Solution

If the localities are so thinly populated that on the one hand even the introduction of a DRT system would be economically ruinous, but on the other hand public authorities want or require that there be a minimum level of service (for example in respect of school children), various solutions may be available which are really untraditional from a Czech point of view, for example:

- supporting 'Ride Sharing' – for example parents may take it in turn to take three schoolchildren by car from an outlying locality for few kilometres to the nearest bus stop;
- combining passenger vehicle with the conveyance of mail (as in the Austrian 'Postbus' system), or with the transportation of foodstuffs to outlying outlets and so on.

5. Other Threads

So far it was pointed out the relationship between accessibility, as the base of the social pillar, and cost, as an important part of the economic pillar. By doing so it emphatically does not mean an implication that the social pillar is only concerned with accessibility nor that the economic pillar of public transport cannot be stabilized in other ways. On the contrary, with regard to both there could be a wider discussion, but it would be beyond the scope of this paper.

It is necessary to point out the fact that, with regard to the social impact of public transport and its competitiveness against individual car transport, factors relating to comfort of travel also play a decisive role, for example:

- direct travel as opposed to the need to change;
- availability of seats;
- cleanliness and noisiness of the vehicle.

It is clear that these factors are also linked to the economy of the operation.

The economic pillar can be stabilized without undermining the strength of the social pillar in any way.

The most effective measures are the following:

- optimization of the establishment and use of the rolling stock, as well as optimization of crew scheduling, for example using KASTOR methods by Palúch (1988), or other methods from the book by Černá and Černý (2004);
- optimization of routes as described e.g. by Černá and Černý (2004).

It is therefore possible to use a wide variety of optimization approaches. It is, however, necessary for politicians to be aware of them and to be willing to base their decisions on them.

Conclusions

The paper has presented several situations where the decision-making on economic and social sustainability of public transport may rely on theoretical support. Mainly the following problems were highlighted:

- choice of network density;
- determining of the average distance of adjacent stops;
- how to minimize costs subject to meeting a given limit on accessibility;
- how to maximize accessibility subject to meeting a given limit on costs;
- how to remove the discrepancy between the spatial and time accessibility;
- how to choose optimal fares;
- how to choose among many alternatives of DRT;
- how to locate stops in the system of DRT–COS;
- how to choose parameters of DRT–OS.

Exact models and methods of solution to them were described in detail.

Moreover, there have been outlined other problems related to economic and social sustainability of public transport. The ways to their solution have also been mentioned.

Acknowledgments

This paper was prepared with the support of the Czech Science Foundation, grant No 402/12/2147.

References

Balkytė, A.; Tvaronavičienė, M. 2010. Perception of competitiveness in the context of sustainable development: facets of "sustainable competitiveness", *Journal of Business Economics and Management* 11(2): 341–365. http://dx.doi.org/10.3846/jbem.2010.17

Banister, D. 2008. The sustainable mobility paradigm, *Transport Policy* 15(2): 73–80. http://dx.doi.org/10.1016/j.tranpol.2007.10.005

Bojnec, Š.; Papler, D. 2011. Economic efficiency, energy consumption and sustainable development, *Journal of Business Economics and Management* 12(2): 353–374. http://dx.doi.org/10.3846/16111699.2011.573278

Cao, X. (J.); Mokhtarian, P. L.; Handy, S. L. 2010. Neighborhood design and the accessibility of the elderly: an empirical analysis in Northern California, *International Journal of Sustainable Transportation* 4(6): 347–371. http://dx.doi.org/10.1080/15568310903145212

Carraresi, P.; Malucelli, F.; Pallottino, S. 1995. On the regional mass transit assignment problem, *Optimization in Industry 3: Mathematical Programming and Modeling Techniques in Practice* (Eds. A Sciomachen), 19–34.

Crainic, T. G.; Malucelli, F.; Nonato, M.; Guertin, F. 2005. Meta-heuristics for a class of demand-responsive transit systems, *INFORMS Journal on Computing* 17(1): 10–24. http://dx.doi.org/10.1287/ijoc.1030.0051

Černá, A.; Černý, J.; Přibyl, V. 2011. Bus route design in small demand areas, *Transport* 26(3): 248–254. http://dx.doi.org/10.3846/16484142.2011.622135

Černá, A.; Černý, J. 2004. *Teorie řízení a rozhodování v dopravních systémech*. Pardubice: Institut Jana Pernera. 150 s. (in Czech).

Hensher, D. A. 2007. Sustainable public transport systems: moving towards a value for money and network-based approach and away from blind commitment, *Transport Policy* 14(1): 98–102. http://dx.doi.org/10.1016/j.tranpol.2006.10.004

Holmgren, J. 2007. Meta-analysis of public transport demand, *Transportation Research Part A: Policy and Practice* 41(10): 1021–1035. http://dx.doi.org/10.1016/j.tra.2007.06.003

Kennedy, C.; Miller, E.; Shalaby, A.; Maclean, H.; Coleman, J. 2005. The four pillars of sustainable urban transportation, *Transport Reviews* 25(4): 393–414. http://dx.doi.org/10.1080/01441640500115835

Končická, K. 2010. *Možnosti zavedení poptávkového dopravního systému v České republice*: *Diplomová práce*. Univerzita Pardubice. 107 s. Available from Internet: http://dspace.upce.cz/handle/10195/36772 (in Czech).

Linda, B.; Kubanová, J. 2008. Operativně řízená autobusová doprava, in *Modelování a rozhodování ve veřejné správě*, 49–51 (in Czech).

Larsen, O. I.; Rekdal, J. 2010. Treatment of seasonal tickets for public transport in estimation and application of mode/destination choice models, *Transportation* 37(3): 573–581. http://dx.doi.org/10.1007/s11116-009-9256-2

Mageean, J.; Nelson, J. D. 2003. The evaluation of demand responsive transport services in Europe, *Journal of Transport Geography* 11(4): 255–270. http://dx.doi.org/10.1016/S0966-6923(03)00026-7

Nelson, J. D.; Wright, S.; Masson, B.; Ambrosino, G.; Naniopoulos, A. 2010. Recent developments in flexible transport services, *Research in Transportation Economics* 29(1): 243–248. http://dx.doi.org/10.1016/j.retrec.2010.07.030

Palúch, S. 1988. Systém KASTOR na optimalizáciu obehových rozvrhov, *Zborník prác Výskumného Ústavu Dopravného v Žiline* 54 (in Slovak).

Peško, Š. 2003. On closed bus line for disabled passengers, *Journal of Information, Control and Management Systems* 1(2): 69–74.

Pojkarová, K.; Ježek, J. 2009. Elasticita poptávky v dopravě a průměrných mezd zaměstnanců, *Perner's Contacts* 4(3): 194–200 (in Czech).

Tunčikienė, Ž.; Bivainis, J.; Drejeris, R. 2010. Integrated DSS for strategic planning in public institutions, *Journal of Business Economics and Management* 11(4): 671–688. http://dx.doi.org/10.3846/jbem.2010.33

Van Reeven, P. 2008. Subsidisation of urban public transport and the Mohring effect, *Journal of Transport Economics and Policy* 42(2): 349–359.

Wanniski, J. 1978. Taxes, revenues, and the "Laffer curve", *The Public Interest* (50): 3–16.