The Impact of Alternative Access Modes on Urban Public Transport Network Design

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Public transport network design determines the quality for travellers as well as operational costs. Network design is therefore crucial for the cost effectiveness of urban public transport. In urban public transport network design it is commonly assumed that all travellers walk to the stops. This might be true for short access distances, but if stop and line spacing increase other modes such as bicycles might become interesting as an alternative access mode. An analytical model is presented that determines optimal network characteristics, i.e. stop spacing, line spacing, and frequency, and that explicitly accounts for alternative access modes. The objective used is maximising social welfare. Results show that, if cycling is considered as an alternative access mode, all three network characteristics mentioned above should be increased, offering benefits for the traveller, the operator as well as the society. However, if there is a large sub-population of travellers who are not able to use the alternative mode, or if there are barriers for using an alternative mode to access the urban public transport system, it is better to assume that walking is the only access mode available. In the case of cycling as an access mode there are possibilities for positive benefits, at least in countries such as Denmark or the Netherlands. It is expected that for other access modes, such as peoplemovers and demand responsive public transport systems, the barriers are too high to have an impact on urban public transport network design.

1. Introduction

It is well known that the costs of urban public transport systems are a point of concern. The costs of providing public transport services should be balanced by the benefits for the travellers and the city. Since public transport network design determines the quality for the traveller as well as the operational costs, it is crucial for the cost effectiveness of public transport. Typical network design variables are stop spacing, line spacing and frequency. Stop and line spacing determine access time, stop spacing influences average vehicle speed, while frequency determines waiting time. The average vehicle speed, line spacing and frequency determine operational costs. In order to improve the cost effectiveness of public transport networks, it is thus essential to know what the main relationships for these design variables are.

There is a considerable amount of studies on the basic relationships for urban public transport network design (see e.g. Van Nes (2000) for an overview). A general assumption in these studies is that travellers walk to the stops. This is certainly realistic in the case that access distances are limited to say 400 metres but if access distances increase this assumption might be questionable. Other modes such as cycling might then become a realistic possibility.

Several of these studies explicitly state that current values for stop and line spacing should be increased, independent whether they deal with the United States (e.g. Black (1978), Furth & Rahbee (2000)) or the Netherlands (e.g. Egeter (1995), Van Nes & Bovy (2000)). Van Nes & Bovy (2000), for instance, found that the stop spacing should doubled for both bus and tram networks and that in the case of bus networks line spacing should be doubled too. As a result the average access distance would become about 400 metres and the maximum access distance 800 metres, that is in the case of homogeneous distribution of the demand and access routes parallel and perpendicular to the lines. Such a maximum access distance is clearly large enough to start considering the possibilities of alternative access modes such as bicycles, peoplemovers, or perhaps even demand responsive transport systems.

If it is assumed, for instance, that all travellers use a bicycle to access urban public transport the access speed will be four times as high compared to the case of walking only. Using square root relationships for stop and line spacing (see Van Nes & Bovy (2000)) this leads to doubling the stop and line spacing once again, resulting in a maximum access distance of 1,600 metres. Operational costs might then be reduced to 50%. Of course, this approach is far from realistic, but it shows the impact of the assumption of the access mode on the network performance characteristics of urban public transport networks.

This paper presents an approach that explicitly considers the choice of the access mode in the assessment of the optimal stop and line spacing. The analysis is based on an analytical model using the building blocks described by Van Nes & Bovy (2000). However, instead of using the advised objective of minimising total costs, the more detailed objective of maximising social welfare is used (Section 2). The model is described briefly in Section 3. Section 4 focuses on the results of the model and implications for urban public transport network design. Section 5 summarises the conclusions and presents recommendations for further research.

2. Maximising social welfare

There are many objectives that might be used in urban public transport network design. It has been shown that the choice of the objective strongly influences the optimal network and the performance characteristics of urban public transport systems (Van Nes & Bovy (2000)). It was concluded from this analysis that the objective of minimising total costs, that is, traveller costs plus operational costs, is most suitable for urban public transport network design. It should be noted, however, that this objective was introduced as an alternative for the preferred but more complicated objective of maximising social welfare. Social welfare is defined as the summation of consumer surplus and producer surplus. The latter can easily be described as the operator's profit: revenue minus operational costs. It is the concept of consumer surplus that makes this objective rather complicated.

Consumer surplus can be seen as the value gained by the travellers, that is, travellers who would be willing to travel at higher costs (or time) and can travel having lower costs, gain the difference in time and money. Figure 1 presents an illustration of consumer surplus in a strict economic context. The demand curve shows that given high travel costs only few travellers will actually use the service. If travel costs are reduced, the use of the services increases. However, in order to accommodate the travellers, the travel costs increase, which is shown in the supply curve. In the situation that there is a balance between supply and demand, the consumer surplus or the costs gained by the travellers who would be willing to travel at higher travel costs can be shown by the grey area.

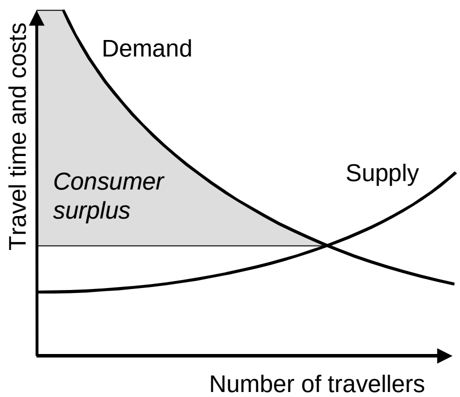

Figure 1. The concept of consumer surplus

In the case of transportation modelling the demand curve might be described using a mode-choice model, for instance a logit-model. Since calculating the consumer surplus using such a model is less tractable in an analytical approach, researchers often use a linear approximation of the logit-model (Kocur & Hendrickson (1982), Chang & Schonfeld (1993), Spasovic et al. (1994), Chang & Yu (1996)). The consumer surplus can then be seen as a triangle for which it is quite simple to calculate the surface. The size of this triangle is determined by the difference between the maximum travel costs and the current travel costs and by the level of demand. The disadvantage of this approach, however, is that the non-linear characteristics of travel behaviour are no longer taken into account.

An alternative is to combine both principles. The consumer surplus is still calculated using a triangle, but instead of a linear approximation of the demand curve, the original logit-model is used to determine the level of demand. This approach is illustrated in Figure 2, which shows the demand curve using a logit-model. It should be noted that the axes are reversed in order to match the economic conventions used in Figure 1. The consumer surplus is then calculated as the surface of the grey triangles. In this way the benefits of both approaches are maintained: it is still simple to determine the consumer surplus and the non-linear characteristics of travel behaviour are taken into account.

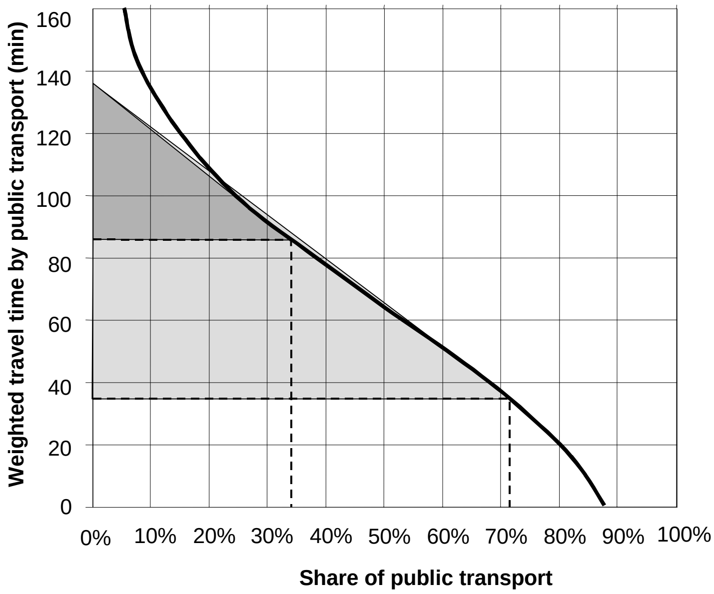

Figure 2. Two examples of the simplified representation of consumer surplus using a logit-model

It has been found that for urban public transport network design this approach for maximising social welfare leads to similar results as the objective of minimising total costs (Van Nes (2000)). Furthermore it was found that this approach is more robust with respect to the way the demand is modelled. It depends on the sensitivity of the demand for the quality of the transport services offered, whether minimising total costs leads to an optimum, which is in fact a local optimum, or to the trivial solution of offering no transport services at all. Offering no transport services, however, is no optimum for the objective of maximising social welfare.

3. Model description

The analytical model is based on the case of a unit area, for instance a square kilometre, in an urban corridor in which a set of parallel lines offer transport services to the city centre (Figure 3). This might seem a rather typical situation for a public transport network, but an analysis of the impact of including other trip types (return trips and transversal trips, with and without transfer in the city centre) on the optimal network characteristics shows that the results of this specific case are representative for an urban network (Van Nes (2000)). Similar results were found for a radial city too.

The design variables are stop spacing (S_s), line spacing (S_l), and frequency (F). The objective is, of course, to maximise social welfare.

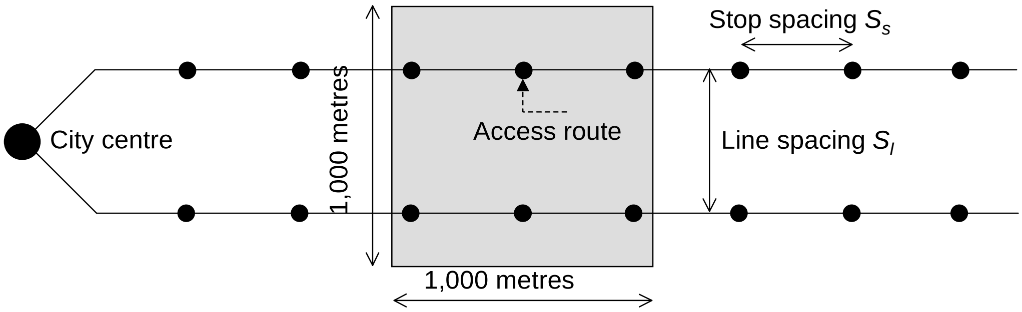

Figure 3. Study area and lay out of the public transport lines

Furthermore, the model is based on the following assumptions:

- Travel demand is homogeneously distributed;
- Fares are fixed;
- Access routes are parallel and perpendicular to the lines;
- All lines offer direct access to the city centre, no transfers are needed;
- Stops in the city centre are located at the main points of interests. Egress times in the city centre are therefore fixed.

The objective of social welfare consists of consumer surplus, determined by the door-to-door travel time and the corresponding level of demand, and the producer surplus, determined by the level of demand and the operational costs. The door-to-door travel time is thus a key variable, which consists of different time elements: access time, waiting time, in-vehicle time, and egress time. Weights are used to account for the fact that travellers have different valuations for the different parts of the trip.

$$T_c = w_a \cdot T_a + w_w \cdot T_w + T_i + w_e \cdot T_e \tag{1}$$

where:

T_c = total weighted travel time
T_a = access time
T_w = waiting time
T_i = in - vehicle time
T_e = egress time
w_x = weight for time element x

3.1 One access mode

The access time depends on the stop and line spacing (S_s and S_l), and on the access speed V_a. Waiting time is determined by the frequency F, and the in-vehicle time depends on the average travel distance to the city centre L_c, the stop spacing S_s, and the time lost at stops due to braking, boarding and alighting, and accelerating (T_s). The weighted travel time can then be written as:

$$T_c = w_a \cdot \frac{f_a \cdot (S_s + S_l)}{V_a} + w_w \cdot \frac{f_w}{F} + \frac{L_c}{S_s} \cdot \left(\frac{S_s}{V} + T_s \right) + w_e \cdot T_e \tag{2}$$

f_a = routing factor for the actual access distance
V_a = access speed
f_w = factor for the waiting time
L_c = average travel distance to the city center
V = maximum speed
T_s = time lost at stops

In the case of access routes parallel and perpendicular to the public transport lines (see also Figure 3) f_a equals 0.25. A typical value for f_w is 1,800 sec leading to a waiting time of half the headway.
Given the weighted travel time, the travel demand can be written as:

$$P(T_c) = P_0 \cdot \frac{\exp(-\alpha \cdot T_c)}{\exp(-\alpha \cdot T_c) + \sum_{m=1}^{n} \exp(-\alpha_m \cdot T_m)} \tag{3}$$

where:
P_0 = total demand for transport per square kilometer in trips
α = mode choice parameter for public transport
n = number of modes excluding public transport
α_m = mode choice parameter for mode m
T_m = weigthed travel time for mode m

The consumer surplus C*S* is then determined by the difference between the maximum travel time T_{cm} (for instance the travel time where demand for public transport vanishes) and the current travel time T_c, the travel demand, and the travellers' value of time c_t:

$$CS(T_c) = 0.5 \cdot (T_{cm} - T_c) \cdot P(T_c) \cdot c_t \tag{4}$$

The calculation of the revenues is rather straightforward:

$$R_o = (r_t + r_s) \cdot P \quad \text{or} \quad R_o = r_t \cdot P + R_s \tag{5}$$

where:
r_t = fare paid by the traveller
r_s = subsidy paid by the authorities per traveller
P = number of passengers
R_s = subsidy paid by the authorities

The operational costs for a unit area of a square kilometre depend on the frequency, the number of lines per kilometre, the travel time of a vehicle per kilometre in two directions, and the operational costs per vehicle per hour c_o:

$$C_o = c_o \cdot F \cdot \frac{1000}{S_l} \cdot \frac{1000}{S_s} \cdot \left(\frac{S_s}{V} + T_s \right) \cdot 2 \tag{6}$$

The objective of maximising social welfare can then be formulated as:

$$MAX\left\{\begin{array}{l}0.5\cdot\left(T_{cm}-T_c\right)\cdot P_0\cdot\dfrac{\exp(-\alpha\cdot T_c)}{\exp(-\alpha\cdot T_c)+\sum_{m=1}^{n}\exp(-\alpha_m\cdot T_m)}\cdot c_t+\\ \left(r_t+r_s\right)\cdot P_0\cdot\dfrac{\exp(-\alpha\cdot T_c)}{\exp(-\alpha\cdot T_c)+\sum_{m=1}^{n}\exp(-\alpha_m\cdot T_m)}-\\ c_o\cdot F\cdot\dfrac{1000}{S_l}\cdot\dfrac{1000}{S_s}\cdot\left(\dfrac{S_s}{V}+T_s\right)\cdot 2\end{array}\right\} \tag{7}$$

The optimal values for stop spacing S_s, line spacing S_l, and frequency F can be determined using enumeration techniques or numerical methods.

3.2 Two access modes

In the case of two access modes, for instance walking and cycling, a distinction must be made between the populations using each mode, that is P_1 and P_2. Each of the populations has its own access time determined by the access distance L_a and the access speed V_{aj}. It is possible that there are more differences between these populations, for instance, with respect to the weight for access time, or the routing factor. Pedestrians for example might have more direct access routes. In this case, however, it is assumed that the access speed is the only difference. The average weighted travel time can then be written as:

$$T_c=w_a\cdot\frac{L_a}{V_{a1}}\cdot\frac{P_1}{P}+w_a\cdot\frac{L_a}{V_{a2}}\cdot\frac{P_2}{P}+w_w\cdot T_w+\frac{L_c}{S_s}\cdot\left(\frac{S_s}{V}+T_s\right)+w_e\cdot T_e \tag{8}$$

where:

$L_a = f_a\cdot\left(S_s+S_l\right)$

V_{aj} = access speed for population j

$P = P_1+P_2$

Please note that it is assumed that the alternative mode is only used to access the public transport system for a trip to the city centre. In this approach walking is still the only egress mode in the city centre.

The size of the sub-populations will depend on the access time per mode, which can be described using the logit-model, just as in Equation 3:

$$P_1=\frac{\exp\left(-\alpha_1\cdot\dfrac{L_a}{V_{a1}}\right)}{\exp\left(-\alpha_1\cdot\dfrac{L_a}{V_{a1}}\right)+\exp\left(-\alpha_2\cdot\dfrac{L_a}{V_{a2}}-\varphi\right)}\cdot P \tag{9}$$

The coefficient φ appears as a mode-specific constant for cycling.

Comparison of both equations for the weighted travel time, that is Equations 2 and 8, shows that the access speed V_a in Equation 2 should be replaced by the average access speed for both populations:

$$\overline{V}_a = \frac{P}{\frac{P_1}{V_{a1}} + \frac{P_2}{V_{a2}}} \qquad (10)$$

Given values for the stop and line spacing, Equation 9 can be used to determine which share of the total population walks to the stop and which share uses a bicycle. Given these shares Equation 10 is used to determine the average access speed, which is then used in the optimisation of Equation 7.

4. Application of the model

The models presented in the previous section are applied to a situation that is comparable with tram network in the southern part of The Hague in the Netherlands. The current values for stop and line spacing are 400 metres and 1,000 metres respectively. The average line length is circa 7.5 kilometres. If it is assumed that the main function of the tramlines is to offer transport between the outer areas of the city and the city centre, the average trip length is 5 kilometres. The weights used for the different time elements were determined for especially such trip types in urban areas in the Netherlands (Van der Waard (1988a)). There is, however, no knowledge of the traveller's attitude to using bicycles as an access mode in urban public transport systems. Therefore, different penalties are used in the analysis. These penalties are added to the access time by bicycle.
The coefficients of the access mode-choice model of Equation 9 are determined in such a way that the resulting shares of walking per travel distance matches those found in the Dutch National Travel Survey (Table 1). It is expected that the maximum access distance ranges between 700 (current value) and 1,700 metres (in the case of cycling only).

Table 1. Walking as percentage of all trips for different travel distances (National Travel Survey)

Travel distance	Share of walking (%)
0 – 500 metres	76
500 – 1,000 metres	47
1,000 – 2,500 metres	23
2,500 – 3,750 metres	8

The following scenarios are analysed:

- Access mode walking only;
- Access mode cycling only;
- Two access modes: walking and cycling with no penalty;
- Two access modes: walking and cycling with a penalty for getting and parking the bicycle (2 min.);
- Two access modes: walking and cycling with a transfer penalty (5.7 min., that is the transfer penalty for public transport trips excluding walking and waiting time).

For each scenario the optimal values for the stop spacing, line spacing and frequency are determined. The values for the frequencies are limited to the values 4, 6, 8, 10, and 12

vehicles per hour. The level of demand that is assumed is representative for an average peak hour. The values of the parameters used can be found in the Appendix.
Figure 4 shows the shape of the objective function in the case of two access modes and a penalty of 2 minutes as a function of the design variables stop spacing and line spacing. It clearly shows that there is a large range of values of the design variables where the value of the objective function is more or less equal: a common phenomenon for this type of analysis (Van Nes (2000)).

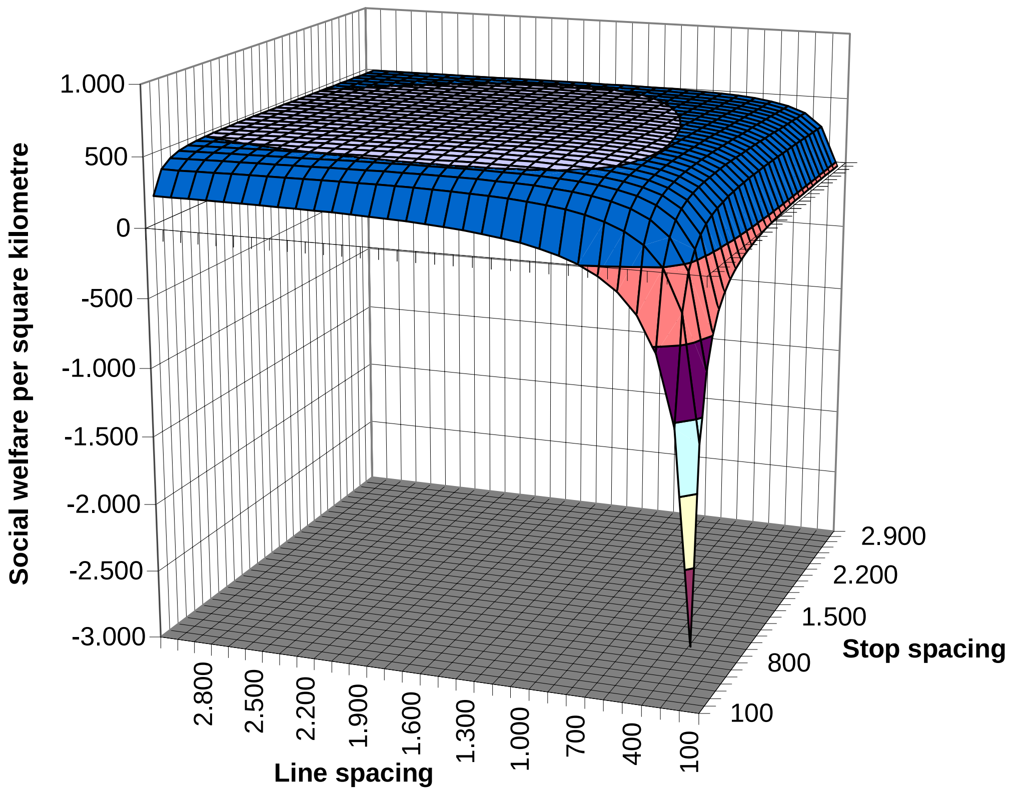

Figure 4. Objective function social welfare for the case of two access modes and a penalty of 2 min.

Given the optimal network characteristics for each scenario all kinds of performance characteristics are calculated, such as, travel time (with and without weights), travel demand, operational costs, total costs and social welfare. The results are presented in Table 2 and summarised in Figure 5.

Table 2. Optimal network parameters and performance characteristics for different access modes for an average peak hour

Scenario	**Reference**	**Walking**	**Cycling**	**Walking and cycling**		
Transfer penalty				**0 min**	**2 min**	**5.7 min**
Stop spacing *(m)*	400	800	1,500	1,100	1,000	900
Line spacing *(m)*	1,000	900	2,100	1,500	1,300	1,000
Frequency *(veh/h)*	6	6	10	8	8	6
Walking as access mode *(%)*	100	100	0	51	57	68
Access speed *(km/h)*	4	4	16	6.4	5.1	3.9
Travel time *(min)*	26.3	23.9	17.3	21.5	22.3	24.4
Access time *(min)*	5.3	6.4	3.4	6.1	6.8	7.3
Waiting time *(min)*	5.0	5.0	3.0	3.8	3.8	5.0
In-vehicle time *(min)*	13.1	9.5	7.9	8.6	8.8	9.1
Weighted travel time *(min)*	35.4	34.4	23.1	31.0	32.5	35.9
Travel demand *(pas/km^2/h)*	125	126	137	130	128	125
Operational costs *(€/km^2/h)*	86	69	41	50	59	60
Producer surplus *(€/km^2/h)*	-15	2	36	24	13	11
Consumer surplus *(€/km^2/h)*	494	503	605	533	520	490
Social welfare *(€/km^2/h)*	479	505	641	557	533	501

In the case of walking only the stop spacing is twice as large. Compared to the reference situation the travel time is nearly 10 % lower. Operational costs are 19 % lower, while social welfare is 5 % higher. If all travellers would use a bicycle, stop spacing is four times as large. In this case the optimal values for line spacing and frequency are higher too. Travel time is 34% lower, while operational costs are more than 50 % lower. Social welfare is 34 % higher. These impacts on the optimal network parameters and performance characteristics are strongly reduced if walking and cycling are considered as two alternative modes, from which the traveller may choose. The larger the penalty, the smaller the impact.

If the case of a penalty of 2 minutes is compared to that the optimum for walking only, the stop spacing of 1,0000 metres is 25 % higher. Line spacing is nearly 45 % higher up to 1,300 metres, enabling a frequency of 8 vehicles per hour. Nearly 60 % of the travellers walk to the stops, leading to an average access speed of 5.1 km/h. Travel times are 5 % lower, while the operational costs are more than 10 % lower. The resulting level of social welfare is an additional 6 % higher leading to a total improvement of 11 % compared to the reference situation.

In all cases, stop spacing and social welfare are higher while travel time and operational costs are lower. All scenarios lead thus to better network structures than the reference situation: less stops but higher quality at lower costs. If cycling is considered as access mode, line spacing and frequency are higher too, except for the case of a high penalty for bicycle usage. In the cases of no penalty or a small penalty for bicycle usage, the combination of walking and cycling as access modes leads to coarser and more attractive network structures for all possible points of view: traveller, operator, and society. If the penalty for using bicycles as an access mode is high, however, the network optimised for walking only is better with respect to travel time, total costs and social welfare. Since there is a small population opting for using a bicycle where walking would be faster, the average access speed drops slightly to 3.9 km/h. Contrary to the expectations, the resulting stop and line spacing are higher, which is the result of the non-linear characteristics of the access time.

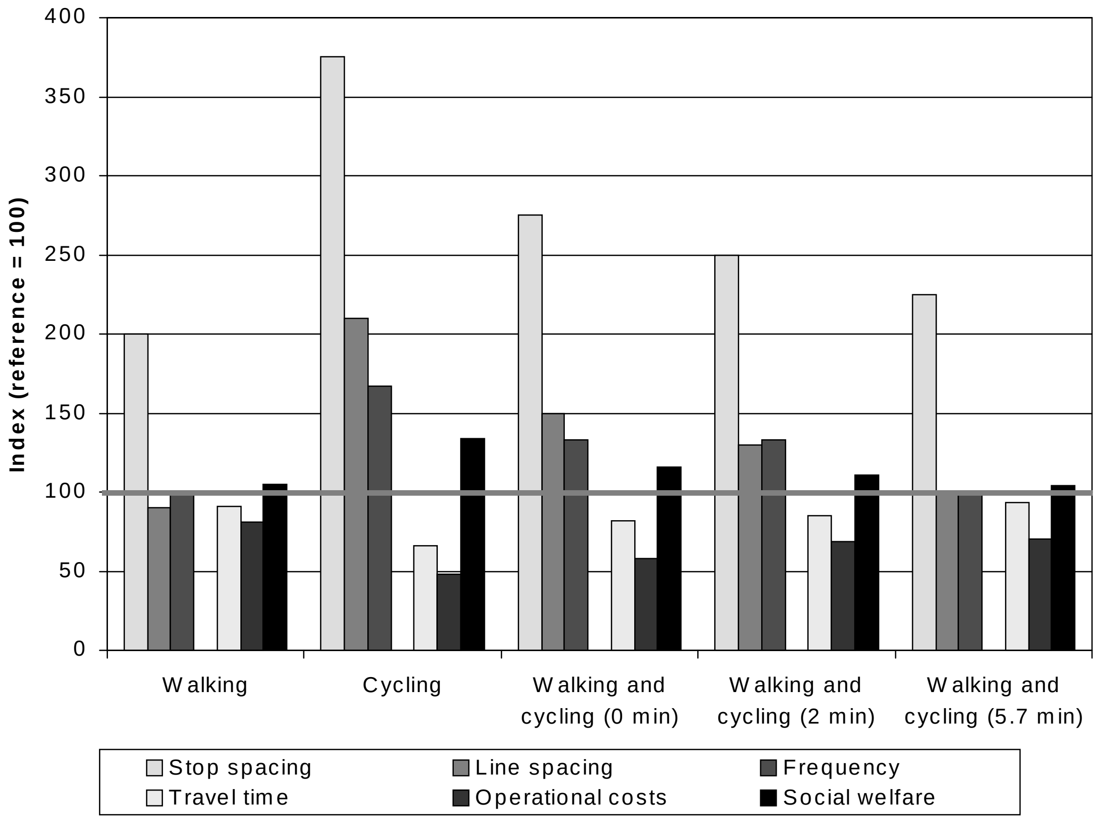

Figure 5. Main network and performance characteristics for different access modes as an index to the reference situation

Walking will always be an important access mode, accounting for at least 50 % of all trips. As a result, the impact of alternative access modes is small, compared to the assumption that all travellers will use faster modes. The expected increase in patronage due to the possibility of using bicycles is limited to 4%, that is, if no penalty is assumed. The reduction of the operational costs, however, is still substantial.

Of course, it is possible that not every traveller can use a bicycle, for instance, because they are too old or that they do not have a bicycle. These travellers will have to walk to the stop even though the access distance has been increased and their weighted travel time will therefore increase. The net effect on the patronage will depend on the population size. For both cases where the combination of walking and cycling seems interesting, that is, no penalty or a penalty of 2 minutes, an analysis is made of the impact on the demand level of a sub-population that is forced to walk given the new network characteristics. The following scenarios were used:

- 100 % of the travellers have to walk;
- 40% of the travellers are captive, that is the share of travellers who stated that they were not able to use a bicycle for that specific trip (Van der Waard (1988b));
- 17% of the travellers, that is, the elderly;
- 0% are captive, which is equivalent to all travellers can choose to use a bicycle or not.

The results are shown in Figure 6. It is clear that if the sub-population that has to walk becomes too large, there is a negative effect on the demand level. The critical size of the population that is captive with respect to walking as access mode is circa 45%.

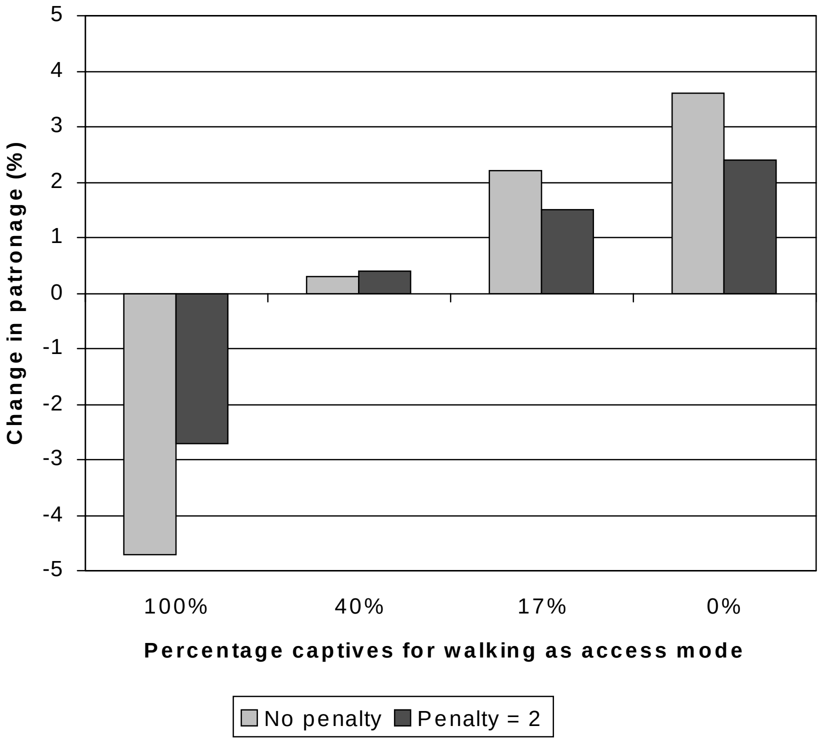

Figure 6. Net impact on demand level of a multimodal network structure for four access scenarios

5. Conclusions and recommendations

The analysis clearly shows that it matters whether alternative access modes for urban public transport networks are considered or not. In the case that cycling is considered to be an access mode too, the resulting network structures have a larger stop and line spacing, leading to shorter travel times and lower operational costs. The impact is less, however, than in the case that all travellers would choose to use a bicycle to access the public transport system. Walking will always be the most important access mode.

An important element in the analysis is the description of the traveller's behaviour. In this context there are two aspects that need further research. First, what is the traveller's attitude to using alternative access modes? This concerns the size of the sub-populations, free to choose or forced to walk, as well as the value of the penalty for using alternative modes to access urban public transport. Second, more knowledge is needed on the traveller's response to larger access distances in urban public transport systems. Are the commonly used weights for access time still applicable, or is there a maximum access distance or a non-linear relationship between access time and the corresponding weight?

The traveller's attitude to using alternative modes determines the implications for planing practice. If there are enough travellers having a positive attitude to using, for instance, a bicycle to access the urban public transport system, an urban public transport network should have larger stop and line spacing and a higher frequency. The net impact on the demand might be small, but travel times and especially operational costs will be reduced. However, if there is only a small population willing to use a bicycle, or if the penalty for using a bicycle is high, then it is better to assume that walking is the only access mode. Of course, it might be interesting in this case to provide parking facilities for bicycles at a subset of stops, for instance, every second stop at the outskirts if the city, to make urban public transport more attractive.

Finally, the discussion presented in this paper focuses on the impact of cycling as an additional access mode to urban public transport systems. The conclusions with respect to the impact on public transport network structures, however, are certainly representative for other access modes too, for instance, peoplemovers or demand responsive transport systems. It might even be expected that for such modes a higher penalty must be used than for cycling. The use of bicycles is widely spread, at least in countries such as Denmark or the Netherlands, and what is more important, the traveller can take care of his own access trip. The use of peoplemovers and demand responsive transport systems introduces a dependency on the quality of these transport systems, for instance, the frequency and the punctuality. This implies that these transport systems should be used as access modes for higher level public transport networks only.

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Appendix: Values of the parameters used

Parameter	**Symbol**	**Value**	**Units**
Travel distance	L_c	5,000	m
Access speed walking	V_{a1}	1.1	m/s
Access speed cycling	V_{a2}	4.4	m/s
Factor access distance	f_a	0.25	
Factor waiting time	f_w	1,800	s
Maximum speed public transport	V	13.9	m/s
Time lost at stops	T_s	34	s
Egress time	T_e	180	s
Weight access time	w_a	2.2	
Weight waiting time	w_w	1.5	
Weight egress time	w_e	1.1	
Travel demand per square kilometre	P_0	175	$/km^2$
Value of time for travellers	c_t	4.55	€/h
Operating costs per vehicle	c_o	164	€/h
Fare	r_f	0.55	€
Subsidy	r_s	0	€
Parameter mode choice model public transport	α	0.03	min^{-1}
Parameter mode choice model private car	α_m	0.08	min^{-1}
Average speed private car		4.2	m/s
Parking penalty private car		300	s
Parameter access mode choice walking	α_1	0.12	min^{-1}
Parameter access mode choice cycling	α_2	0.08	min^{-1}
Mode specific constant cycling	ϕ	1.0	