Multimodal travelling
and its impact on public transport network design.

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Abstract
Multimodal tripmaking, that is trips using a combination of several modes between origin and destination, is expected to be beneficial to society because of its lower consumption of scarce resources. Combining the strong points of specific forms of transportation in terms of their accessibility, speed, efficiency, etc might offer advantages to the traveller as well. This paper looks at some of the implications of multi-modality in trip making for the design of public transport systems since these play a dominant role in multi-modal transportation systems. Assuming that the level of multi-modal trip making needs to be increased, the question is at stake whether and how public transport systems might be improved and enhanced in order to achieve that objective. In this respect, the paper looks at the strategic design characteristics of public transportation service networks, that is at subdivision into (hierarchical) service levels, line density, stop density and service frequencies at various supply levels (local access, urban connection, interurban connection, etc). Contrary to initial expectations the paper concludes that specific design adaptations of public transport service networks in order to support increased multimodal travelling are not imperative. Notwithstanding that, the analyses show that significant improvements of urban public network design are possible that are also beneficial for multimodal mobility.

1. Introduction

1.1 It is a widespread belief that multi-modal trip making is beneficial to society because of its lower demands on scarce resources such as space, clean air, silence, etc. In this respect, the term *multi-modal* means the combination of distinct forms and modes of transportation within a trip from origin to destination. By combining the strong points of specific forms of transportation in terms of their accessibility, space consumption, speed, efficiency, etc for particular parts of a trip, an overall optimal travel performance might be attained.
Well-established forms of multi-modality in personal mobility already exist for some time, such as Park & Ride, or various combinations of public transportation within a single trip. Notwithstanding this, policy makers and planners are convinced that further stimulation of multi-modality is needed which should be pursued by improving existing forms and by introducing new forms. One of the claims is that improving multi-modality in the transportation system would increase the use of public transport at the cost of using the private car, thereby contributing to the generally accepted policy goal of shifting travel demand towards more environmentally friendly modes.

1.2 In this paper we will look at some of the implications of multi-modality in trip making for the design of public transport systems. We do this since public transportation plays a dominant role in multi-modal transportation systems. In nearly every multi-modal trip, one or more of the legs of such a trip consist of some form of a public transport service, apart from various forms of private transportation with car, bicycle or by foot [Van Nes, 2002b]. Therefore, if the level of multi-modal trip making needs to be increased, the question is at stake whether and how public transport systems might be improved and enhanced in order to achieve that objective. To that end, in this paper we look with a particular design objective in mind at the strategic design characteristics of public transportation service networks, that is at subdivision into (hierarchical) service levels and at network structure, line density, stop density and service frequencies at various supply levels (local access, urban connection, interurban connection, etc).

1.3 We first look at improvement opportunities of network design for single-level urban public transport services when passenger access to stops mainly is by foot, as is currently the case. In a second step we investigate the impact of introducing multi-modal access (bicycle, car, shared taxi, etc) on the systems design of urban public transport. In a third step we look at multi-level systems, investigating under what conditions distinct and different levels of interconnected PT services may lead to overall service improvements for the travellers. This analysis includes optimisation of network designs for a two-level PT system consisting of an urban and an interurban network where the former subsystem partly functions as a feeder to the latter subsystem. We study the interdependency of the designs of both networks under different assumptions of competition and cooperation of the PT service providers. In this paper we confine ourselves to multimodal travelling with public transport as main modes.

2. Research into Multimodal Personal Transportation (SMM)

2.1 The question of increasing the level of multi-modal transportation is a challenging one both from a planning and implementation as well as from a research point of view. In contrast to unimodal private trips, multi-modal trips are complex because they consist of different legs that need to be attuned. Multi-modal trip making requires from the traveller a lot of effort in organizing and preparing his trip, in acquiring information, in making transfers between legs. Because of its complex composition, the planned completion of multi-modal trips is much more vulnerable to deviations because of multiple potential distortions of the services in each one of the several legs of the trip.
Also from the service providers, multi-modal travelling requires more and better organization, better service information provision, perfect performance of operations, and service disruption management.
Essential and difficult elements in each multi-modal trip are the necessary transfers between modes and services. Quick and easy transfers are critical to the success of every multi-modal transportation system. Such transfers require special facilities, require harmonisation of the timetabled services, require monitoring and control of the transport services in order to match the time tables at the transfer nodes. Because of the service dependencies in the transfer nodes, service disruption of one run easily can cause disruptions in other runs thereby spreading out over multiple lines of a network.
One of the pre-conditions for attractive multi-modal transportation therefore is that the distinct subsystems (transportation services, information services, transfer facilities, etc) working together in a multi-modal system each are designed optimally and function properly in the light of their function within the total system.

2.2 At the Delft University of Technology a broad multi-year multi-disciplinary and multi-faculty research programme called SMM (Seamless Multimodal Mobility) has been launched in 1997 to tackle a variety of scientific questions that need to be answered in order to significantly improve the supply and attractiveness of multi-modal personal transportation services [Bovy, 1999]. This programme is organized around three decision levels distinguished in planning practice: that is strategic planning of multi-modal systems, tactical planning of distinct services, and operational execution of services.
At the *operational* level, research in SMM is directed among other matters towards improvement of punctuality and synchronicity of public transport services as well as to real-time management of service disruptions. To that end, intelligent service operations monitoring tools are being developed [Muller & Furth, 2000] and decision support tools that can predict in real-time network-wide impacts of service interventions by traffic controllers [Goverde & Hansen, 2001]. An innovative analytical tool based on max+ algebra has been developed that can predict exact network conditions resulting from proposed control measures [Goverde et al., 2000].
A central issue of SMM at the *tactical* level concerns time table design. Mathematical optimisation models are being developed that specifically optimise the temporal and spatial distribution of buffer times to ensure on the one hand efficient travel and transfer times for the passengers while on the other hand guaranteeing a sufficient level of robustness of the time table against disruptions [Goverde, 2000, 2001].
Innovative dynamic pedestrian flow models have been established enabling impact analysis of transfer station design and time table characteristics of interconnected

services on passenger flow characteristics in stations [Hoogendoorn et al, 2001, 2002, Daamen et al, 2001, 2002]
The questions at the *strategic level* among others deal with:

- development of organizational arrangements for cooperative ventures among all parties involved in supply of different services (transport, information, infrastructural facilities, etc). The German and Swiss Verkehrsverbund are examples of a type of organizational arrangement.
- Development of analytical tools for market analysis of multi-modal services; this includes developing traveller behaviour theory and related choice models specifically dedicated to individual multi-modal trip making [Benjamins et al., 2002; Catalano et al., 2002];
- Optimal design of public transport service networks specifically given their role in multi-modal transportation [Van Nes,2002b].

2.3 In the remainder of this contribution, we will exclusively focus on the subject of network design, namely on the resulting implications for an optimal public transport network design if public transport services are considered as part of an integrated multi-modal transport system. First, the next section will outline the research approach followed in tackling this question. Then, design rules will be derived for single-level urban PT systems, respectively without and with multi-modal access possibilities. This will similarly be followed for the case of multilevel PT systems.

3. Definitions and market size of multi-modal travel

3.1 In this paper we mean with *multi-modal* the combination of two or more different forms of transport within a single trip from origin to destination. This may consist of different vehicles, such as car, bicycle, tram, bus or train, or different services, such as stop or express services. We use the generic term *mode* to indicate different forms (in a vehicular or functional sense) of transportation. A multi-modal trip thus always consists of two or more legs with different modes between which a transfer by foot is necessary. Typical examples of multi-modal trips are chains such as walk-bus-train-walk, or bicycle-train-walk, or car-train-walk. However, the chain walk-city bus-regional bus-walk also is a multi-modal trip.
Single-leg chains are by definition uni-modal. Multi-leg chains with only a single vehicular leg, such as walk-car-walk or walk-bus-walk, also are defined as uni-modal in this paper because a transfer process is absent.
A multi-modal transportation system is a system that offers different transportation services (in a vehicular or functional sense) connected by interfaces (e.g. stations) that facilitate transfers between the distinct modal services. Larger public transport systems are hierarchically organized as multi-level systems with short distance, low-speed access and feeder services as a bottom level service layer up to long distance, high speed services as top level service layer. A multilevel PT system is by definition a multi-modal system, even if it uses the same vehicle type (e.g. bus) at all levels.

3.2 Currently in most developed societies, multimodal trips constitute only a relatively small market segment of about 5% or less of total trips (3% in The Netherlands [Van Nes, 2002b]). However, when looking at specific spatial conditions, such as city-oriented trips in larger urbanized areas, this share can be significant (20% or more in The Netherlands). It is generally expected that this share might be increased substantially by dedicated transport policies.

4. Design of Multimodal Public Transport Systems: approach

4.1 The methodology used to derive optimal design characteristics for public transport service networks consists of the following elements:

- specification of the *spatial setting* of travel demand;
- specification of the *parties* involved in service supply including their operations *objectives*;
- specification of the *design variables* of the PT service supply system;
- modelling the *demand* for PT services;
- modelling the *optimisation* of the service network design.

We aim at deriving fairly general rules for optimal network design that are applicable to a large class of spatial settings. The design rules specify optimal values for network-averaged design parameters such as line density, stop density, service frequency, etc valid for a closed PT service system. These average values may then be applied in specific cases to determine number, alignment and frequencies of lines, and number and location of stops by line, depending on specific local conditions such as street pattern.

4.2 We assume an abstract *spatial setting* consisting of an hierarchical settlement pattern discretely distributed in space connected by a PT service network and other transport infrastructure networks to serve travel demand between settlements. Within settlements of sufficient size a local PT service system exists serving travel demand within each settlement and to other settlements. Settlements are assumed to have one (or more) centres of activity to which travel demand is predominantly oriented. Flows within settlements are assumed organized in centre-oriented corridors (radial flow pattern). Within the corridors travel demand is assumed uniformly distributed over continuous space. Consequently, the PT service network is assumed regularly spaced in each corridor.
It appears that this spatial model is sufficiently robust to cover a large variety of spatial configurations, the impact of which on PT network design has been studied by quantitative sensitivity analysis [Van Nes, 2000].

4.3 In designing an optimal PT service network, basically three *parties* are involved, that is travellers, operators, and authorities respectively, each having their own *objectives* in optimising service network design. Travellers are best served by networks minimizing their (perceived) travel costs or travel disutilities, possibly given an operational budget. Operators are inclined to design networks that maximize their net profit (revenues minus operational costs) or maximize cost-effectiveness (revenues-cost ratio). The authorities responsible for transport services in their jurisdiction may strive for networks that minimize total costs (sum of traveller and operational costs) or maximize patronage, the latter being equivalent with the travellers' objective of minimizing perceived travel disutilities. From a welfare-economic perspective it is suggested [Berechman, 1993] to apply maximization of social welfare as desirable design objective for transportation systems, where social welfare is defined as the sum of consumers surplus and producer surplus. Consumer surplus is the value travellers in total gain by travelling at specific actual costs (or disutilities including monitarised travel times) although they are prepared to travel also at higher costs (or disutilities) as given by the PT demand function, while producer surplus equals the operators profit (revenues minus operational costs).

It depends on the prevailing market situation which objective best serves as criterion for optimising the service network at hand. In most urban situations, local authorities determine service conditions which means that welfare maximization should be adopted. In some interurban conditions, operators may have concessions in which they have ample freedom of designing their services.

4.4 In our network design optimisation, we deal with average *design parameters* for a whole service network, possibly consisting of various service levels. In principle, the following five network design variables can be distinguished:

- space accessibility, derived from line and stop spacings;
- time accessibility, determined by line frequencies;
- network speed, determined by the design speed of vehicles and infrastructure;
- network structure expressed by the number of service levels;
- network type, such as rectangular, radial, or triangular line configuration;
- network density, determined by line spacings and number of radials.

Figure 1 shows the relationships of these design variables with relevant objective variables on the supply and demand sides respectively, connected by relevant intermediate variables.

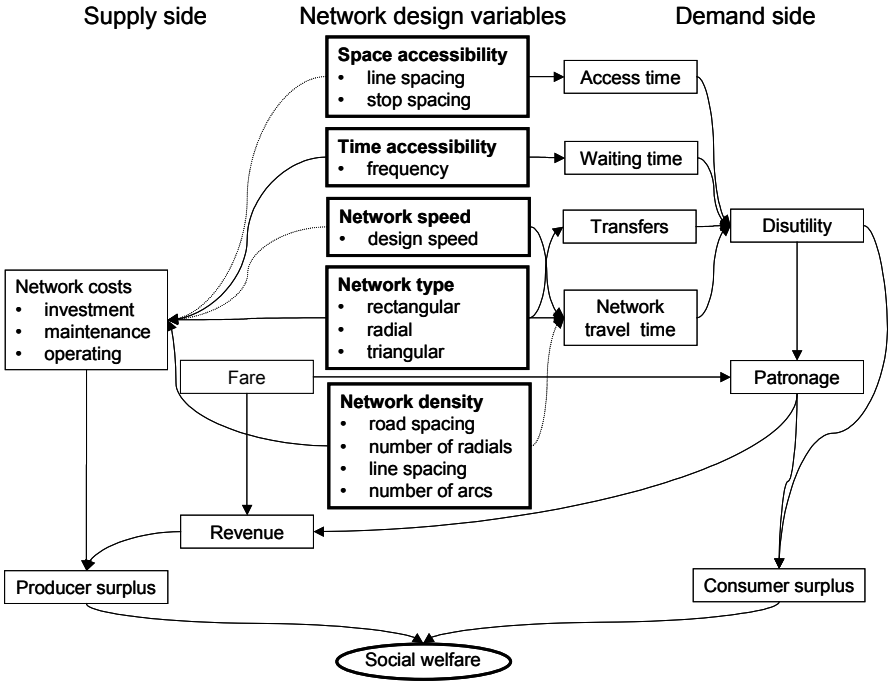


Figure 1: System description of public transport network design problem

Finding the optimal settings of these design variables is not a trivial task since most design variables cause opposing effects on components of the objective functions: for example, improving travel quality generally will lead to increased costs, improved spatial access leads to lower travel speeds, higher frequencies lead to less waiting time but a lower space accessibility if an upper limit is given to the operational costs, etc.

4.5 In the following analyses, fares and network speed are assumed given exogenously. Their impact on network design will be studied by sensitivity analysis. Even so, network type is not considered a design variable in our problem, although in theory it is. Preliminary analyses (Van Nes, 2000) have shown that our corridor

network approach for the urban level is sufficiently robust for answering our design questions; in addition, planning practice shows that by far most urbanized regions are served by radial systems (Vuchic & Musso, 1991).
If we first look at the urban level only, the following *four design parameters* are at stake:

- number of service levels: whether a single-level (only stop services) or a multi-level system (distinct stop and express services) should be adopted;
- average line spacing (or line density) at each distinguished level;
- average stop spacing (or stop density) at each distinguished level;
- service frequencies at each distinguished level.

In sections 5 and 6 we deal with design optimisation of a single-level urban PT system, after which in sections 7 and 8 consideration is given to the design problem of multi-level service networks.
Looking at the inter-urban network level, only service frequency is treated as a design variable to be optimised since in this case line and stop spacing are predominantly determined by the given structure of the settlement pattern.

4.6 *Travel demand* in the urbanized areas is assumed homogeneously distributed over space and predominantly directed towards the city centre. The design parameters of the PT services network depend on the level of PT demand which in turn depends on the quality of the PT services relative to other travel opportunities (among which non-travel). The service quality of a PT trip is expressed in a generalized cost function (or travel disutility function) which is a weighted sum of access time to stops, waiting time, in-vehicle time, transfer time, and possibly fares. The values of these PT trip time elements directly follow from the considered design variables such as stop distance, line distance, line frequencies, transfer, etc. The demand for PT usage is modelled using a binomial logit function (PT versus non-PT) where the PT network characteristics vary while the other travel options are assumed constant. This logit function also is used to calculate the consumer surplus using an approximation that sufficiently retains the non-linear characteristics of travel choices [Van Nes, 2002b].

4.7 Finding the optimal design parameter values for the design cases at hand is based on the formulation of a *bi-level optimisation problem* (Figure 2) where the upper-level describes the optimisation problem of the operator or authority (choosing design parameter values which maximize his objective function, taking account of traveller

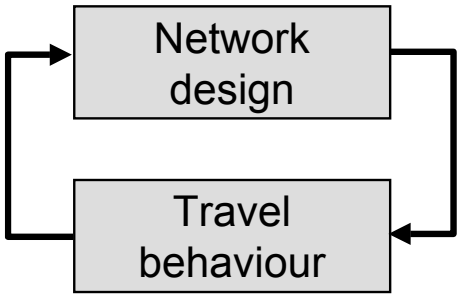


Figure 2: Network design as a bi-level optimisation problem

responses) while the lower level describes the optimisation problem of the traveller (choosing the travel option that maximizes his benefits or minimizes his costs, given the PT service network properties). It turns out that for the cases studied this bi-level

problem simplifies to an unconstrained single-objective formulation that can be solved analytically in some cases, and need to be solved numerically in some other cases.

5. Optimising single-level urban public transport networks

5.1 In this and the following section we will deal with two questions:

- first, whether current design rules for urban PT networks can be improved to the benefit of a better PT service per se, as well as, consequently, to the benefit of multimodal travelling;
- second, whether improvement of *multimodal access* to the urban PT network might increase PT service attractiveness and possibly might induce changes in the network design (see section 6).

We have established analytical optimisation models to answer these questions. To this end, we define an urban area consisting of corridors within which a number of parallel equidistant lines offer PT services to the city centre (see figure 3).

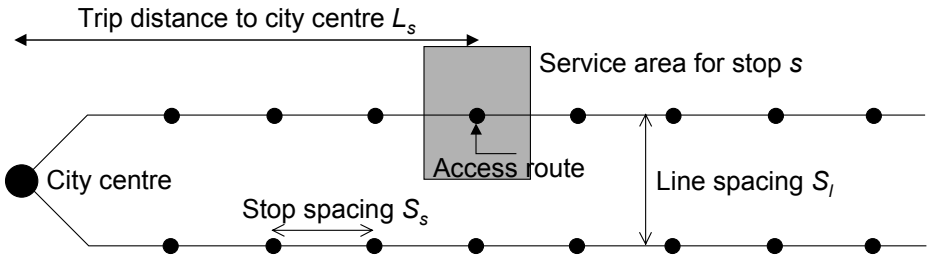


Figure 3: Schematic lay-out of urban corridor served by public transport lines

This might seem a rather typical situation for a transit network, but analyses of the impact of considering other trip types (return trips and transversal trips, with and without transfer in the city centre) on the optimal network characteristics show that the findings of this specific case are representative for most urban network types [Van Nes, 2000].

The decision variables are stop spacing (S_s), line spacing (S_l) and frequency (F) for which optimal values are to be determined given an objective function (such as maximising social welfare or minimising total costs). The main components for these objectives are weighted trip travel time, patronage, and related quantities such as revenues, consumer surplus, travel costs, and operational costs (see figure 1). Table 1 shows a general mathematical representation of the optimisation model.

The following assumptions were made:

- travel demand is homogeneously distributed, independent of distance to city centre (which can be relaxed in more refined analyses);
- fares are fixed;
- access routes are parallel and perpendicular to the lines;
- all lines offer direct access to the city centre without need of transfer;
- egress times in city centre are fixed.

In each objective function, the weighted door-to-door travel time is a key variable which consists of access time to stop, waiting time, in-vehicle time, and egress time.

Table 1: General specification of network design optimisation model

Item	Function
Objective: maximising social welfare	
Access time	$T_a = f_a(A_s)$
Waiting time	$T_w = f_w(A_t)$
Time spend on the network	$T_n = f_n(L, N_t, D_n, V_n)$
Total travel time	$T_t = f_t(T_a, T_w, T_n)$
Patronage	$P = f_p(T_t)$
Revenues	$R = f_r(P)$
Consumer surplus	$CS = f_{cs}(P, T_t)$
Network costs	$C_n = f_n(D_n, N_t, A_t, A_s, V_n)$
Producer surplus	$PS = f_{ps}(R, C_n)$
Social welfare	$SW = f_{sw}(CS, PS)$
Objective: minimising total costs	
Patronage	P = constant
Travel costs	$C_t = f_{ct}(P, T_t)$
Total costs	$C = f_c(C_n, C_t)$

A_s = space accessibility A_t = time accessibility

Weights are used to account for the differences in valuation of trip elements by the travellers.

$$T_t = w_a T_a + w_w T_w + T_n + w_e T_e \quad (1)$$

where:
T_t = total weighted door-to-door travel time
T_a = access time to nearest stop
T_w = waiting time at stop
T_n = in-vehicle travel time, spend on network
T_e = egress time
w_x = weight for time element x

Typical values for time weights relative to in-vehicle time are: w_a= 2.2, w_w= 1.5 and w_e= 1.1 (Van Nes,2002b).
Access time depends on decision variables S_s and S_l as well as on access speed V_a and the geometry of the access network described by the access detour factor f_a. Waiting time is a function of service frequency F. In-vehicle time is determined by trip length L_c, number of stops ($1/S_s$), maximum vehicle speed V and time T_s lost at stops.
Travel demand to the city centre is expressed in number of trips per unit area. PT use depends on quality of PT service expressed in a disutility function including weighted travel time and possibly travel costs. Level of PT use (patronage) is calculated using a binomial logit function which is also the basis to calculate monetarised consumer surplus (using monetary values of time) and operator revenues. The revenues are determined by the fares and the subsidy, which may be a fixed amount or performance related.

The operational costs depends on the service frequency F, the number of lines per unit area, the vehicle speed, and the operational costs per vehicle per hour.
The formulae to calculate these quantities and the objectives are straightforward (see Van Nes, 2000, 2002). Given the expression for the objective, optimal values for the three design variables can be derived analytically (in the case of minimising total costs) or numerically (in the case of maximising social welfare).

5.2 The resulting expressions for optimal design parameters reveal the following relationships:

- the three design variables of interest are clearly interrelated showing the trade-off to be made between them: higher frequencies permit larger line spacing and vice versa, smaller line spacing compensates for larger stop spacing.
- optimal *stop spacing* increases with access speed, with time lost per stop, with operational and investment costs, and with average trip length (or corridor length), while optimal stop spacing decreases with access time weight and access network geometry factor;
- optimal *line spacing* shows similar relationships except for the corridor length which does not have a direct influence;
- the optimal *frequency* increases with the waiting time weight, with maximum speed, and with time lost at stops, while optimal frequency decreases with increasing operational and investment costs.

These general relationships show the importance of the access conditions for an optimal network design, reason why the potential of improvement of stop access by introducing other modes than walking will be studied in section 6.

5.3 With these models two typical urban situations have been analysed. The first is a bus network for a medium–sized city (250,000 inhabitants) with corridor length of about 5 kilometres. Currently in the Netherlands, such a situation (e.g. suburbs Zuilen and Overvecht in the city of Utrecht) is traditionally served by about 5 bus routes with average spacing of 550 metres, stop spacing of 350 metres, and peak frequency of 5 vehicles per hour.
The second case is a larger conurbation with a corridor of 7 kilometres length served by tram routes having a line spacing of 1,000 metres, a stop spacing of 400 metres, and an average peak frequency of 8 vehicles per hour. This case is exemplified by the southern part of The Hague (Netherlands).
We calculate optimal design values for these two corridors and compare these with current values. The behavioural and cost parameters used in the optimisation models are derived from Dutch mobility surveys and PT company data (see Van Nes, 2002b). Demand and supply conditions refer to a peak period. The access mode considered is walking only.

5.4 Table 2 summarises the *results* of the two network optimisation exercises in comparison with traditional design characteristics. Included are the optimal values calculated for the decision variables stop spacing, line spacing, and frequency, the related densities, the values of the objective functions, and the consequences of the resulting design for travel time, patronage, operational costs, and operator profit.
The optimised results show that traditionally designed networks certainly can be improved from a social welfare point of view implying better travel quality at lower costs (compare columns 1 and 2 respectively 4 and 5). The same holds when the networks are optimised according to other objectives (see Van Nes, 2000). For the *bus*

service, network density can significantly be reduced by doubling stop spacing and by increasing line spacing by 50%, while frequency can substantially be increased. These changes lead to higher network speeds and therefore to shorter travel times and thus somewhat higher patronage, while at the same time give rise to lower operational costs in the range of 15 to 25%.

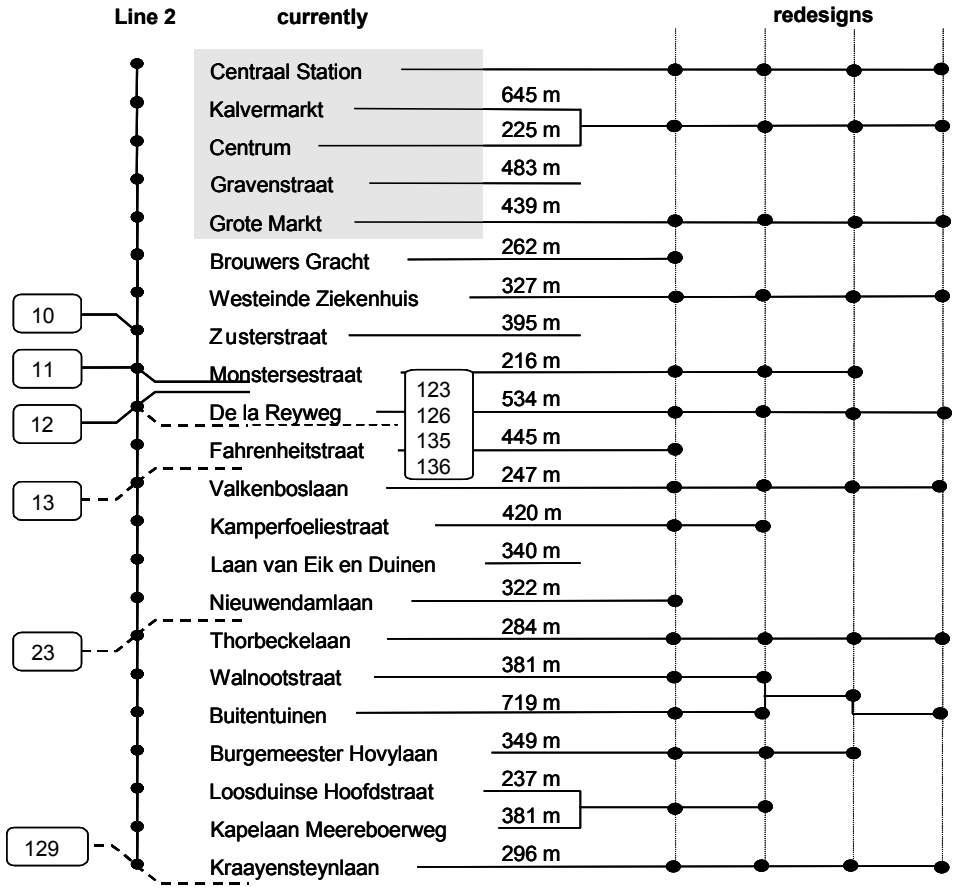
Table 2: Comparison of optimised network designs with current values for two cases

	Bus (average trip length 3 km)			**Tram** (average trip length 5 km)		
	Tradi-tional	Max. Social welfare	Min. Total costs	Tradi-tional	Max. Social welfare	Min. Total costs
	(1)	(2)	(3)	(4)	(5)	(6)
Stop spacing [m]	350	640	641	400	757	762
Line spacing [m]	550	752	759	1,000	797	820
Frequency [veh/h]	5	8	7	8	7	7
Stop density [/km^2]	5.2	2.1	2.1	2.5	1.7	1.6
Line density [km/km^2]	1.8	1.3	1.3	1.0	1.3	1.2
Social welfare [€/km^2]	411	434	430	744	779	772
Total costs [€/km^2]	299	281	276	515	485	481
Travel time [min]	20.8	18.2	18.8	25.1	22.8	22.9
Weighted travel time [min]	28.2	26.7	27.5	33.5	32.3	32.5
Patronage [/km^2]	**100**	102	**100**	**150**	151	**150**
Revenues [€/km^2]	34	35	34	85	86	85
Operational costs [€/km^2]	68	59	51	104	85	83
Profit [€/km^2]	-34	-24	-17	-19	0	2
Total costs per trip [€]	2.98	2.76	2.76	3.44	3.20	3.21
Total costs per kilometre travelled [€/km]	0.99	0.92	0.92	0.69	0.64	0.64

For the *tram* system, optimised stop spacing also is significantly larger (again nearly doubled) than currently is adopted while line density should be increased by about 20%. Also frequency might be slightly reduced in the optimal design which is compensated by higher network speeds because of less stops. Also in this tram case, travel times decrease and patronage therefore slightly increases. The reduction of operational costs is substantial: up to 20%.
Since local PT also serves as feeder to higher level services, these improvements in local services imply a higher attractiveness of multimodal travel as well.

5.5 In order to test the plausibility of this modelling approach to PT network design, the optimal design parameter values found have been applied in a case study to redesign tram line No.2 in The Hague, Netherlands (see Schäffeler, 1999; Van Nes, 2000). In a number of steps the stop density of currently 21 stops over 7,4 kilometres (average stop spacing of 370 metres) has been successively reduced to finally 8 stops. The performance of each design has been judged by output measures such as travel time and operational cost (see Figure 4). The redesign exercise shows that indeed a significant operational improvement may be attained by coarsening current networks

without any loss in service quality. The operational gains of more than 20% might be used for increasing the service frequency and thus attracting additional patronage.



21	Number of stops	16	13	10	8
370	Average stop distance [m]	450	600	750	1000
21.8	Travel time [min]	21.4	21.1	21.3	22.1
29	Operational costs [€/km²]	27	25	22	20

Figure 4: Redesign exercise The Hague tram line 2 with coarser stop spacings

5.6 From the analyses it appears that the resulting optimum value of the objective is fairly robust and shows a flat surface around the optimum. This holds for all relevant objective functions (see Van Nes, 2000). This gives some flexibility in choosing design values. On the other hand, the optimum values of the three design variables appear sensitive to the chosen objective, meaning that the type of objective chosen significantly matters for the eventual optimal network design.
Equally, the resulting optimal design parameters appear sensitive to a number of input parameters, especially the perceived access time, which is determined by access speed, access network geometry, and access time weight. All three design parameters are significantly dependent on this access factor, with access time elasticities of about:

- -.3 for stop spacing
- -.4 for line spacing
- -.3 for frequency,

meaning: a 10% shorter access time enables a 4% larger line spacing, etc. Improving access conditions to stops thus seems a beneficial planning strategy.

5.7 The network design figures shown in section 5.4 (Table 2) will be used as a benchmark for subsequent extensions. The benchmark refers to an urban single-level PT system with walking only as access mode. The performances of extensions such as multi-modal access, inner-urban express lines, and feeder-trunk systems will be judged in relation to this benchmark.

6. Multimodal access to urban PT services.

6.1 If we look at higher-level PT systems such as express services in larger conurbations or intercity train services, the access to the nodes of these higher systems already is of a multimodal nature since virtually all modes are adopted (walking, cycling, bus, kiss&ride, park&ride, etc). Changing the access conditions in this case (e.g. by strongly improving bicycle access) will not influence the PT network design at this functional level since its spatial configuration is predominantly determined by the spatial settlement pattern. Changing access conditions will however have an impact on the patronage of these networks and indirectly therefore also on the patronage of the urban feeder network.
For the lower level public transport network in urbanized areas, however, the question remains whether introducing complementary access modes additional to walking might influence its network design. So far, planners of urban PT networks exclusively take walking to the stops as the only mode to consider for network set-up. It seems plausible, however, which is corroborated by the design optimisation formulae, that increasing the access speed may strongly affect the optimal design. The formulae roughly indicate that network density would decrease with the square root of the access speed. Taking bicycle or kiss&ride to the stop would imply an access speed about four times higher than walking and consequently a doubling of stop and line spacing if all travellers would adopt these access modes. This would lead to a sensible reduction in travel time as well as a substantial reduction of operational costs. However, not every PT user will use the bicycle or other mechanized mode: it depends on the distance to the stop, on his physical abilities, and on vehicle availability.
In the sequel, we will first give a qualitative reasoning about possible shifts in demand and then will present results of a quantitative analysis of the potential of increasing bicycle use as an access mode for improving urban PT services.

6.2 Compared to the traditional walking-only situation, consideration of bicycle use as additional access mode would change access travel as follows. Using a bicycle is only open to travellers being able to use a bike, and for them it is only a worthwhile option if the shorter access time outweighs the terminal costs of parking the bicycle (including the risks of damage and theft), which will only be the case for longer access distances. The total PT market segment will increase at the cost of non-PT due to the extra access mode making PT relatively more attractive. The size of this increase depends on the perceived attractiveness of cycling to the stop relative to walking and on the level of non-PT users that is able to choose the bicycle. Additionally, a number of walkers will switch to bicycle if they can improve their access quality, which might be the case only at longer distances from the stop. Again, this substitution depends on the relative attractiveness and on the vehicle availability

among the walking group. Both switching categories will experience improved access travel conditions (shorter perceived access). In total, average perceived access time will decrease. This new demand condition in turn gives rise to re-designing the service network towards coarsening the network which may further improve travel conditions and thus patronage.

6.3 The described travel choices are modelled using an extended (nested) logit model. Extended mode-specific access disutility functions were specified for walking and cycling including mode-specific time parameters and a time penalty for bicycle use reflecting parking costs and the like. Parameter values were derived from statistics on bicycle use, as was an estimate of the share of walking captives. Currently in The Netherlands, the bicycle use as urban PT access mode is negligible (it is however large for inter-urban PT travel). The percentage of walking captives was estimated at 40% while the time penalty for bicycle use for urban PT access was estimated to be fairly high at 35 minutes (Van Nes, 2002).
Using the logit access mode choice model, the binomial logit model for PT travel choice was extended with an adapted access time component.

Table 3: Design impact comparison of alternative access mode scenarios

	Reference	**Walking and cycling as access modes**				
	Optimal for walking only	**Base**	**Penalty -50%**	**Captives – 50%**	**Penalty and captives – 50%**	**Penalty 2 min captives – 50%**
Penalty for cycling [min]	**-**	**35**	**17.5**	**35**	**17.5**	**2**
Walking captives [%]	**-**	**40%**	**40%**	**20%**	**20%**	**20%**
Stop spacing [m]	757	764	778	766	785	849
Line spacing [m]	797	804	820	806	829	942
Frequency [veh/h]	7	7	7	7	7	8
Social welfare [€/km^2]	779	786	801	788	808	855
Total costs [€/km^2]	485	480	468	478	463	425
Percentage walking [%]	100	98	92	97	90	75
Weighted travel time walking only [min]	32.3	32.4	32.5	32.4	32.6	33.0
Weighted travel time walking and cycling [min]	-	31.5	29.8	31.6	29.9	25.4
Patronage [PT-trips/km^2]	151	152	153	152	154	158
Revenues [€/km^2]	86	86	87	86	87	89
Operational costs [€/km^2]	85	84	82	84	81	79
Profit [€/km^2]	0	2	5	2	6	10
Total costs per kilometre travelled [€]	0.64	0.63	0.61	0.63	0.60	0.54

6.4 With this adapted demand model a series of design optimisation exercises on an urban corridor have been carried out in order to determine the potential impact of multi-modal access on optimal network design (see table 3). The corridor of 7 kilometres length with average trip length of 5 kilometres is assumed to be served by parallel tram lines. An example of such a network is the southern part of The Hague, The Netherlands, with currently a stop and line spacing of 400 and 1000 metres respectively, and a peak frequency of 8 services per hour. Apart from the base case

with estimated parameters, a number of scenario's were analysed with reduced parameter values for terminal penalty and captivity which reflect possible improvements of bicycle access resulting from dedicated planning measures. In order to find out what the maximum impact of improved cycling access to urban PT could be, a maximum scenario is analysed having a time penalty of only 2 minutes and a walking captivity share of only 20%.

6.5 A first *finding* is that in the base case (given the adopted demand model) only 2% of the tram users travel by bicycle to the tram stops (which fits reality well). The result is that this base case shows nearly identical design values as the walking-only reference. The bicycle improvement scenario's show that reducing the penalty has a much larger impact on bicycle access use than reducing captivity as appears from the resulting service characteristics (social welfare, travel times, operational costs, etc). Realistic intermediate scenarios show only small differences in optimal network characteristics compared to the walk-only reference. The maximum scenario shows that still 75% of the travellers will presumably walk to the stop. Only in that case, sensible differences in design and in system performance relative to the reference situation show up: coarser network, higher service frequency, travel time reduction of 20%, lower operational costs of 7%, etc.

6.6 The impact of introducing cycling as an alternative access mode on urban PT network design thus is small, which is contrary to earlier expectations. This unexpected finding also implies that the impact of other alternative access modes or services will even be less. Transport services such as peoplemovers or demand responsive transport systems introduce limitations in space and time which lead to penalties probably larger than the one for cycling. In the case of people movers, the fixed routes might also lead to an increase of the percentage walking captives. We may conclude from this that the concept of multimodal travel thus has a negligible influence on the design of urban PT networks. Extra attention to the combination of cycling and urban PT nevertheless makes sense. Providing cycle parking facilities at specific locations, e.g. at stops farther away from the city centre or at stops having large access distances, will certainly make urban PT more attractive. However, this does not justify adapting the network structures.

7. Optimising multi-level urban public transport systems

7.1 Most PT systems in larger urban areas are functionally organized as multi-level systems with high density stop services at local level and quicker express services at lower spatial density at higher, mostly inter-urban levels. These subsystems are connected at multi-modal transfer points such as railway stations. Lower level systems have a double function in that they not only offer origin-destination connecting services at shorter distances but also play an important role as feeder to higher level long-distance interconnecting express services. Multi-level services by definition are multi-modal since a large part of the trips need a transfer between different service types, mostly also between different vehicle types (from bus or tram to train and vice versa). From a survey of larger conurbations worldwide (see Van Nes, 2002b) it turns out that:

- stop spacing between levels differs by a factor of about 2.5;
- line length between levels differs by a factor of about 2.2;
- service speed between levels differs by a factor ranging from 1.7 to 2.6.

Some typical configurations found in practice are shown in figure 5 (See Vuchic & Musso, 1991).
For a discussion of the functional differences between these service configurations (see Van Nes, 2002b).

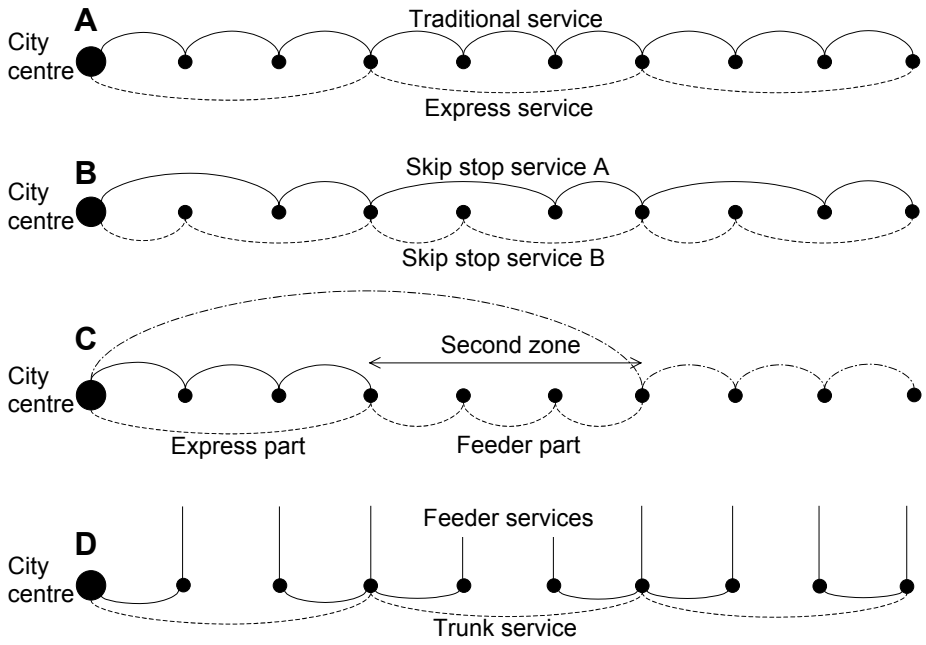


Figure 5: Main types of multilevel urban PT networks: A. skip-stop system, B. express system, C. zone system, D. trunk-feeder system.

7.2 We would like to analyse the question under what conditions a multi-level PT service system for a continuous urban area is beneficial from a social welfare point of view. Related design questions then are how many distinct levels are optimal (1, 2 or 3?) and which are the optimal values for stop spacing, line spacing en service frequency at the distinct levels. Given the assumption of a continuous urban area with homogeneous travel demand, the first question turns down to determining the break-even length of the corridor to be served at which introduction of a higher-level service with higher speeds and lower access density is beneficial.
The precondition for a multilevel PT system is that higher-level services have a much higher travel speed due to higher vehicle speed and larger stop distances. Long distance travellers may benefit from this higher speed as long as it outweighs the time loss and discomfort associated with the necessary transfers between the subsystems. The operators will have higher costs for the express services because of their higher speeds and special infrastructure which should be counterbalanced by attracting additional patronage and revenues.

7.3 To study the optimal design characteristics of multi-level systems, a similar modelling approach consisting of travel demand calculation and design optimisation is followed as in section 5, which is applied to an urban corridor of some length (typically 15 to 20 kilometres) with uniformly distributed centre-oriented demand served by parallel equidistant lines with equidistant stop pattern. Travellers in the corridor are assumed to choose between different service types dependent on service attractiveness and their origin location. The optimum design values for this case will

then be discussed in relation to more realistic assumptions with respect to travel pattern and demand distribution.
Three bi-level service types will be analysed: express services, trunk-feeder services, and zone system services respectively, and compared to a single-level network. For the higher-level lines a 50% higher maximum speed is assumed enabled by an own infrastructure such as busses on separate bus lanes or light rail systems. Since the bus system is clearly cheaper while offering the same travel speed the quantitative analysis relates to a system with separate bus lanes. For both levels the same service frequencies are assumed for sake of a fair comparison of network alternatives.
For the *express system*, line spacing and frequency of both networks are equal while higher-level stop spacing is a multiple of the lower-level stop spacing. Design variables are thus: line spacing, frequency, lower-level stop spacing, and its scale factor. For *trunk-feeder services* two lay-outs may be distinguished, perpendicular feeders where the trunk stop spacing is related to the feeders line spacing, and radial feeders where the trunk stop spacing is twice the feeder network radius. In a *zone system*, a line combines the collecting/distributing function within a zone with the express function from the zone to the city centre (vice versa). Essential difference with the trunk-feeder concept is that travellers don't need to make a transfer between the network levels.

7.4 Table 4 shows *results* for the case of a 17 kilometres long corridor, comparing the outcomes of an optimised single-level reference case (according to section 5) with the optimised results of the three bi-level system types. The three bi-level systems show clearly different network designs, although the lower-level stop and line spacings are surprisingly similar. It should be noted that these stop distances (about 600 m), although much lower than the optimised single-level distances (900 m), are much higher than the distances currently found in practice (about 400 m). The express and trunk-feeder systems, however, do not show clear advantages compared to a single-level system. The break-even corridor length for a better social welfare outcome is certainly beyond 20 kilometres. This is partly due to the need of transferring between the two networks for a large part of the travellers. A zone system however appears beneficial, even at much lower corridor sizes. Break-even corridor length is already about 5 kilometres. The higher operational costs of a zone system are clearly outweighed by the lower travel times. Even a zone system without expensive special high-speed facilities appears attractive if the corridor is longer than about 6 kilometres.
It has been shown that these results generally hold, also for other demand patterns not exclusively oriented towards the city centre (Van Nes, 2002b).

7.5 The analysis so far dealt with hierarchical networks under the assumption of uniformly distributed demand. The introduction of a higher-level network then will reduce travel times for travellers with origins near the higher-level stops but will lead to larger travel times for all others due to longer access distances or to transfer costs to the higher-level network. Combined with the inevitable increase in operational costs due to the added high speed services this leads to lower social welfare results. These findings may change however if densities around the higher-level stops in terms of inhabitants, workplaces or facilities are substantially higher than in areas farther away. The number of travellers that benefit from the higher-level service quality will increase substantially possibly leading to a net positive benefit of introducing a more expensive higher-level network.

Table 4: Optimal designs of bi-level urban PT services compared to single-level network (17 km corridor)

	Reference (single level) (1)	**Express system** (2)	**Trunk-feeder system** (3)	**Zone-system** extra (4)	**Zone-system** simple (5)	**Express system** concentration x 2 (6)
Level 1						
Stop spacing [m]	905	626	630	603	693	400
Line spacing [m]	770	965	969	969	868	1,000
Frequency [veh/h]	7	5	9	6	6	4
Transfers	No	No	Yes	No	No	No
Level 2						
Stop spacing [m]	-	1252	2,908	-	-	1,200
Line spacing [m]	-	965	4,032	-	-	1,000
Frequency [veh/h]	-	5	9	-	-	10
Scale-factor for stop spacing	-	2	3	-	-	3
Number of zones	-	-	-	3	2	-
Weighted travel time [min]	39.1	39.3	38.6	34.4	37.4	35.2
Operational costs [€/km^2]	44.3	52.9	66.4	53.5	48.3	74.7
Profit [€/km^2]	52.2	43.5	30.3	44.6	48.8	54.7
Total costs [€/km^2]	363	373	382	334	353	348
Social welfare [€/km^2]	691	681	673	714	699	-
Break even distance two levels [km]	-	> 20	> 20	> 5	> 6	> 10

To show the impact of demand concentration at higher-level stops, scenarios of an express system with various levels of concentration have been analysed. These show (table 4, column 6) that already at a level of doubling the demand concentration an express system is beneficial with lower total costs than a single-level system. The bi-level break-even distance drops from more than 20 kilometres corridor length (uniform demand) to less than 10 kilometres. Interestingly, demand concentration also leads to clear differences in importance of both networks with much higher frequencies for the higher-level network at the cost of the lower-level network (with a ratio similar to that found in practice).

7.6 The modelling results confirm the wisdom that spatial patterns strongly determine the set-up of multi-modal PT systems, especially in larger conurbations. As long as demand is more or less uniformly distributed but predominantly centre-oriented, zone systems are attractive as multi-level services giving already benefits over single-level systems for corridors of about 5 kilometres length or more. Surprisingly, zone systems are seldom found in practice. If demand is sufficiently concentrated in activity nodes, express systems can offer benefits over single-level systems for corridors of about 10 kilometres length or more. The analyses show that introducing a multi-level PT service system in larger conurbations may improve PT travel quality significantly and thus may stimulate multi-modal travelling. Serving multimodal travelling by offering

multi-level services clearly leads to a shift in network design towards shorter stop spacings at the feeder level. The findings show that for a hierachical system to make sense there need to be clear differences between the levels (stop spacing scale factor of least two).

8. Interdependence of local and intercity PT network design.

8.1 A usual case in multi-modal travelling is an intercity trip (e.g. by train) with local access and egress by modes such as local bus or tram, or private modes such as walking, cycling, or car. We finally investigate the question of the optimal network design of both the intercity line-haul PT services and local access PT services to the intercity stations. To that end, we consider a two-level PT system consisting of two interconnected subsystems: an urban network (called network 1) and an interurban (line-haul) network (called network 2). The urban network serves local trips to the city centre as well as offers access to network 2 (see figure 6).

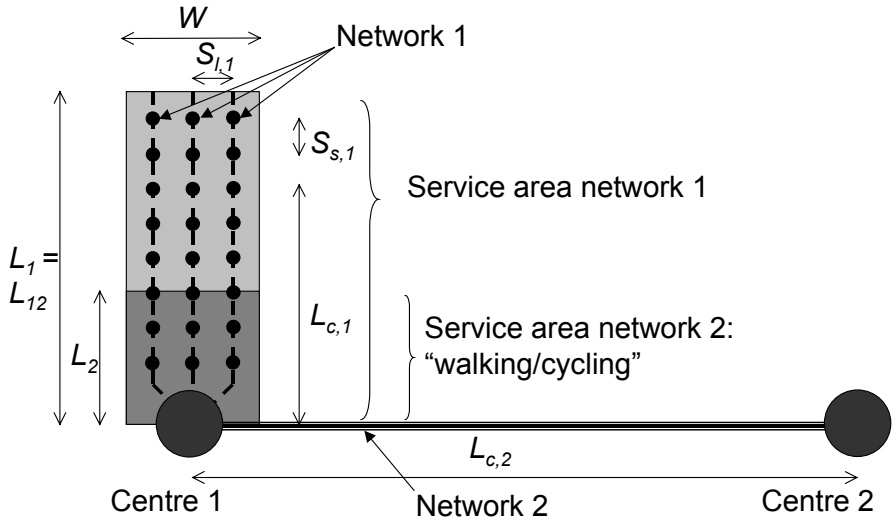


Figure 6: Schematic lay-out of bi-modal PT system with urban corridor (network 1) and intercity trunk link (network 2).

Similar to the approach in sections 5 and 6, the urban PT network is represented by a corridor having parallel lines offering services to the city centre. Design variables of this local PT network (bus or tram) are again stop spacing $S_{s,1}$, line spacing $S_{l,1}$, and service frequency F_1. The interurban network is represented by a single line offering transport from centre 1 to centre 2. Since in interurban transport the location of the stops is primarily determined by the spatial organization of settlements, the set of design variables in network 2 is limited to the frequency F_2 only.

8.2 The demand consists of two traveller groups partly using the same network 1: that is travellers to city centre 1 and travellers to city centre 2 respectively. Apart from the non-PT travellers, we distinguish three relevant PT-traveller groups:

1. Travellers P_1 using the urban public transport network 1 to travel to centre 1 ;
2. Travellers P_2 using interurban network 2 for going to centre 2 by accessing network 2 on foot or by bicycle or any other non-PT mode;

3. Travellers P_{12} using both PT networks to travel to centre 2. This group has a transfer at the station in centre 1.

As in earlier sections, travel demand is distributed homogeneously over space and is given as a number of trips (for each of the two centres) per square unit. Demand for PT use depends on PT service quality specified by perceived travel time functions $T_{c,p}$ for each of the three PT traveller groups respectively:

$$T_{c,1} = w_{a,1}T_{a,1} + w_{w,1}T_{w,1}+T_{i,1} + w_{e,1}T_{e,1} \quad (2)$$

$$T_{c,2} = w_{a,2}T_{a,2} + w_{w,2}T_{w,2}+T_{i,2} + w_{e,2}T_{e,2} \quad (3)$$

$$T_{c,12} = w_{a,1}T_{a,1} + w_{w,1}T_{w,1}+T_{i,1} + w_{w,12}T_{w,12}+T_{I,2} + w_{e,2}T_{e,2} \quad (4)$$

where:
$T_{c,p}$ = total weighted door-to-door travel time for traveller group P
$T_{a,n}$ = access time to nearest stop in network n
$T_{w,n}$ = waiting time at stop in network n
$T_{i,n}$ = in-vehicle travel time in network n
$T_{e,n}$ = egress time from network n
$w_{x,n}$ = weight for time element x in network n.

In absence of knowledge it is assumed in the following analyses that corresponding travel time weights $w_{x,n}$ are equal for all travellers groups and for both networks 1 and 2 except for $w_{w,12}$ which is larger than w_{w1} or w_{w2} because it includes the intermodal transfer penalty.
The level of demand in each traveller group then is determined by locational conditions relative to the services (local stops and station) and by mode specific preferences. This is specified in binomial logit models for the PT versus non-PT choice for each of the two destinations separately.
For simplicity sake we assume P_{12} to be a fixed percentage of the travellers going to centre 2 by public transport. In order to find out the potential impact of multimodal travelling on PT network design values, a relatively high percentage of 40% is chosen derived from Dutch travel figures. If the impact of multimodal tripmaking appears low with this percentage for P_{12}, it will certainly be lower with smaller percentages.

8.3 Because we deal with two distinct networks (urban and interurban), we separately investigate the cases with a single operator for both networks and with a different operator for each of the two networks separately. In addition we assume that depending on the political situation the operators may adopt different objectives in optimising their network design, that is profit maximisation or social welfare maximisation. Whereas social welfare maximisation will be pursued mostly by public authorities acting as commissioner of public services, the current trend in Europe towards an increased free-market approach makes profit maximisation a relevant alternative especially for interurban services which often prove to be profitable. In the case of two operators we assume their design behaviour to follow a so called Cournot game which means that they maximise their own objective (profit or welfare) taking account of the best design achieved by the other operator and vice versa. This behaviour eventually leads to a Nash equilibrium in which no operator can improve on its own objective. Accordingly, we distinguish five scenarios, two of which are single operator scenarios for the integrated network with profit or welfare as design optimisation objective, while three of which concern multiple operator scenarios where the operators may adopt the same or different objectives (see top of table 5). The scenarios will be calculated for an urban area represented by a 5 kilometre

corridor to its centre (centre 1) and an interurban rail line of 20 kilometres length to centre 2. The scenarios will be compared to a reference design for the same case according to currently applied traditional design principles. For further details of the analysis set-up see [Van Nes, 2002a,b].

8.4 Table 5 summarizes the outcomes of the five scenarios (columns 2 to 6) and the reference (column 1) ordered according to optimal values for the design variables of each of the two networks, and related values for profit, social welfare, travel times, and costs.

Table 5: Optimal network designs for bi-modal urban-interurban case

	Reference	**Single operator**		**Two operators**		
	traditio-nal	**profit total**	**welfare total**	**profit/ profit**	**welfare/ welfare**	**profit / welfare**
	(1)	(2)	(3)	(4)	(5)	(6)
Stop spacing level 1 [m]	400	833	717	950	728	732
Line spacing level 1 [m]	500	1,397	847	1,996	894	916
Frequency level 1 [veh/h]	4.0	6.8	10.2	4.2	9.4	9.0
Frequency level 2 [veh/h]	4.0	1.8	3.0	1.7	3.0	1.7
Profit level 1 [€]	113	346	60	408	139	109
Profit level 2 [€]	210	1,271	964	1,095	960	1,384
Total profit [€]	323	1,616	1,024	1,502	1,099	1,493
Welfare level 1 [€]	3,874	3,443	4,149	2,824	4,150	3,569
Welfare level 2 [€]	4,218	3,928	4,860	3,401	4,807	4,084
Total welfare [€]	6,629	6,535	7,459	5,676	7,450	6,709
Travel time P_1 [min]	30	31	25	39	26	26
Travel time P_2 [min]	53	67	57	68	57	68
Travel time P_{12} [min]	68	86	65	98	66	83
Operational costs level 1 [€]	557	243	641	101	554	517
Operational costs level 2 [€]	3,290	1,474	2,489	1,398	2,468	1,398
Total operational costs [€]	3,847	1,717	3,130	1,499	3,022	1,915

Two general conclusions emerge from comparing the various scenarios: first, as was also found in the single-level network case (see section 5), optimisation of the design, separately or jointly, leads to more efficient networks than currently adopted in urban practice. In general, urban networks should be much coarser while operated with higher service frequencies. A clear difference in frequencies emerges between the urban and interurban services. Second, it matters for the design which objective is used in optimisation. In general, welfare maximisation (columns 3 and 5) demands for denser networks at higher frequencies compared to pure profit maximisation (columns 2 and 4).
Importantly, integrated optimisation (columns 2 and 3) of the local and the line-haul sub-networks by a single operator (which we call the multi-modal approach) appears to lead to denser (urban) networks and higher frequencies than separately optimised sub-networks with the corresponding two-operator cases (columns 4 and 5) showing clearly better travel qualities for all three PT-traveller categories (compare column 2 with 4 and 3 with 5) with equal or higher social welfare outcomes. If social welfare is the objective however, these differences appear to be only small.

Concluding, if maximising social welfare is the objective, the impact of consideration of multi-modal travelling through joint network optimisation is only limited. If profit maximisation is the objective however, there is a sensible difference in optimal network design between multi-modal approach and the uni-modal approach.

9. Conclusions

9.1 A modelling system has been developed to quantitatively analyse PT network design options. This model system on the one hand consists of dedicated PT travel demand models handling multi-modal access to stops as well as multi-level service systems. On the other hand it consists of optimisation models to determine optimal values of system-wide design variables such as number of levels, stop and line density, and average frequency. This modelling system has been used to assess the possible impact for the design of PT networks of an increased share of multi-modal travelling.
A market analysis has shown [Van Nes, 2002b] that the travel segment of multi-modal trips with PT legs is relatively small (only a few percent of all trips) and will presumably remain small in the future. The impact of this category of trips on optimal PT network design is therefore expected to be relatively small and will be restricted to urban networks since the set-up of higher level PT networks is predominantly determined by spatial patterns of settlements [Van Nes , 2002b].

9.2 The optimality analysis of single-level urban PT service networks has shown that current systems are far from optimal in a social welfare sense because the networks are too fine-meshed. Especially stop distances are too small. Coarser networks with higher frequencies lead to higher door-to-door speeds and higher patronage at lower operational costs. This result urges reconsideration of current design guidelines. Improving access conditions by introducing other access modes than walking alone, such as cycling, will only slightly alter the optimal design of urban PT systems. This is due to the high behavioural transfer penalty of an intermodal transfer. Access improvements may however increase PT ridership. In urban conditions, walking will remain by far the major access mode with a share of 80 % or more.

9.3 The analysis of multi-level urban PT systems shows that unless a hierarchy in demand densities is given, a single level network is optimal from a social welfare point of view. Only when the number of travellers who benefit from an added higher-level network is substantial, a hierarchical network structure will increase social welfare. The analysis showed that this demand concentration should be twice or preferably three times higher than average. Multi-level urban PT services therefore are only justified in larger cities or agglomerations having a clear hierarchical spatial structure.
Ideally, in multilevel systems, the designs of the distinct subsystems should be optimised jointly under the responsibility of a single operator. If there are separate operators for the distinct subsystems, they can each benefit from co-operating, e.g. by subsidization of the lower-level services by the higher-level operator.

9.4 The study shows that consideration of multimodality in personal tripmaking only marginally affects optimal PT system set-up. The impact of spatial pattern is dominant in this respect. The level of multimodal tripmaking can however

significantly be increased by optimising current designs of the various subnetworks, especially local PT networks.

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