

PUBLIC TRANSPORT NETWORK DESIGN AND RELIABILITY

S. Tahmasseby MSc, Delft University of Technology, S.Tahmasseby@TUDelft.nl

Dr.ir. R. van Nes, Delft University of Technology, R.vanNes@TUDelft.nl

Ir. N. van Oort, HTM, N.van.Oort@HTM.net

1 INTRODUCTION

Design of public transport networks is usually based on a deterministic point of view: it is assumed that all components of the system perform as planned. In reality, however, there are a large number of regular and irregular variations influencing public transport services such as variation in demand, service operation, and infrastructure availability. The question thus is how these phenomena affect the network design problem. As a first step in answering this question, the main design dilemmas of public transport network design will be briefly described. Next, the impact of reliability on network performance will be discussed, thereby introducing new design dilemmas. As an illustration results are presented from a network analysis for a set of hypothetical networks, focussing on the role of infrastructure availability on the reliability of public transport networks. The paper concludes with recommendations for further research.

2 PUBLIC TRANSPORT NETWORK DESIGN

The question in transport network design is to determine a network that has an optimal performance given a specific design objective. Thus on the one hand there is a set of decision variables that determine the characteristics of the network, while on the other hand there is an objective against which the performance of the network is evaluated. Furthermore, there might be a set of constraints that limit the set of possible solutions.

Typical decision variables in public transport network design are either aggregate network variables such as stop spacing and line spacing (e.g. Van Nes & Bovy (2000)), or binary indicators for including lines in the network (e.g. Ceder & Israeli (1998)). Commonly used objectives are minimisation of total costs, maximisation of social welfare, and profit maximisation. In case of objectives like minimising travel times, the available budget or the available fleet are likely constraints.

The network design problem is a well-known complex problem due to its combinatorial nature and the complex relationship between network design and travel behaviour. The latter is nicely illustrated by structures used to represent the problem, such as the bi-level formulation or the representation as a Stackelberg-problem (Cascetta (2001), Van Nes (2002)). In both cases there is an upper level problem which relates to the designer with his objectives, and a lower level problem which stands for the way travellers react to the network offered. Depending on the way the public transport system has been modelled, the lower level problem may include route choice, mode choice or even destination choice.

Another way to illustrate the complexity of public transport network design is by considering the dilemmas involved. The obvious dilemma is the contrasting interests of the main actors involved: travellers versus operators. However, from the perspective of the traveller several other dilemmas can be distinguished (Egeter

(1995)). For instance, travellers would like to have short access distances as well as fast transportation between stops. However, short access distances are related to a short stop spacing, implying slow transportation. A second example is the dilemma of line density, which refers to the choice between having few lines with high frequencies and of course transfers, or facilitating more travellers with trips without transfers, thus having many lines and low frequencies. The network design problem deals with all these dilemmas simultaneously.

The complexity of the public transport network design problem can be increased by considering the design of the infrastructure network as well, which is especially relevant for rail bound transport services. Introducing new links in the infrastructure network could easily lead to a huge number of new solutions for the public transport service network design problem. In fact such an extension would lead to a tri-level problem, in which the upper level is the infrastructure network designer, the middle level the service network designer, and the lower level representing travel behaviour.

A common assumption in literature on public transport network design is that all types of input are assumed to be known exactly and to be constant over time. Although this assumption limits complexity, it is clearly unrealistic. The demand pattern varies between hours and over days, while transport supply varies as well, either due to all kinds of organisational aspects in a public transport company, or due to changes in the quality and availability of infrastructure. In fact both demand and supply in transport systems are stochastic phenomena. The question then is what the influence of this stochasticity is on the design of public transport service networks. In the next section we'll elaborate further on this topic.

3 INFLUENCE OF RELIABILITY ON DILEMMAS AND OBJECTIVES

Practice shows that the quality of public transport services varies substantially. Van Oort & Van Nes (2006) analysed the performance of the urban public transport network of The Hague in The Netherlands. It was found that the standard deviation of in-vehicle times are almost linearly dependent on the line length, which suggests that for more reliable transport services it might be better to limit line lengths. Consequence, however, is that this would increase the number of transfers. Thus a new dilemma appears: reliability of services versus transfers.

Another finding is that the time spend at stops has a large variation. For a single tram line it varies between 5 minutes and 17 minutes per run. This is mostly due to the fact that for some runs several stops are skipped. Reducing the number of stops would increase the probability that every stop would be used, even in situations having lower levels of demand. This introduces a new dimension to the earlier discussed dilemma between access time and in-vehicle time.

Van Oort & Van Nes (2004) described an analysis of lines which have coordinated services for about half of their route, a typical network structure reducing the number of transfers. Such coordination, however, proves to be an important source of unreliability, which would indicate that such network structures should be avoided. Again a typical example that considering reliability brings in a new dimension in existing design dilemmas, in this case the dilemma of line density.

An analytical study by Turnquist & Bowman (1980) also indicated that network structure affects transport service reliability. The centre node in a radial network structure for instance is very critical for delays along routes in comparison with the more dispersed pattern of transfers in grid networks. Furthermore, they found

that higher service frequencies are less sensitive for travel time variations than low service frequencies: an extra dimension for the line density dilemma.

Of course, it is possible to achieve more reliable services by other means as well. Especially at the operational level many means are available to improve regularity and punctuality, e.g. Wilson et al. (1992) and Muller & Furth (2000). However, having such measures doesn't imply that reliability should not be considered in network design: prevention is better than cure.

Considering reliability in public transport network design also leads to a more important role of infrastructure network design. Special situations, such as traffic accidents blocking streets or a broken-down tram, might require detours in order to continue regular operations. However, suitable infrastructure should be available for such adjusted transport services. This might be easily achievable for road bound public transport services, although many residential streets might not be accessible for buses, but for rail-bound services this requires special attention. In the latter case detours are only possible using infrastructure used by other rail-bound services, or using additional short-cuts in the rail infrastructure. A possible design question thus is to determine which short-cuts should be provided in an infrastructure network.

Apart from new or extended design dilemmas, reliability also influences the network design objectives. From the travellers perspective reliability can be defined as the variation in travel times, expressed as standard deviation, variation, or bandwidth between 10th and 90th percentile. In case of public transport services variation in travel times might have a larger impact due to the possibility of missed transfers. Furthermore, it might be possible that due to specific circumstances certain runs should be skipped. If no alternative routes are available in the remaining service network, this makes it impossible for travellers to make their trips for that period. Reliability thus not only relates to travel time reliability, but also to connectivity reliability.

Reliability might also affect the operator costs. In order to provide more reliable services time buffers might be introduced at stops, between stops and at end points, thus increasing total run time and thus operational costs. Providing detours in case of incidents might lead to additional costs as well. Obviously, if additional infrastructure is proposed to provide more reliable transport services, this would lead to additional investment costs too. All these components should be accounted in the objective function, either as the prime objective or more likely as additional components to traditional objectives like minimising total costs or maximising social welfare.

3 EXTENDED NETWORK DESIGN PROBLEM

The discussion above showed the implications of including reliability of transport services in the network design problem: new dilemmas and extended objective functions. The new trade-offs are illustrated in Figure 1. Apart from traditional components as travel costs, operational costs and infrastructure costs, new components are added:

- Reliability costs: e.g. extra travel costs due to delays or rescheduled trips;
- Extra operational costs: e.g. costs of additional detours or additional vehicles;
- Extra infrastructure costs: e.g. costs of short-cuts in the infrastructure network.

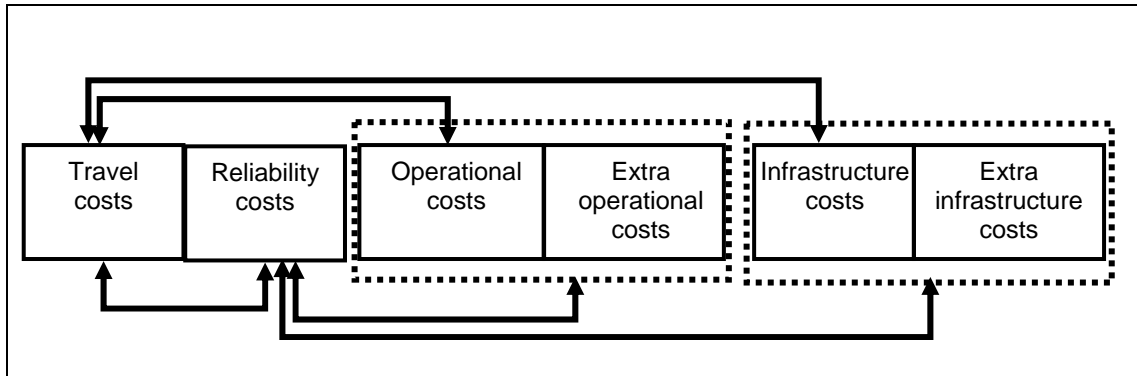


Figure 1: Trade-offs between network design components in the deterministic case (top side) and the stochastic case (bottom side)

The top side shows the traditional trade-offs between traveller costs versus operational costs and if included infrastructure costs. Including reliability introduces new trade-offs (bottom side): reliability costs versus travel costs (faster or more reliable?), versus total operational costs and if included versus total infrastructure costs too.

A second method to illustrate the extension of the design problem is using the bi-level representation (see Figure 2). The upper level is the actual network design problem. Its output, the network design, is the input for the lower level, travel behaviour. The performance of the network design given the choices of the users is again input for the upper level. Incorporating reliability in the network design problem implies that the input for the lower level is no longer deterministic. The network designed at the upper level might suffer from all kind of stochastic events. A distinction can be made between planned services and actually provided services, which differ because of all kinds of external events. Furthermore, demand might vary as well. As a result the performance of the network design should also include all kinds of reliability indicators such as the variation of travel times and the number of trips that had to be rescheduled due to cancelled runs. The lower level of the bi-level problem has become a stochastic process, which has serious implications for network optimisation algorithms.

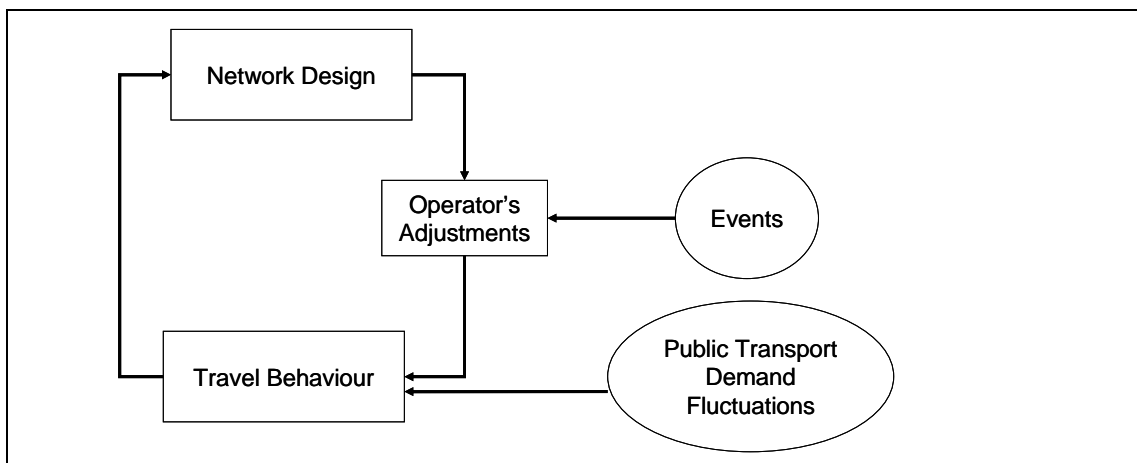


Figure 2: Extension of the bi-level representation for stochasticity due to events

5 ILLUSTRATION OF THE EXTENDED NETWORK DESIGN PROBLEM

As an illustration of the extension of the design problem with reliability, we focus on the role of events that can affect the availability of infrastructure for public transport services. Typical examples of such events are accidents blocking a road, heavy weather conditions and road works. Due to such events detours might be implemented in the service network, that is, if suitable infrastructure is available, otherwise services might be temporarily skipped. Detours might lead to additional travel time as well as to additional operational costs. However, detours might also lead to new connections that might be advantageous for travellers as well. Cancelled services might result in rescheduled trips.

We consider a city having a ring-radial structure with the city centre in the middle, plus 4 subcentres. An obvious service network structure for such a situation would be a radial network. However, non-centre oriented trips might benefit from a ring line. The choice whether or not a ring line should be provided is a typical example of the line density dilemma. Furthermore, suitable ring infrastructure might allow for detours in case of blocked infrastructure.

In the analysis a distinction is made between road-bound public transport services (i.e. bus) and rail-bound services (i.e. tram). In the first case the infrastructure of all rings is accessible for public transport, while in the second case only one of the possible rings is suitable for tram services. In both cases radial transport services are provided, while it is an option to use the ring infrastructure for a ring line too or to use it for detours only.

The following variants are studied:

1. Radials only;
2. Radials and centre ring with the option of a centre ring line;
3. Radials and small ring with the option of a small ring line;
4. Radials and large ring with the option of a large ring line;
5. Radials and outer ring with the option of an outer ring line.

For example, Figure 3 shows the transport service network for variant 3 in which a ring line is provided as well. The dashed lines indicate the location of the rings for the other variants.

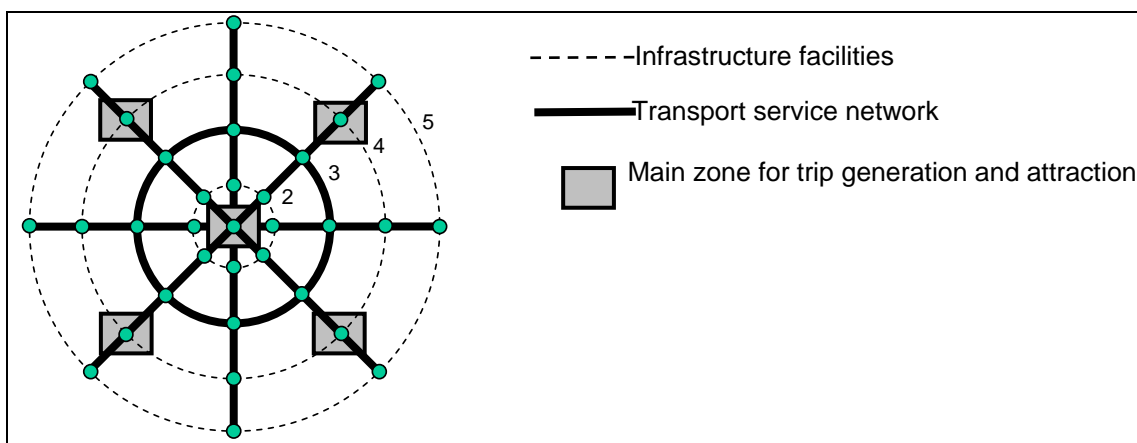


Figure 3: Lay-out of the infrastructure network for variant 3: radials and small ring (dashed lines indicate the infrastructure for the other variants)

The operational budget is identical for all alternatives. As a result the frequencies are highest for variant 1 (radial only) and lowest for variant 5 (radials and

outer ring). The demand pattern is assumed to be the same for all variants. The network is analysed for 20 simulations representing a period of a year, in which events take place as incidents, bad weather, and road works. It is assumed that additional travel time is valued twice as high as normal travel time, while the penalty for cancelled public transport trips equals to one hour additional travel time. The performance of these networks is assessed by the following criteria:

- Extra travel costs due to blocked infrastructure: costs of additional travel time plus the costs of cancelled trips;
- Total travel costs: travel costs of trips which are not disturbed by events plus the extra travel costs;
- Total network costs: consisting of travel costs, operational costs and infrastructural costs.

The results of the analysis are shown in Table 1. A distinction is made between bus networks having a ring line, tram networks having a ring line and tram networks having ring infrastructure as a back up.

Table 1: Assessment results for the hypothetical networks

	Extra travel costs (M€)	Total travel cost (M€)	Total network costs (M€)
Bus - Transport services include ring line			
Variant 1: No ring	0.73	262.18	314.36
Variant 2: Centre ring	0.87	264.21	315.80
Variant 3: Small ring	1.04	275.39	327.40
Variant 4: Large ring	1.19	279.23	331.26
Variant 5: Outer ring	1.55	290.21	342.83
Tram - Transport services include ring line			
Variant 1: No ring	18.12	285.38	387.59
Variant 2: Centre ring	11.00	283.73	389.32
Variant 3: Small ring	6.05	291.26	404.56
Variant 4: Large ring	2.94	292.90	413.91
Variant 5: Outer ring	3.11	325.37	454.10
Tram - Ring infrastructure is used only as backup facility			
Variant 1: No ring	18.12	285.38	387.59
Variant 2: Centre ring	8.47	279.99	383.23
Variant 3: Small ring	5.12	278.13	385.33
Variant 4: Large ring	1.08	276.04	385.15
Variant 5: Outer ring	0.97	275.64	387.96

Due to the larger flexibility of bus services the extra travel costs are very low. If ring lines are used the extra travel costs increases since these ring lines suffer from infrastructure failures as well. For tram networks, the extra travel costs are lowest for variant 4 (large ring) in case of a ring line and for variant 5 (outer ring) if only back-up facilities are considered. Compared to the radial network only variant, the extra travel costs are reduced to 16%. If the ring infrastructure is used as back-up facility only, the extra costs are reduced to 5%, which is again due to the fact that the ring line itself might also suffer from limited infrastructure availability.

For the total travel costs, including the extra travel costs, variants 1 (no ring) and 2 (centre ring) are best if ring lines are considered, while variant 5 (outer ring) is

again best for the back-up only case. In the cases of ring lines, the location of the subcentres lead to only a few percent higher travel costs for variant 4 (large ring), while the costs for variant 5 (outer ring) are substantially higher. The differences in travel costs between bus and tram services are due to differences in extra travel costs.

Obviously, the bus networks have the lowest total network costs: operational costs are lower than for tram, while no infrastructure costs are required. Variant 1 (no ring) appears to be optimal, however, the differences with the other variants are limited. Variant 5 (outer ring), however, has substantial higher total costs. The results for the tram network are similar, although the higher infrastructure costs are higher. If the ring infrastructure is only used as a back-up facility, the differences between the alternatives become smaller again. The costs for a larger ring are higher, but also lead to a larger reduction of the extra travel costs in case of limited infrastructure availability.

The extra travel costs vary between .3% and 4.7% of the total network costs. Since it is a well-known characteristic of the network design problem that there are many near optimal solutions, the impact of extra travel costs is large enough to lead to different optimal solutions.

6 CONCLUSIONS

In this paper we addressed the public transport network design problem in relation with reliability. We showed that considering transport service reliability obviously leads to adjusted design objectives, but moreover to new dimensions for the design dilemma's involved. Reliability considerations lead to new trade-offs in the access density dilemma - fewer stops might lead to a more regular service performance - and to the line density dilemma: lower line densities might lead to more reliable service networks. Reliability might provide arguments for a maximum line length, while network structures focusing on facilitating trips without transfers might have negative effects with respect to the travel time variation. Furthermore, infrastructure facilities for short cuts and detours become an important topic for rail bound public transport services.

Extending the network design problem with reliability introduces new components in the formulation of the design objective. More important, it requires stochastic approaches for modelling the performance of the network in the well-known bi-level problem structure. Simulating events that affect system performance might be a way to deal with this stochasticity, but this sets new challenges for network optimisation.

An example focusing on the impact of limited infrastructure availability showed the way the line density dilemma is affected by reliability issues. Furthermore, it showed the impact of having infrastructure facilities for detours in case of infrastructure failures. Focusing on network reliability would obviously lead to different optimal network solutions, while the impact of reliability costs in terms of extra travel time and rescheduled trips are substantial enough to affect the optimal solution for more comprehensive design objectives as well.

Further research will be carried out to determine the events and their characteristics that affect the public transport service reliability. Different types of public transport networks will be analysed, while considering different strategies public transport operators might have to cope with events that might hamper their services. Furthermore, a network design model will be developed that is able to account for such stochastic events.

ACKNOWLEDGMENT

This study is supported by the Next Generation Infrastructures Foundation and by the Transport Research Centre Delft.

REFERENCES

- Cascetta, E. (2001), *Transportation systems engineering: Theory and methods*, Kluwer Academic Publishers, Dordrecht
- Ceder, A, Y. Israeli (1998), User and operator perspectives in transit network design, *Transportation Research Record* **1623**, pp. 3-7
- Egeter, B. (1995), Optimizing public transport structure in urban areas, In: Lall, B.K. & D.L.Jones (ed) *Proceedings of the Transportation Congress, Civil Engineers: Key to the world's infrastructure*, American Society of Civil Engineers, New York
- Muller, Th.H.J., P.G. Furth (2000), Integrating bus service planning with analysis, optimal control and performance monitoring, *ITS 10th Conference*, Washington DC
- Turnquist, M.A. and L.A. Bowman (1980) The Effects of Network Structure on Reliability of Transport Service. *Transportation Research B*, Vol. **14B**, pp 79-86
- Van Nes, R. (2002) *Design of multimodal transport networks, a hierarchical approach*. Trail Thesis Series T2002/5, Trail Research School, Delft
- Van Nes, R., P.H.L. Bovy (2000), The importance of objectives in urban transit network design, *Transportation Research Record* **1735**, pp. 25-34
- Van Nes, R, S. Tahmasseby, and P.de Jong (2006) Robustness of transport service networks, effects of infrastructure availability, CD-ROM *9th TRAIL-congress: TRAIL in Motion*, Trail Research School, Delft
- Van Oort, N., R. van Nes (2004), Service regularity analysis for urban transit network design, CD-ROM *83rd Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington DC
- Van Oort, N. R.van Nes (2006) Reliability of urban public transport and strategic and tactical planning, CD-ROM *9th TRAIL-congress: TRAIL in Motion*, Trail Research School, Delft
- Wilson, N.H.M., R. Macchi, R. Fellows, A. Deckhoff (1992), Improving service on the MBTA green line through better operations control, *Transportation Research Record* **1361**, pp. 296-304