IMPROVING SERVICE RELIABILITY IN URBAN TRANSIT NETWORKS

Dr. Shahram Tahmasseby.
Transport Consultant- Ecorys Nederland BV
Watermanweg 44, 3067 GG
Rotterdam, the Netherlands
Phone: +31 10 453 88 00
Fax: +31 10 453 07 68

Dr. ir. Rob van Nes
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Transport & Planning
P.O.Box 5048
2600GA Delft, the Netherlands
Telephone: +31.15.2784033
Fax: +31.15.2783179

ABSTRACT

Design and operation of transit networks is usually based on a deterministic point of view. All types of input are assumed to be known exactly and to be constant over time. These are clearly unrealistic assumptions since in reality transit demand and supply vary within time. Variations in the demand and the supply pattern are causes of service performance variations for travellers and operators in transit networks. Given variations and distortions in all layers of transit networks, in this paper we take a close look at suitable methods at different levels of network planning to mitigate disturbances in transit networks and consequently to improve service reliability. The main focus is on methods applicable at strategic and tactical levels of transit planning for enhancing transit system resilience.

1 INTRODUCTION

Reliability of transit systems has been considered imperative by transit users, operators and the government. Transit systems often fail to provide reliable services due to regular and irregular disturbances, caused by traffic congestion, varying passenger demands, vehicle breakdown or failure of equipment or infrastructure, and incidents. Unreliability in transit services leads to uncertainty and consequent delays aggravating inconveniences for the passengers. Transit reliability has thereby become an increasingly important attribute for assessing the performance of transit networks *(Friman et al 1998,)*.

Regarding the serious impacts of potential disturbances on transit network performance and service quality, operation and design of transit networks concerning network resilience and service reliability have not received sufficient attention in literature especially in network planning levels. This paper demonstrates the relevancy of strategic and tactical levels of transit planning on disturbance mitigation and thus transit service reliability enhancement.

2 IDENTIFYING VARIATIONS IN TRANSIT NETWORKS

It is a clearly inappropriate assumption to consider all types of input consisting of infrastructure facilities, transport operation characteristics, and traveller's demand as being constant. Variations on demand and supply cause disturbances for travellers and operators in transit networks. Many sources contribute to these variations. Basically, they might be classified as follows:

- Variations in traveller's behaviour;
- Variations in infrastructure quality and availability;
- Variations in operator's performance.

Figure 1 illustrates these variations where a distinction is made between external and internal sources of disturbances.

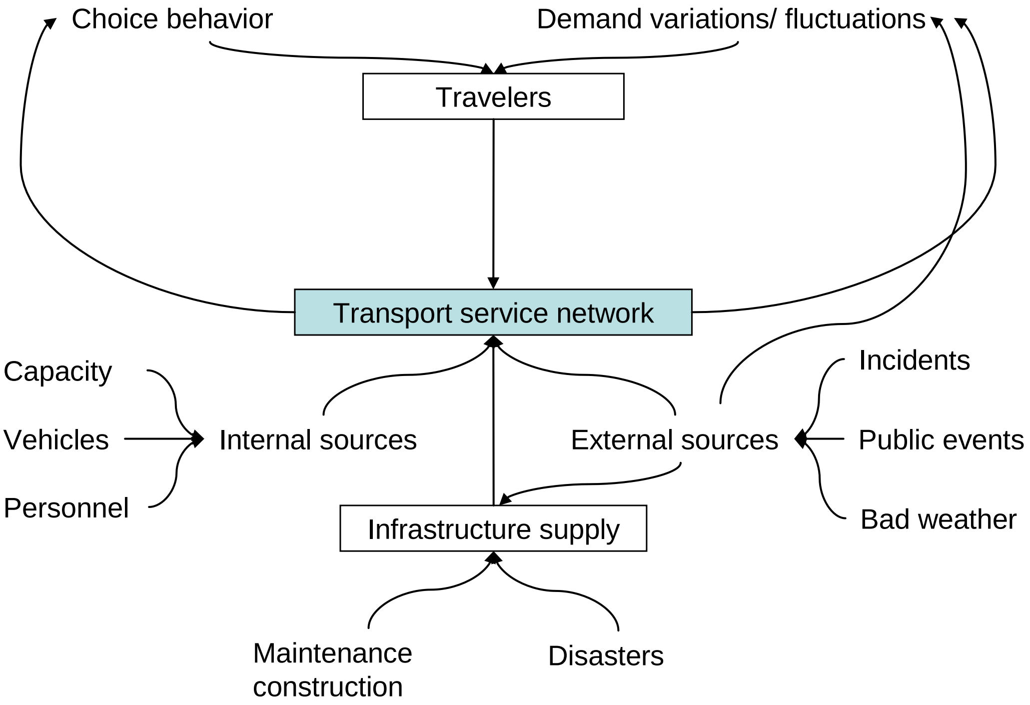


FIGURE 1: Stochastic forces acting on transit systems

2.1 Variations in Traveller's Behaviour

In the above figure stochastic choice behaviour and demand alterations cause variations on traveller's behaviour. For the demand side, regular fluctuations of travel demand over periods of the day, days of the week, and seasons of the year are sources of uncertainties. Furthermore, stochastic nature of traveller's choice behaviour should not be forgotten. Normally, there is randomness in traveller's behaviour which can be observed in departure time choice, mode choice and route choice *(Bovy 1996; Nielsen 2000)*. Of course, these variations in transit demand will definitely influence transit quality and its level of services.

In addition to variations that take place based on regular demand pattern, there are irregular demand fluctuations arise due to external factors in a short time scope. For instance, in case of bad weather, cyclists normally shift to either private car or transit, thus increasing transit demand. A second example is the temporary demand pattern due to public events.

2.2 Variations in Infrastructure Quality and Availability

An implicit requirement in transit network evaluation studies is that the necessary infrastructure is available with appropriate quality. In reality, however, this is not always the case. Basically, infrastructures fail due to construction activities as well as to destructive events. An example is road works. Urban Infrastructure needs maintenance, and since it is part of the city it might be affected by other building or maintenance activities for example sewers, cables, et cetera; even though it is possible to schedule these kinds of activities in such a way that their impacts on transportation networks are minimum in terms affected service frequency *(Higgins et al 1994)*. As an example of destructive events a Norwegian study shows that infrastructure faults are a major source for delayed and cancelled rail bound transit services *(Veiseth et al, 2007)*. They show that more than 4000 delay hours which is about 30% of the total amount of delay hours in Norwegian rail networks in 2005 was caused by failures in infrastructures such as: track, signal (including safety and communication systems), power supply, planned work, and blocked tracks.

External conditions such as bad weather, incidents, and public events are other sources of infrastructure failures *(Schmöcker & Bell 2002; Immers et al, 2004)*. For instance, heavy snow can block tracks and roads. In this condition, trains and cars can not use the affected infrastructures until snow removal operations are done.

2.3 Variations in Operator's Performance

In addition to infrastructure networks' disruptions, transport service networks might be affected as well. Basically, different sources affect a transport service network and cause service variations. We outline them as follows:

- Internal factors such as vehicle breakdown;
- External factors such as bad weather.

The transit service itself might suffer from failures. Vehicles might breakdown leading to blockades, or personnel might not turn up *(Schmöcker & Bell 2002)*. Furthermore, transit services have their own variations in service quality due to variations in driver's behaviour, traffic conditions, traffic signals, et cetera *(Muller & Furth 2000, Van Oort & Van Nes 2008)*. Some of these events are regular events. They take place frequently and cause regular variations in transit operations (e.g. driver behaviour, fleet or staff shortage). For example, consider the London transit system. London Underground reports that they cancel on average 5% of all services almost every day and this rate is even higher during the morning peak period *(Schimamoto et al 2007)*. In the Netherlands running time of bus lines in city of The Hague was measured *(Van Oort & Van Nes 2008)*. Results show that during rush hours running time of a tangential bus line with short exclusive right of way (6%) increases around 12 % and travellers suffer from increase in average waiting time. A Norwegian study *(Veiseth et al, 2007)* shows that 5820 hours delay registered in Norwegian trains in 2005 belongs to operational variations and failures. This rate is about 37% of total delays in Norwegian trains.

3 SERVICE RELIABILITY IMPROVEMENT IN TRANSIT SYSTEMS

Improving service reliability is an aim of operator companies and can increase patronage as well. Literature shows a lot of attention is given to improve service reliability at the operational level, however, by applying prevention measures, the transit planner can increase network resilience and can reduce the vulnerability of both the service network and the infrastructure network. Possible actions can be performed at the tactical level, at the strategic level of service network planning, the strategic planning level, and in the infrastructure network. Table 1 summarizes the corresponding strategies.

4.1.1 Tactical Level of Planning

Prevention measures can be applied in timetable planning to improve service reliability in transit networks *(Israeli & Ceder 1996, Carey 1998)*. The measures that are used at this stage aim at increasing spare capacity in the timetable of transit services to prevent delay propagation and thus to reduce service vulnerability. One way to increase the spare capacity at the tactical level is adding adequate slack times to the timetable. They will enable vehicles to catch up. This extra time is a trade off between the operational speed and travel time reliability. The longer slack time is assigned, the higher travel time reliability, the lower the average operational speed and thus longer service running time are expected.
Basically, the slack time can be added to service runs by two different ways:

- Slack time within runs at particular instants;
- Slack time between runs at the end points.

In the first way, a small amount of slack time is added to the running time. This amount depends on the characteristics of the line. Especially lines in the city centre need some slack time, because of crowded junctions and shared tracks with other traffic. It is also possible to plan extra dwell time per stop. The slack time depends on the expected distribution of dwell time and the effects of vehicles waiting longer than necessary at a stop.

To use the extra dwell time efficiently, it is recommended to dwell longer at stops with a high number of boarding and alighting. This provides longer transfer times and thus reduces the probability of missing connections. This tactic is recommended for train networks as well. For instance, Dutch researchers recommend increasing of train speed to have more transfer time in connection points to improve the travel time reliability of the Dutch train network *(Rietveld et al, 2001)*.

TABLE 1 Reliability Enhancing Tactics in Transit Networks

Service network design		**Infrastructure network design**
Tactical planning	**Strategic planning**	
Allocating slack times in the timetable	Planning independent service lines	Planning additional infrastructures (e.g. shortcuts) to create flexibility
	Shortening service lines	Designing exclusive right of way
	Increasing stop spacing	Covering/ Preserving transit infrastructure from external sources of disturbances
	Planning redundancy in fleet	Allocating prioritisation in signalising system for transit services
	Planning the service network with redundancy/ flexibility	

In the second way, operators add extra time to the layover time (recovery time) to achieve a high punctuality of departing vehicles. This extra layover time can prevent delay propagation for the next run. It is clear that both tactics are oriented toward resetting the service schedule and thus maintaining travel time reliability high.

Of course, adding the slack times to the timetable will decrease transit performance in terms of service running time and service frequency. Thus, there are 2 design dilemmas with respect to reliability: 1) Faster services with higher travel time variations versus slow services with higher reliability; 2) High service frequency timetables with short slack times and lower reliability versus low service frequency timetables with sufficient slack time and higher reliability. Hence, to set an efficient timetable, the planner should consider these dilemmas carefully.

4.1.2 Strategic Level of Planning

At the strategic level of transit network planning, reducing vulnerability, increasing redundancy, and creating flexibility in the transit network layers are relevant approaches to improve service reliability.

There are few methods at the strategic level to improve service reliability in transit networks. We will elaborate on these methods in this subsection. These methods have been indicated in table 2 as well.

Planning independent lines

Basically, the independent operation of lines in a transit network is simple, but it might impose additional transfer to transit users. Vuchic & Musso *(1991*) compare the independent and the integrated operation of metro lines in terms of service reliability. They state that the integrated line operation may decrease total travel time for transit users, albeit, it might increase unreliability for them as well. The main reason is that integrated service lines are more vulnerable compared to independent service lines because of using common links. Common links might hamper and hinder successive services.

This is more critical for integrated lines where service frequency is high in common links. In metro and train networks due to automatic control systems, the headways between services should be greater than a minimum threshold (e.g. 2 minutes). In tram and LRT services which are run on sight, the dwell time of the preceding vehicle may affect running time of the following vehicles. It may influence prioritizing systems in the network in such a way that the following vehicle can not benefit from prioritizing signals.

With respect to the discussion above, using independent line operations with less vulnerability are advised to achieve higher service reliability, while extensive passengers' transfers are facilitated through careful layout and design of stations, providing update information, and security. As examples we refer to the Paris and Tokyo metro systems which consist of independent lines only.

Shortening lines

In addition to operating independent service lines in transit networks, planning short service lines is an appropriate way to reduce the service network vulnerability and thus to improve service reliability. Basically long lines suffer from higher regular and irregular service variations than short lines. Hence, by modifying service line configurations, it is possible to reduce travel time variations and also the probability of line failures.

Reducing running time variations leads to improvement of travel time reliability, whereas a decreasing probability of lines' failure improves network robustness and connectivity reliability.

Replacing long service lines by short service lines has also negative consequences for travellers. It may increase the required number of transfers for transit travellers. Thus, a trade off between service line length and reliability is observed.

Planning redundancy in fleet

Increasing redundancy in transit fleet by implementing reserved vehicles is a proper way to improve service reliability (Table 2). Having spare capacity in transit fleet is a means to ensure sufficient capacity in case of a sudden rise in transit demand. Having redundancy in the fleet will enable the operator to serve the entire transit demand in some instances and to maintain service reliability high in the long term.

Planning service networks with redundancy

Increasing line density in a certain way results in higher redundancy in the service network and consequently can improve service reliability. Including tangential lines into a service network could facilitate operational remedies during disturbances (e.g. applying detour) and also offer alternative(s) to transit travellers. The availability of required infrastructure enables the transit operator to divert from the regular path via a detour to pass the blocked right of way. Furthermore, the availability of several line options enables travellers to switch between transit lines in case of disturbances and find an alternative route for making their trip.

Figure 2-A illustrates a ring service line is added to a radial based transit service network. Thus, in case of blockades in the CBD radial trips might be diverted using the ring line. The availability of several line options enables travellers to switch between transit lines in case of disturbances and to find an alternative route for making their trip. However, as a negative impact planning the service network with higher redundancy may also lead to a service frequency reduction. Hence, the trade-off between service frequency and service reliability should be considered in service network design.

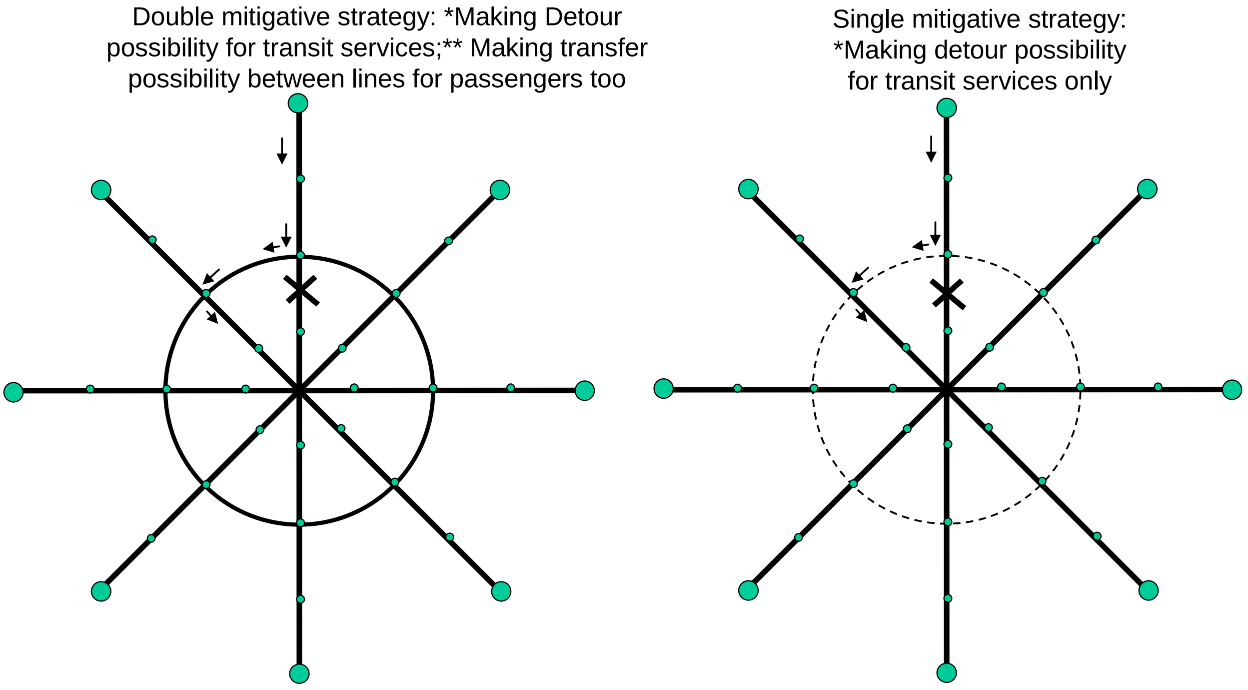
4.1.3 Infrastructure Network

At the infrastructure network level, building additional infrastructures such as shortcut facilities create flexibility in the infrastructure and consequently in the service network and thus will increase network resilience and robustness. It will enable transit operators to apply operating remedial solutions (e.g. applying detours, or short runs) and improve connectivity reliability. Facilities that are commonly used are *shortcuts, bypasses, and turning facilities*. Applying detours via shortcuts and bypasses and applying short runs via U turns are achievable by using these infrastructures. Figure 2-B illustrates how ring shortcut infrastructure can enable the transit operator to divert from the line's original alignment through the shortcut to avoid probable blockades in the CBD area. In the infrastructure network, other efforts are mainly oriented towards:

- Providing separated right of way for transit services with minimum interference with private car traffic. This is especially the case for bus and tram. Obviously for train and metro networks, the right of way is completely exclusive.
- Preserving the physical network from disturbances caused mostly by external major discrete events such as extreme bad weather, and incidents. Covering network segments physically (e.g. by tunnels) could be a feasible

solution for reducing infrastructure vulnerability and thus increasing network robustness and connectivity reliability.

Both measures are costly and mainly require strong motivation before implementing. At a less costly level, facilitating transit lines with prioritizing systems (for transit systems with partly shared right of way such as tram) is a proper way to reduce regular running time variations, to increase punctuality and regularity and thus to maintain high service reliability.



Double mitigative strategy: *Making Detour possibility for transit services;** Making transfer possibility between lines for passengers too

Single mitigative strategy: *Making detour possibility for transit services only

A- Increasing redundancy in the transit service network by establishing a ring service line

B- Making flexibility in the service network by using additional infrastructures

FIGURE 2: increasing redundancy and creating flexibility in transport service networks to improve network resilience

5. CASE STUDY

In order to demonstrate the potential of the aforementioned reliability enhancing measures, we use the case study of the tram network of the city of The Hague in the Netherlands *(Tahmasseby 2009)*. Figure 3 shows a schematic illustration of the tram network including nodes number and links number (*Bold italic numbers*).
The tram network of the city of The Hague consists of 11 service lines with a total length of 135 km. The network can be characterized as a radial network with a grid structure in the city centre. The tram network has a high percentage separate right of way (85%). The average tram speed is 20 km/hour. The operation time is

18 hours (from 6 o'clock till 24 o'clock). About 140 million trips are made annually for the transit network, of which about 90 million are made by tram.

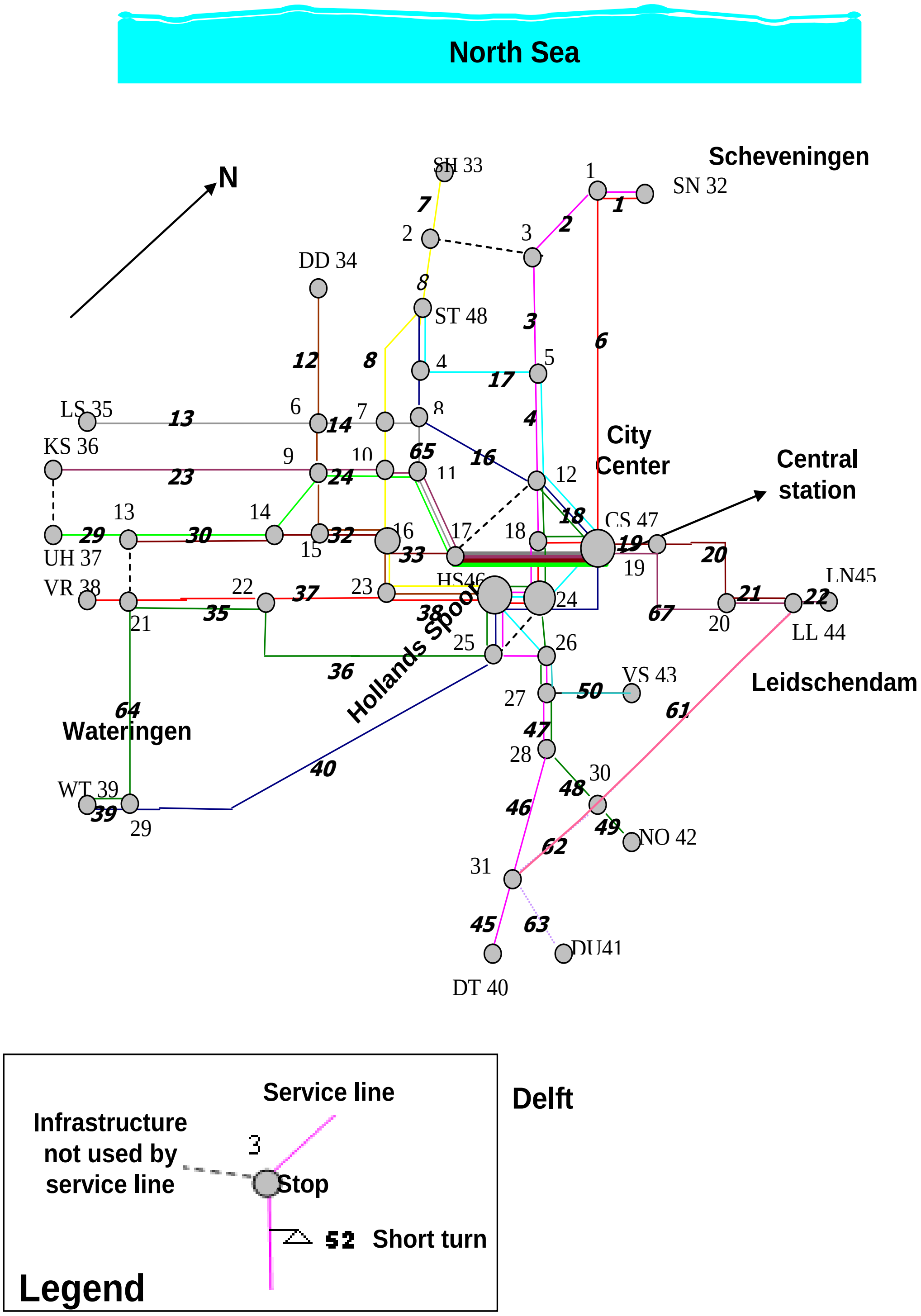


FIGURE 3 Tram network of The Hague (Reference network)

Transit demand is primarily centre oriented, while some sub centres (e.g. the cities of Delft, Wateringen, Scheveningen and Leidschendam) also attract their share of the demand. The waiting time, which is assumed to be half of the headway, is 5 minutes.

HTM, The Hague service operator, as well as the local authorities would like to achieve a reliable tram service network. Obviously, the bus network might be used as a back up in case of emergencies. However, due to the tendency to tender different networks independently, it is preferred to achieve maximum service reliability for each sub network.

5.1 Assessment of the existing network performance

To have an overview of the current performance of the network, the network is analyzed for several years (20 different simulating runs representing 20 different years) in which all kinds of events take place

On average the network suffers from disturbances in 102 days of a year (28%). Due to disturbances, 89% of the trips are made with less than 10 minutes delay. Moreover, in terms of the connectivity reliability about 2.1 % of the annual trips are cancelled due to disturbances (1,890,000 passenger trips). The disturbances will also raise travel costs on average 2.0 % due to the extra travel time imposed to travellers.

At a more detailed level we can look at the way the tram lines are affected, the impact of the detours on the links' load (passenger) and the origins that suffer most from transit trip cancellation.

Figure 4 illustrates the number of affections per line due to disturbances in a year. It clearly shows that some lines are more vulnerable than others. It appears that there is a strong correlation between vulnerability and the line length. For example, line 1 with length of 19.7 km and the combined line 15+16 with length of 20.1 km suffer from events about 2.5 times and 2.9 times respectively as much as line 3 having a length of 8 km. This is an obvious phenomenon since long lines are more highly in exposure of events' consequences compared to short lines. Furthermore, if a line is affected by more than one event simultaneously, it might even be more difficult to provide detours or other adjustments. This might influence transit trip cancelation rates as well.

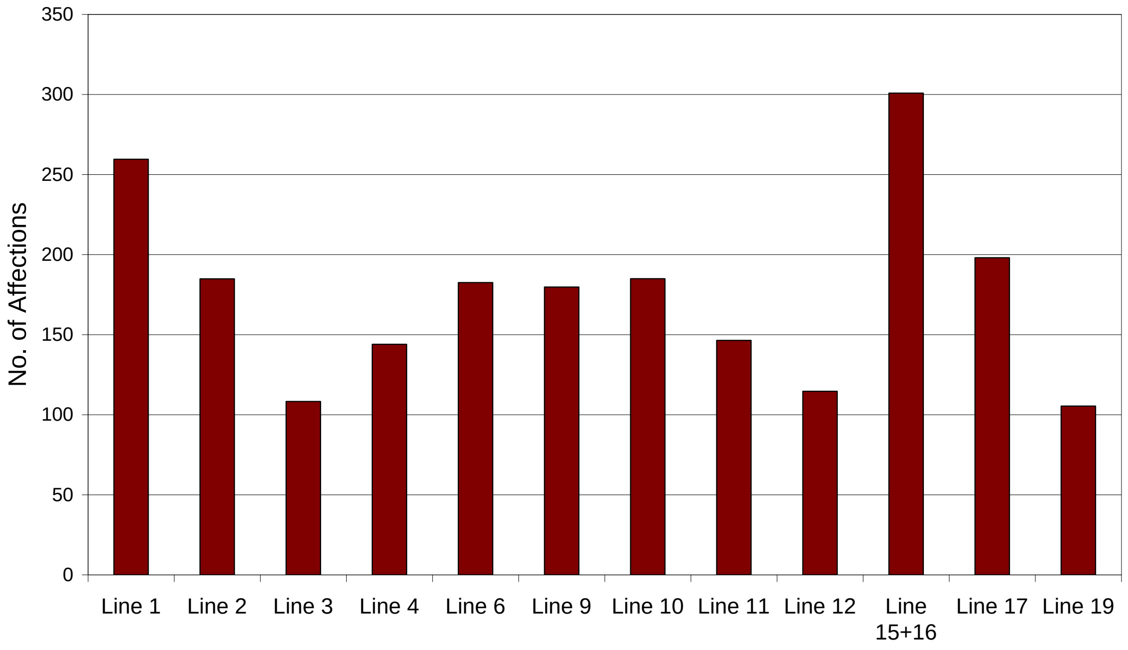


Figure 4: Degree of vulnerability of the tram lines of The Hague (expressed in no. of affections/year)

Finally, Table 2 outlines the ten most vulnerable origins in terms of the connectivity reliability expressed by transit trip cancellation. The result shows that terminal Delft Tanthof is the most vulnerable one. The results clearly shows that the most vulnerable nodes are terminal points located at the end of service lines and do not have any alternatives when their corresponding lines are affected.

TABLE 2: Connectivity Reliability; the Ten Most Vulnerable Nodes

Origin number	**Origin name**	**The annual percentage of trip cancelation (mean value)**
40	Delft Tanthof	7.0%
43	Voorburg Station	5.9%
45	Leidschendam Noord	5.6%
41	Delft University	5.3%
31	Delft Station	4.6%
34	Duindorp	4.2%
44	Leidschenhage	3.8%
36	Kraaijenstein	3.7%
20	Essesteijn	3.4%
30	Scholekstersingel	2.9%

5.2 Improving Service Reliability of the Transit Network

The assessment of the current network shows that quite a lot of trips (2.1% of all trips) should try to find an alternative to reach their destination or should reschedule their trips. Furthermore, the more detailed analysis indicated several network components that be improved. In this section we will analyze different options to improve transit service reliability. In the first option, it is studied whether splitting line 1 might improve the connectivity reliability, as short lines tend to be less vulnerable. The other options all relate to adding extra infrastructure which enables the operator to provide detours in case of non recurrent events.

5.2.1 Enhancing Reliability by Changing Service Line Configuration

In this analysis we focus on tram line 1 which was shown as one of the most vulnerable lines. Moreover, it serves several of the most vulnerable origins. One of the reasons that line 1 is so vulnerable is that it one of the longest tram lines, which increases the probability of suffering from two or more events simultaneously. In those cases, it proves to be nearly impossible to maintain a proper service level. Thus, splitting the line into two parts might reduce this probability substantially. Disadvantage, however, is that travellers might have to transfer which increases their travel time consequently.

To improve the reliability of line 1, we split it into two radial lines as follows:

- Line 1-A: From Scheveningen (SN32) to Hollands Spoor (HS46) in the city centre with the length of 7.2 Km.
- Line 1-B: From to Hollands Spoor (HS46) to Delft Tanthof (DT40) with the length of 12.5 Km.

The assessment of this option shows that the results are according to our expectations. Changing line 1 into two radial lines will result in 1% reduction in the total number of cancelled trips in the entire tram network. Of course, for Delft Tanthof, which is directly served by line 1, this rate is much higher (22% or around 416,000 trips). Therefore, no longer is station Delft Tanthof most vulnerable station in the network. However, splitting line 1 increases travel costs due to additional transfers of through going passengers. Thus, splitting line 1 will enhance the connectivity reliability for the tram network while increasing travel costs as well. The net result proves to be positive for network performance.

5.2.2 Extra Infrastructure to Enhance Connectivity Reliability

In this part, we investigate the role of additional infrastructures on improving the reliability of the tram network.

Scenario 1: Bypass

Basically, a bypass is used as backup for vulnerable links, thus enabling the operator to provide detours in case of events. The HTM planning department suggested an at-grade bypass for link 19, an elevated tramway which is heavily used by two tramlines and two light rail services. Since, this link is the only connection between Leidschendam and The Hague, a blockade of this link thus leads to transit trip cancelation as be seen in Table 2: three origins are located in Leidschendam area (origins: 20, LL 44, LN 45). The at-grade bypass is connected with the at-grade tram network near Central Station, which also connects to the existing alternative route for the tram tunnel (link 28). This link proves to be very vulnerable as well. The location of the new bypass is illustrated in Figure 5.

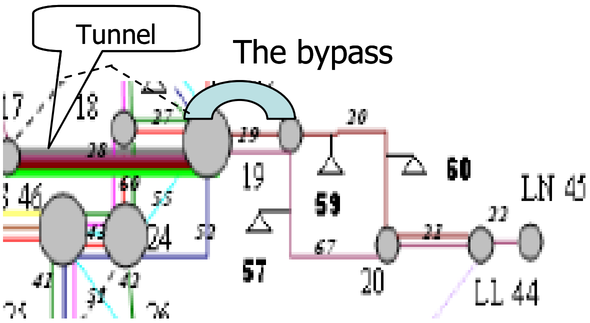


Figure 5: Details of the tram network between Centraal Station and eastern part of The Hague

Analysis of the network performance including this bypass shows 9% reduction in the total number of cancelled transit trips. In some simulated years this rate rises even up to 24%. In other words, on average 170,000 more passenger trips are made annually. Furthermore, because of this bypass, tramlines 2 and 6 can maintain service quality for a longer period and many travellers in other parts of the city do not need to make a detour or to choose alternative routes. So both the connectivity reliability and the travel time reliability are substantially improved. Also as overall performance estimation, despite of the fact that the infrastructure costs for an at-grade tramway is rather high, the total network costs decreases on average with 0.4%.

Scenario 2: Shortcuts

Connecting service lines with shortcuts provides a substitution opportunity for vulnerable service lines in case of link failures. In this scenario we introduce an additional shortcut infrastructure that connects two vulnerable lines, being tram lines 2 and 3. The origins located at the end of these lines have a high level of trip cancelation (Loosduinen (LS 35) and Kraayenstein (KS36) (see also table 2)). Figure 6 shows geographic characteristics of the area, the itineraries of tram lines 2 and 3 and the proposed shortcut.

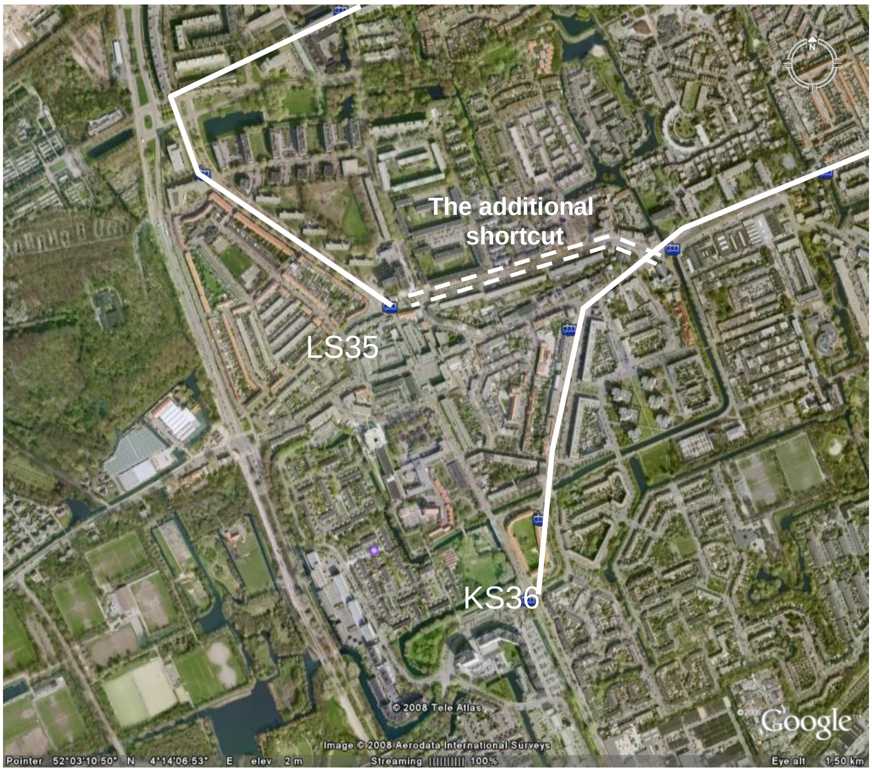


Figure 6: Satellite Image of Tram Lines 2 and 3, Geographic Features, and the Proposed Additional Infrastructure Shortcut

Note that this shortcut could be a single track since it is not heavily used like the bypass and thus, its construction cost could be lower than for the bypass. The shortcut will be used in case of disturbances at links 13 or 23 (figure 7). Thus, the corresponding lines can be diverted from the original path, use another track, and still terminate at their original terminal via the shortcut and vice versa.

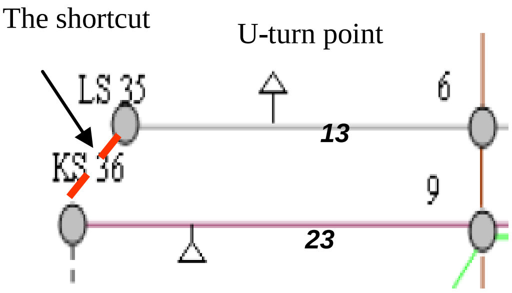


Figure 7: Shortcut Connecting Terminals KS 36 and LS 35

Network assessment results show that there is 2.4% reduction in the total number of cancelled trips on average (around 45,500 trips). This rate rises even up to 12 % for some simulated years. However, since more trips are made using a detour, extra travel costs increase about 1.5%.

The impact of shortcut infrastructure in terms of the connectivity reliability is smaller than in case of the bypass. However, the infrastructure cost could also be lower, which would again lead to a reduction of the total network costs.

6 CONCLUSIONS

Synthesizing the discussion above, there are many methods to improve service reliability at all planning levels.

At the strategic level of service network planning applying relatively short service lines and planning for the service network redundancy are two influential measures for improving service reliability.

In the infrastructure network planning for redundancy by means of additional infrastructures and thereby creating flexibility in service networks enables transit operators to repair service lines using detours and short runs and thus to maintain service operations. Applying these measures improve service reliability in transit networks especially in rail bound networks. The results of case study in The Hague demonstrate that adding extra infrastructures not only significantly reduces the number of cancelled transit trips (9%), but also it decreases extra travel costs around 4%.

The Hague case study analysis results in following noteworthy findings:

- Increasing the service network redundancy in transit networks by combining tangential lines with radial networks improves service reliability significantly, but it may not necessarily lead to better overall network performance. In case of vulnerable networks it is more likely to be an interesting option;
- Reducing transport service network vulnerability by smartly planning short service lines may improve both service reliability as well as overall network performance considerably;
- Using the existing infrastructure smartly by equipping the existing infrastructure network with additional infrastructures such as shortcuts, bypasses, and turning facilities proves to be a cost efficient way to improve service reliability. Combining these additional infrastructures with the existing infrastructure network in rail bound transit will facilitate operational adjustments in case of network disturbances and thus improve reliability. Furthermore, these additional infrastructures can lead to a significant improvement in travel costs and network performance.

ACKNOWLEDGEMENT

This study is supported by the Next Generation Infrastructures Foundation and by the Transport Research Centre Delft. The authors would like to thank HTM for providing data on their tram network.

REFERENCES

1. Friman, M, B. Edvardsson, & T. Gärling (1998). Perceived Service Quality Attributes in Transit: Inferences from Complaints and Negative Critical Incidents. *Journal of Transportation, 2*, , pp.67-89.
2. Bovy, P.H.L. (1996) *Stochastic traffic assignment technique enhancements for congested networks. Transportation Modeling For Tomorrow*. Delft University Press. Delft, pp. 129-146.
3. Nielsen, O.A. (2000) A stochastic transit assignment model considering difference in passengers' utility functions. *Transportation Research Part B: Methodological*. Vol.34, Issue 5. pp. 377-402.
4. Higgins, A., L. Ferreira, & M. Lake. Scheduling rail track maintenance to minimize overall delays. *In Proceedings of the 14th International Symposium on Transportation and Traffic Theory.* 20-23 July 1999. Jerusalem, Israel.
5. Veiseth, M., N. Olsson, & I.A.F. Saetermo. (2007) Infrastructure's Influence on Rail Punctuality. *In Proceedings of Urban Transport XIII: Urban Transport and the Environment in the 21st Century*. September 2007, Coimbra.
6. Schmöcker, J.D. & M.G.H. Bell. (2002) The PFE as a Tool for Robust Multi-modal Network Planning. *Traffic Engineering and Control. No. 44(3)*. pp.108-114.
7. Immers, L.H., J.E., Stada, I., Yperman, & A., Bleukx. (2004) Robustness and resilience of transportation networks. *In: Proceedings of the 9th International Scientific Conference MOBILITA*, Bratislava, Slovenia.
8. Muller, T.H.J. & P.G. Furth. (2000) Conditional bus priority at signalized intersections: better service with less traffic disruption, *Transportation Research Record 1731*, pp.23-30.
9. Van Oort, N. & R. van Nes. (2008) Improving reliability in urban public transport in strategic and tactical design. *In proceedings of the 87th Annual Meeting of Transportation Research Board*. Washington DC.
10. Shimamoto, H., F. Kurauchi, J.D. Schmöcker, & M.G.H. Bell. (2007) Evaluating Critical Lines and Stations of London's Underground Network Using Transit Assignment Model. *Proceedings of 3rd International Symposium on Transportation Network Reliability*, 19-20 July 2007, The Hague.
11. Israeli Y. & A. Ceder.(1996) Transportation assignment with passenger strategies for overlapping route choice. *Transportation Research Record 1623*. pp.3-7.
12. Carey, M. (1998) Optimizing scheduled times, allowing for behavioral response. *Transportation Research Part B*, Vol. 32, No. 5, pp. 329-342.

13. Rietveld, P., F.R. Bruinsma, & D.J. van Vuuren. (2001) Coping with unreliability in transit chains: A case study for the Netherlands. *Transportation Research Part A: Policy and Practice*. Vol.35, No. 6, pp.539-559.
14. Vuchic, V.R., & A. Musso.(1991) Theory and practice of metro network design. *Transit International. Vol.40. No. 3/91.* pp. 298-325.
15. Tahmasseby, S. (2009), *Reliability in urban public transport network assessment and design*, Ph.D. Thesis. Faculty of Civil Engineering and Geosciences. Transport and Planning Section. Delft University of Technology. NGinfra PhD Thesis Series on Infrastructures No. 31