Reliability in Urban Public Transport Network Assessment and Design

Shahram Tahmasseby

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Reliability in Urban Public Transport Network Assessment and Design

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Preface

The work reported in this thesis was supervised by Professor dr.ir. Piet Bovy as promotor and Dr.ir. Rob van Nes as daily supervisor at the Transport and Planning Department of the Delft University of Technology. I am grateful to both Piet and Rob. Together they supported my research from both the theoretical and the practical point of view. Despite of the fact that combining these two aspects is a difficult task, they supported me and encouraged the progress of my research.

I would like to express my appreciation to all my committee members for the time spent on reviewing my thesis and stating constructive comments, which enrich my thesis significantly.

I also thank the TRAIL research school, especially for the courses that helped me develop my research skills. I acknowledge the efforts of the members of my PhD committee and appreciate their constructive remarks on my research.

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Furthermore, I would like to express my thanks and gratitude to HTM (the public transport operator of The Hague) for providing me necessary data to perform a realistic case study.

Especial thanks go to Rob. Thanks for all the useful discussions on my research which always stimulated me to work harder and to achieve better results. Furthermore, thank you very much for translating the English summary and propositions into Dutch.

Finally, I want to thank my wife (Ghazaleh) persuading me to complete my study, and my parents and my sister for their love and tolerance throughout the time I am absent. I would like to dedicate this thesis to them for their support during my tough times.

Contents

1 INTRODUCTION

1-1 Research motivation

The sustained growth of the economy and the continued improvements to the quality of life lead to an increase in the value of time, especially in the developed countries. Thus, reliability has recently emerged as an important factor in transportation and pertains to determine how well a transportation network provides service quality for its users.
Reliability of public transport systems has been considered imperative by public transport users, operators and the government. Public transport systems often fail to provide reliable service 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 public transport services leads to uncertainty and consequent delays aggravating anxiety and discomfort for the passengers. Furthermore, reliability is targeted by the operating companies, firstly to improve their internal efficiency and reduce operating costs, and secondly to benefit from increased patronage due to service improvements. Public transport reliability has thereby become an increasingly important attribute for assessing the performance of public transport networks. In a Swedish study reliability has been found one of the most important attributes of quality of public transport services (Friman *et al*., 1998).

In order to increase public transport's share compared to private modes and maintain its competitiveness, reliability of public transport services among all other influencing factors such as speed, accessibility, and safety should be improved. Empirical evidences show that public transport patronage growth will result from service reliability improvements (Oldfield et al, 1977; DETR 1997; BCSR 2003; Balcombe et al, 2004; Vuchic 2005; Currie et al, 2007). For instance, the results of a British study (BSCR 2003) demonstrate that improving reliability will result in more than 12% increase in use of urban public transport (bus, and light rail) within 10 years. Hence, reliability plays an important role in attractiveness of public transportation.

With respect to the importance of reliability, now the question might be raised how the impacts of reliability might be accounted for in public transport network design and assessments? Consequently, does considering reliability as an influential factor lead to extensions in public transport network design and assessments? Given the serious impacts of potential disturbances on public transport network performance and service quality, assessment and design of public transport networks concerning reliability have received astonishingly little attention in the literature. The research presented in this dissertation thesis aims at extending the classical public transport network design procedure by including service reliability as an important aspect in public transport network design and assessments.

1-2 Research background

A number of previous studies from past several years have found reliability of the public transport timetable one of the most important characteristics of public transport services (Golob et al. 1972; Paine et al. 1969; Wallin and Wright 1974). Turnquist and Bowman (1980) examined the effect of network configuration on network reliability showing that service network pattern and line density impact service reliability. Vuchic and Musso (1991) give some guidelines on designing reliable public transport networks especially for metro lines stressing independent service line operation to enhance service reliability. Rietveld et al. (2001) evaluated various reliability enhancing strategies for Dutch public transport networks indicating that service reliability could improve by timetable modification. Schmöcker and Bell (2002) design a network observation tool named PFE (path flow estimator) to identify which link failure probabilities cause the most increase of expected trip costs in a multimodal transport network.

Ceder (2001) recommends improving operation plans and schedules such as applying priority and control techniques, to improve the reliability of transit service lines as well as of the entire public transport network. Chang et al. (2003) and Levinson (2005) suggest using Intelligent Transportation Systems to increase reliability in public transport operations. De Kort et al (2003) develop a methodology to compute the maximum number of train movements per hour per direction that can be executed on a particular infrastructure element in order to achieve a certain desired level of reliability. They apply their approach to a planned high-speed double-track line in the Netherlands. Recently Van Oort and Van Nes (2007) have evaluated some strategies for improving the service reliability of the tram network in The Hague by coordination of tram lines, and modification of stop spacing between stops.

Most of the aforementioned attempts focus on coping and adjusting public transport networks in case of disturbances to weaken their impacts on services and consequently public transport travellers. However, the important question remains whether it is possible to design a public transport network in such a way that its design inherently has higher service reliability and mitigates the consequences of service disturbances'.

By looking at the public transport network design procedure, it generally consists of three stages as follows:

- Strategic design;
- Tactical design;
- Operational design.

We will discuss these stages in this thesis. Reliability in network design can be dealt with in the tactical and the operational design steps such as in timetable design, in synchronisation, in fleet and crew planning, in determining prioritisation tactics, and in operational management and control stage for an existing public transport network. However, is it possible to deal with reliability at the strategic level of planning where network spatial characteristics are determined, too? In other words, is it possible to extend strategic public transport network

design in such a way that the yielded designed network has the capability of being more robust against potential disturbances?
On the basis of available literature it can be concluded that there is a lack of sufficient research at the strategic design level regarding reliability. Hence, we intend to deal with this challenge in this thesis. In the next part therefore we will elaborate on the research objectives and scopes of our dissertation thesis.

1-3 Overview of research objective, research questions and scope

Regarding the previous discussions, this thesis aims at proposing an appropriate methodology for public transport network design assessments with adequate consideration of service reliability. The objective that is going to be achieved in this thesis is:
Extending classical public transport network design and assessment by including service reliability into the design problem and assessment criteria.

In order to tackle the aforementioned objective, there are three main research themes that should be addressed adequately. These research themes are:

1. The diagnosis issue, identifying causes of variations in public transport networks, impacts of events, and the notion of service reliability;
2. The development of a public transport network planning, design philosophy and procedure including new design dilemmas, extension of network performance criteria to capture service reliability as well, and extension of the bi-level relationship between network design and traveller's behaviour to include impacts of stochastic events;
3. The implementation issue including the identification, implementation, and empirical testing of possible reliability improving measures.

For the 1st theme on diagnosis the following questions might be raised:

- Why is classical public transport service network assessment and design not appropriate?
- Which are relevant random variations pertaining to urban public transport networks?
- Which are the impacts of stochastic events on public transport network operations?
- How do transit travellers perceive service variations suffered by them?
- What are relevant notions of service reliability in public transportation?
- What are relevant impacts of service reliability on traveller's choice behaviour?

Regarding the 2nd theme on planning, relevant research questions are:

- How can service reliability be improved in the public transport planning stages?
- Which are relevant consequences of reliability improving measures for the public transport network design problem?
- Does considering service reliability lead to new network design dilemmas?
- Does considering service reliability require an extension of the classical network design objective functions?
- Which are relevant consequences follow from considering impacts of stochastic events for the classical bi-level network design framework?

The 3rd theme on implementation leads to raising the following questions:

- What are promising reliability enhancing measures for the service network and infrastructure planning?

- What are relevant outcomes of applying reliability enhancing measures at the strategic level for overall network performance?
- Do reliability enhancing measures at the strategic level of network planning really work for realistic cases? And if yes, what are their consequences in terms of improving overall network performance?

The scope of this research will be urban public transportation in which we concentrate on line bound public transport networks.

1-4 The research approach

In this research, we use several methodologies depending on the context of the study. Regarding contexts of theme 1 we synthesize qualitatively outcomes of experimental and empirical studies in order to identify and to categorise probable stochastic events which may impact public transport networks. We use common probabilistic formulations to estimate time interval, and duration between stochastic events. These probabilistic formulations are applied for the simulation of stochastic events. In order to determine impacts of events on network performance, we opt for the most relevant operational measures using empirical studies such as service running time, punctuality, regularity. Regarding service reliability notions in public transport, the focus will be on travel time reliability, and connectivity reliability. The latter relates to network robustness. All these measures are discussed extensively and the relationships between them are distinguished. Finally, impacts of service variations on traveller's behaviour are studied by synthesising empirical findings.

Regarding our approach in theme 2, we identify and categorise commonly used operational measures that are applied by transit operators to cope with impacts of stochastic events on urban public transport networks. Given the impacts of operational measures on public transport network design, we extend the public transport network design problem conceptually by using classical public transport network design and traveller's behaviour concepts. We develop public transport network design in relation with service reliability and network robustness to identify appropriate reliability enhancing measures at the strategic level of network planning.

Regarding the methods used in theme 3, we design an assessment tool based on the extended network design problem discussed in theme 2. This tool will have the capability of capturing all potential variations and distortions in public transport network including infrastructure, as well as traveller's behaviour. The tool determines and locates temporally random disturbance(s) affecting public transport service networks, infrastructure and public transport travellers.

With respect to the operational adjustments applied by transit operators to cope with disturbances in services, the tool assesses various cases at the strategic level of network planning to enhance service reliability. The defined cases aim at preventing public transport networks from random service disturbances and thus improve service reliability. They lead to modifications and extensions in the transport service network and infrastructure. After implementing cases, the corresponding outcomes in terms of overall network performance including service reliability are compared and evaluated. We apply heuristic methods in combination with engineering judgments to find an optimal service network and infrastructure in terms of network performance including service reliability. This approach fits in the context of *Decision Support Systems* methodology. *Decision Support Systems* are related to the design of single-level (urban) public transport networks.

1-5 Scientific contributions of the thesis research

This thesis contributes to the State-of-the-Art of service reliability considerations in the public transport network design in various aspects categorized into three groups:

Group 1:

- Establishment of a classification system of stochastic events, impacting urban public transport networks and causing disruptions, according to their characteristics in terms of time, location, severity, predictability, and regularity;
- Establishment of a categorising system of operational measures and adaptive remedial solutions, commonly applied by transit operators to mitigate disturbances caused by stochastic events, according to disturbance type;
- Identification and formulation of new design dilemmas in the context of the public transport network design problem as a result of accounting for service reliability;

Group 2:

- Establishment of an extended PT network design framework by incorporating service reliability on the supply and demand sides. Consequently, network design objective functions which accounts for service reliability have been developed;
- Identification and modelling of the impacts of service variations offered to passengers on route choice behaviour according to event regularity;
- Formulation of an extended route choice model including the route set generation procedure with the capability of incorporating public transport travellers' perception of service reliability in their regular route choice behaviour and of their responses to unexpected variations;

Group 3:

- Establishment of new measures at the strategic level of network design for both transport service networks and infrastructure with positive impacts on network robustness and service reliability;
- Establishment of a new planning procedure for infrastructure of urban rail bound public transport network demonstrating the effective role of additional infrastructures on improvement public transport network reliability.

1-6 Practical relevance of the research

At least the following two practical merits emerging from this research are considered relevant for public transport planning:

- Modifying spatial characteristics of service networks in terms of network type, line density, and line length to enhance service reliability based on a decision support system methodology will enable public transport planners to adapt their existing transport service network design to achieve higher reliability.
- Including additional infrastructures e.g. shortcuts, bypasses, and turning facilities in existing infrastructure networks based on the decision support system methodology

will enable the infrastructure providers (especially in urban rail bound public transport) to be ensured of infrastructure quality (offered to transit operators).

Given these outcomes the following practitioners would gain from this research:

- *Urban infrastructure planners* will benefit from the recommendations given in this research for planning additional infrastructures such as on shortcuts, bypasses, and turning facilities. Planning of such infrastructures would lead to more flexible public transport infrastructure networks especially for rail bound networks and could facilitate adequate transit operations in case of disturbances.
- *Public transport planners* get recommendations for their public transport service network design. That is how to reconfigure their existing public transport service networks in terms of network type, service line type, and service line length in order to improve network performance including service reliability.

An example of practical relevance of this research is the cooperation with HTM (the public transport operator of The Hague) with respect to analysis and advise to plan additional infrastructures for vulnerable service lines, and also splitting a vulnerable line into two parts.

1-7 Thesis outline

This section briefly describes the contents of each chapter of this dissertation and the connections between them.
Figure 1-2 illustrates the structure of the main body of this thesis. *Chapter 2* summarizes the classical public transport network design procedure. It deals with diagnosis theme 1 already discussed in section 1-3 by addressing why the traditional public transport service network design problem is not appropriate. The commonly used urban public transport network patterns are studied and their spatial characteristics evaluated. The public transport network design problem including its design dilemmas, and design complexities are discussed and consequently commonly used design methodologies found in the literature are assessed and categorised. A bi-level design framework based on game theory is proposed to deal with design complexities. Also classical public transport design objective functions with different perspectives are presented. These objective functions are formulated mathematically. All design aspects presented in this chapter are according to the deterministic point of view by assuming constant transport system characteristics.

Chapter 3 focuses on stochastic events impacting urban public transport service networks. This chapter deals with diagnosis theme 1 too. The main focus of this chapter is to identify potential variations in public transport networks and their impacts on public transport service networks and operation.
Thus, in this chapter the event's characteristics and their consequences for public transport networks including their infrastructure are extensively discussed. Several distinctions are made based on event's characteristics in terms of time (interval, duration), predictability, regularity, and location. Furthermore, event-adaptive adjustment strategies and remedial solutions that are normally used by public transport operators are reviewed and categorised.

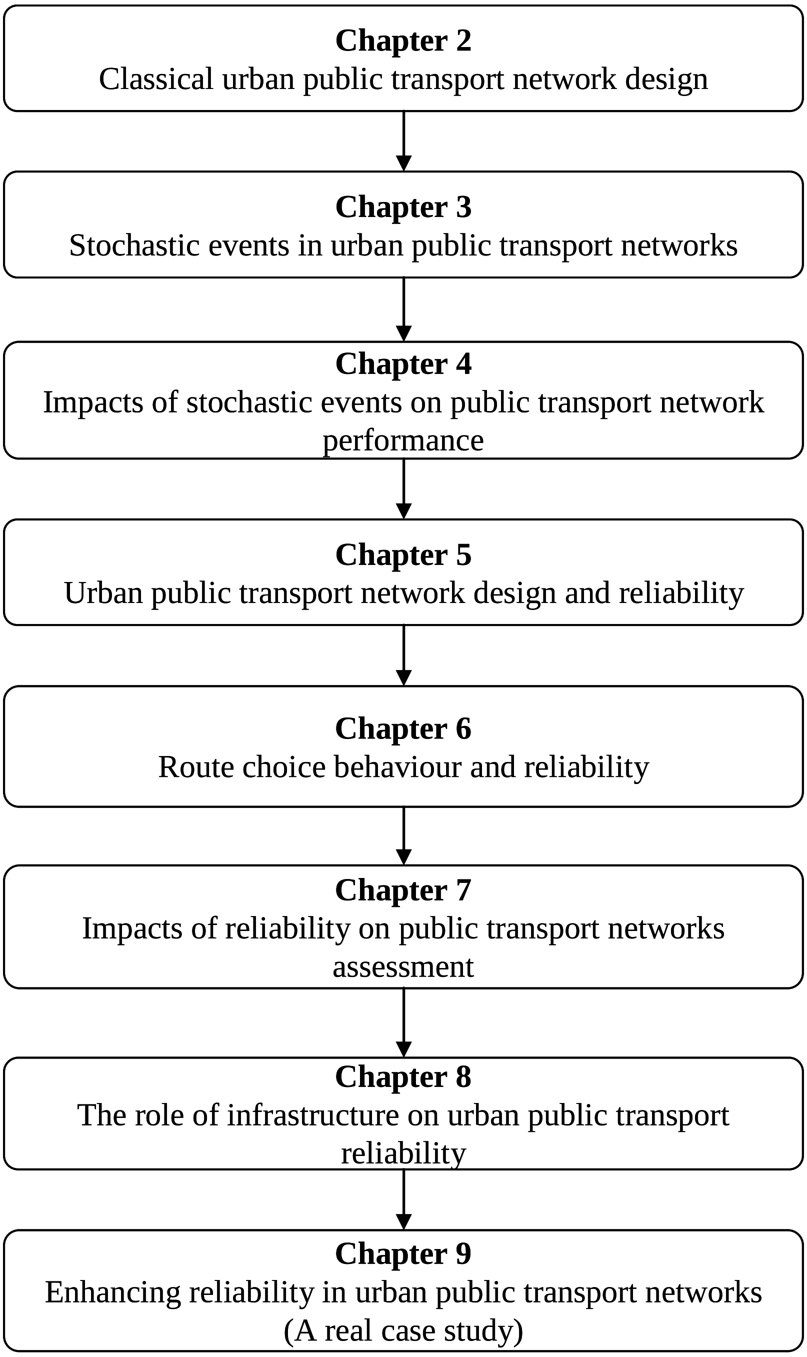

Figure 1-2: Schematic overview of the main body of this thesis

Chapter 4 addresses impacts of stochastic events on service performance. This chapter is also related to diagnosis theme 1 and addresses the following questions:

- Which impacts of stochastic events are exerted on public transport network performance?
- How do transit travellers perceive service variations suffered by them in short run?
- Which notions of reliability are relevant in public transportation?
- How can service reliability be perceived by public transport travellers according to regular and irregular service variations?

- Which impacts of service variations and service reliability determine travellers' choice behaviour in the short term and the long term respectively?

Therefore, operations performance criteria addressing service reliability are presented and formulated mathematically. Service quality variations suffered by public transport travellers reduce service reliability perceived by them. Thus, several definitions, measurements and criteria related to service reliability are reviewed and accompanied by mathematical formulations. Moreover, these definitions and measurements are verified by empirical results gained in various reliability-oriented studies by many researchers. In this chapter a distinction is made between events according to a regularity criterion. Finally, in this chapter impacts of service reliability on traveller's choice behaviour with respect to route choice, departure time choice, mode choice, and destination choice are studied using empirical study results.

Chapter 5 relates to planning theme 2 and elaborates on how best incorporating service reliability in public transport network design. Commonly used approaches for enhancing reliability at the operational, the tactical, and the strategic levels of network design are introduced, categorised and exemplified. Incorporating service reliability at the strategic level of network planning raises several new public transport design dilemmas. Moreover, it results in a new network design framework and an extended network design objective function. In this formulation the impacts of disturbances in the network are captured. In fact, this chapter expresses public transport network assessment and design considering reliability in a stochastic perspective. Accordingly, the assessment criteria addressing service reliability, discussed in chapter 4 are included in network performance measures. Thus, this chapter forms an extended public transport network design problem addressing service reliability.

Chapter 6 also deals with planning theme 2 and studies the impacts of random disturbances on public transport traveller's route choice behaviour. In this chapter, a distinction is made between impacts of regular variations and irregular variations on choice behaviour. Furthermore, two different types of choice behaviour named pre-trip choice and en route choice are expressed in case of irregular variations in the network. These types of behaviour depend on the event types in terms of predictability and also the current knowledge of a traveller from the network situation. Thus, this chapter extends on classical route choice models by incorporating service reliability. Two different problems are dealt with in this chapter: First, how do public transport travellers strategically include their perception of reliability in their regular route choice behaviour? Second; how may public transport travellers respond to an unexpected event by changing their route choice?

Chapter 7 deals with implementation theme 3. In this chapter the extensions of public transport network design in terms of extended service performance criteria regarding service reliability, operational measures applied in case of disturbances, and strategic measures applied to enhance service reliability are implemented in an assessment tool. The methodology used in this chapter is to exemplify the extended design framework, described in chapter 5, by a hypothetical case study resembling an ideal commonly used tram network. The focus is on public transport service network design at the strategic level. Different tactics for modification of an existing transport service network are defined, applied and their outcomes are evaluated in terms of service reliability and overall network performance.

Chapter 8 deals with implementation theme 3 as well. It focuses on public transport infrastructure network design accounting for reliability. The objective of this chapter is evaluating impacts of additional infrastructure on improving service reliability of the urban public transport networks. Hence, several variants are defined and implemented in the hypothetical case study and the corresponding outcomes are assessed in terms of service reliability and overall network performance.

Chapter 9 in relation with theme 3 validates the research findings from previous chapters in a real case study (tram network in the city of The Hague), with realistic spatial network characteristics. This chapter is the engineering core of this thesis and exemplifies the research findings in practice. In this chapter the service performances of the existing tram network in terms of reliability are assessed. Given the assessment results, appropriate recommendations are provided to enhance service reliability in the studied tram network. Design recommendations that are introduced in this chapter and appreciated by transit operator of the city might be applied in the network in the near future.

Finally *Chapter 10* concludes the thesis, outlines findings, and proposes recommendations for further elaboration regarding service reliability.

2 CLASSICAL URBAN PUBLIC TRANSPORT NETWORK DESIGN

2-1 Introduction

In this chapter classical public transport network design and related issues are discussed. The network design problem is chosen as the overall framework for analyses to be done in this research, despite of the fact that the main focus of this dissertation is on public transport network assessments.

As the first context of this chapter we indicate that a public transport network is a part of the transport system. In addition to the public transport network, infrastructure is the other part of the transport system. Making a distinction between these two components is essential since each one has its own characteristics in the design and assessment process. The distinction between these two components will be clarified in this chapter by using a common layer model.

We will also indicate by a common hierarchical scheme that public transport network design is a part of the planning process. The planning process is usually addressed in three different levels, whilst public transport network design is the context of one planning level specifically.

Regarding public transport network design, we will discuss network descriptive characteristics that are dealt with in the design problem. Service network type and service line types are two important spatial attributes of public transport networks that are extensively elaborated in this chapter.

Classical public transport network design is focused on a single level service network predominantly in a deterministic perspective. The main goal in the unimodal transport service network design problem is to determine an optimal service network given a specific design objective. We will show that this is a complicated problem due to several reasons such as the conflict between viewpoints of the public transport operator and authorities, and travellers.

Hence, as the second context of this chapter we'll elaborate on classical unimodal public transport network design in the deterministic perspective by discussing complexities and methods that are commonly used to deal with them.

The results of this chapter are providing a public transport network design framework that is a basis of public transport network design and assessments in the stochastic perspective. This framework will be extended in upcoming chapters, mainly in chapter 5, in such a way that service reliability as an influential factor is included in network assessments.

2-2 Transportation system and its components

In this section we categorise the involved parts of the transport system and express a clear definition of each part. These definitions and relations are essential to define a public transport network and assess its components correctly since a public transport network is a part of a transport system. A transport system consists of different parts. The layer model provides a framework to analyse the transportation system and relationships between its components. The basic model (Schoemaker et al. 1999) consists of three layers, namely Activities, Transport Services and Traffic Services, and two markets between them namely:

1. The Transport market between activities and transport services;
2. The Traffic market between transport services and traffic services.

The *Activity-layer* relates to the activities performed by people, companies, and organisations. Typical activities are living/dwelling, work, study, shopping, visiting, and recreation, while production, assembling and storage are examples of activities for companies and organisations. Since activities have different locations in space and time, people have to make trips and goods must be shipped. Thus the spatial distribution of activities leads to a demand pattern in space and time of trips for people and goods.

The *Transport Services-Layer* offers transport facilities to people and shippers. Just as in the activity-layer, many actors are involved from individual persons driving their own car or bicycle to professional organisations, each offering transport services to facilitate the demand pattern. In fact, this layer provides a supply pattern in space and time for the transportation of people and goods. Typical characteristics of this supply are the level of service (e.g. travel time, reliability), prices, and quality (e.g. comfort).

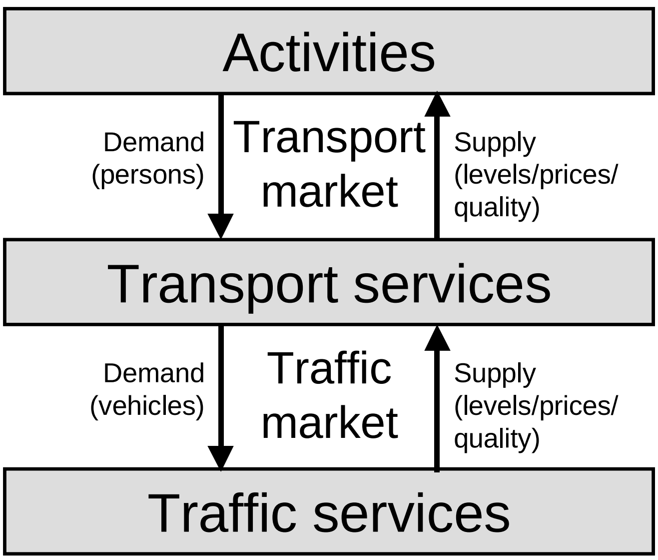

Figure 2-1: Layer model of the transportation system

The *Transport Market* balances demand and supply, yielding the actual trip patterns for travellers and freight. Please note that the actual trip pattern, which might be observed by surveys, is not equivalent to the desired demand pattern. For example, travellers might choose activities nearby instead of the originally intended activities because of the long travel times or high prices that are related to the transport services available. Although the transport market is not a real market in an economic sense, economic concepts such as utility maximisation have proved to be very useful for describing phenomena in the transport market. Units that might be used to describe the transport market are number of persons, volume, or weight of goods, or distance related characteristics such as traveller-kilometres and ton-kilometres.
In order to provide transport services, the transport service provider uses vehicles, or traffic means, for performing the actual displacement of people and/of good, which leads to a traffic demand pattern in space and time. It should be noted that this pattern will be different compared the demand and supply patterns in the Transport Market. A typical example is a public transport route that will only partially coincide with the actual trips using the service. Another common phenomenon is the “empty vehicle” trip needed for logistic reasons such as a taxi driving to a customer or a truck returning to the depot after delivering its goods.

The *Traffic Services-Layer* provides the possibility for vehicles to make a trip. Traffic services thus consist of various traffic infrastructures and the regulations for using these infrastructures. Ultimately, they might consist of precise trajectories (paths in space and time). The supply of traffic services can thus be seen as a pattern in space and time for the movement of vehicles containing travellers or goods or for (re)positioning of vehicles logistical reasons. Related characteristics are again level of service (travel time), prices, and comfort (e.g. related facilities).

The *Traffic Market* balances the traffic demand and supply, yielding the actual trip pattern of vehicles. Again, the actual pattern is not necessarily identical to the demand pattern, for instance vehicle trips might be cancelled (no capacity available), rerouted or delayed. Please note that in this way the Traffic Market influences the quality of the services offered in the Transport Market as well. Units that might be used to describe the Traffic Market are number of vehicles or vehicle-kilometres.

In the case of public transport the concept of a transport service is quite clear. The public transport company determines nearly all characteristics of the transport service: the vehicle type, the service network that is lines and timetables, and all service attributes, such as availability of travel information, travel costs, and the quality of the services offered. However, the public transport companies usually do not determine the infrastructure network that is available for the service network. This mostly is determined by the authorities. In the case of private transport such as private car, however, the meaning of a transport service needs some explanation. The main point is that the driver provides transport to himself: the driver as service provider and the traveller are the same person. Just as the public transport company, the car-driver determines the quality of the vehicle and of the service during the trip, while the authorities determine the quality of the network used.
We can conclude from the discussion above that the design of a public transport network as a part of the transport system deserves a special attention because of its characteristics and a large number of involved attributes. The design scope covers the transport service network and might be oriented to the infrastructure network too. In the next part the planning process in public transport networks is discussed.

2-3 Planning process in public transport networks

In this part we discuss the planning process in the design of public transport networks. The planning scheme is mainly important for planners to differentiate among design stages and focus on the desired design level. It is generally accepted that planning and control systems within companies can be divided into hierarchically ordered types of activities which differentiate themselves according to the scope of the planning issues addressed and the planning horizon. This can be carried out for public transport just as for other products offered on markets. Based on various theoretical definitions (see, e.g. Anthony, 1988 ; Hellriegel 1992; Van de Velde 1999) the public transport planning process may be viewed as consisting of three levels namely:

- The strategic level;
- The tactical level;
- The operational level.

At the strategic level the design of the transport service network is realised; however depending on the public transport network type and the situation of existing infrastructure, the design of the infrastructure network might also be included in the planning scope.

At the strategic level of network planning, spatial attributes of the service network including the service network type, the service lines and associated service frequency are usually designed (Hellriegel 1992; Van de Velde 1999). These are then inputs of the tactical level. At the tactical stage the timetable is designed. In addition to timetables that are published for travellers, internal scheduling including staff timetable, number of drivers and required vehicles are planned. After planning both the transport network and the timetable, the operational planning are considered to use of the given public transport network efficiently and to provide service for the users in an adequate level of convenience. Figure 2-2 illustrates the relationship between the aforementioned design stages. Ideally operation level gives feedback to the tactical and the strategic level, and also, tactical level gives feedback to the strategic level. However, in practice feedback from the lower level to the upper level is limited.

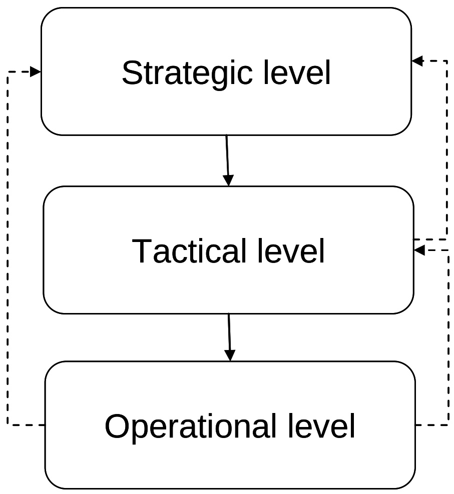

Figure 2-2: Three stages in public transport planning

The focus of this thesis will be on the strategic level and especially the network design problem. As will be shown in later chapters considering service reliability this implies that operational measures should be incorporated in the analysis as well.

2-4 Urban public transport network characteristics

A common approach in defining the infrastructure network is representing the network as a set of nodes together with a set of links (Mandl 1979). Transport service networks however include lines as well. Service lines are a series of subsequently connected links and the corresponding nodes. Furthermore, service lines are associated with service frequencies.
Considering public transport networks, there are important notions that describe service network spatial characteristics. These descriptive notions are categorized as follows:

- *Network hierarchy*: the combination of different network levels in a network;
- *Service line type*: the service line structure and configuration;
- *Network type*: the topological structure of the network.

The Network hierarchy represents the functionality of different network layers forming a transport service network. Each network level is suited for serving specific trip types, especially with respect to trip length, while also providing access to higher level networks. Each level has its own characteristics regarding access density, network density and network speed. Network density is defined as the length of the service network or link network per unit area, whereas access density expresses the number of entry and exit points per unit area. Network speed can be expressed as the average travel speed within the network.
Higher level transport networks are suited for long distance travel and have low access densities, low network densities, and high network speeds. Lower level networks are meant for short distance travel, and thus have high access densities, high network densities, and low network speeds.

The *service line type* represents spatial and temporal specifications that give public transport lines certain functional and operational characteristics. Although some lines have irregular forms, most can be classified into the following types:

- Lines heading towards/ originating from the CBD/ downtown;
- Lines passing the CBD;
- Lines not passing the CBD.

Typical examples of lines heading towards or originating from CBD/downtown are *radial lines*. Radial lines, with one terminal in the city centre the other in the suburbs; tend to follow the major demand directions and connect regions on one side of the CBD (Vuchic 2005) (figure 2-3-A). The highest density of travel in urban areas is usually concentrated in radial directions converging on the city centre area. Consequently, most of the heavily used lines lie between the central area and suburban centres. Service lines with radial or semi radial patterns are widely used in European cities (e.g. Amsterdam, The Hague, Zurich, and Vienna).
There are two major disadvantages for radial lines. First, they provide only limited distribution in the centre, involving long access distance or transferring by passengers (Vuchic 2005). The second one is that their terminals are located in high –density areas where land is precious and space is unavailable. Consequently, the storage of vehicles for peak hour service is very difficult.

Regarding service lines passing through CBD, *transversal lines* are the typical example. Transversal lines connect suburbs on different sides of the city centre (figure 2-3-B). They follow radial directions, passing through the central area (Vuchic 2005). Transversal lines have a major advantage compared to radial lines since they serve larger area, provide better distribution in the CBD, and might offer more opportunities for transfers with other lines. Moreover, they have no city centre terminal. Transversal lines are widely used in European cities too.

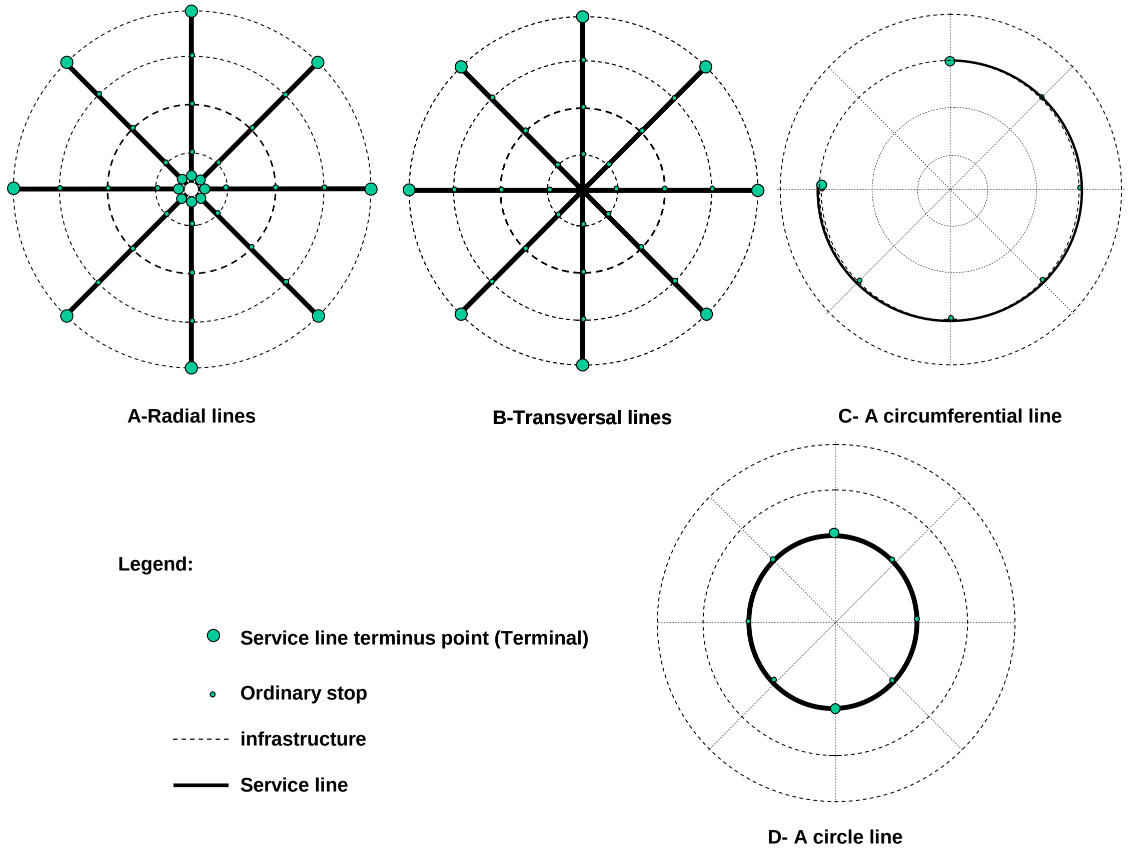

Figure 2-3: Example of network service lines

Service lines that do not pass through CBD can be categorised into two types:

- Open lines;
- Closed lines.

Open service lines are located distantly from CBD, encompassing CBD through suburbs. Their itinerary has two different terminals and does not pass through CBD. Relevant examples of open lines might be *circumferential lines* and *tangential lines.* Circumferential lines are laid out around central city (Figure 2-3-C). They intersect radial and transversal lines enabling transfers with them (Vuchic & Musso 1991).
Tangential or cross-town lines are common in cities with a grid infrastructure network pattern. In the network with a grid pattern, roads, and streets are horizontally-vertically designed. For example, North American cities have usually the grid pattern and use tangential lines. Tangential lines follow a tangential direction with respect to the city centre. They often operate on streets with major commercial activities, schools, etc. and by a reasonable distance from each other. Chicago, Philadelphia, and Toronto are cities using this type of public transport line in addition to other line types.

Closed service lines are usually located closely to CBD, encompassing CBD through areas around CBD. Their itinerary has only one depot and does not pass through CBD. Typical example of the closed service lines is a circle line. Circle or ring lines usually have two main functions. First, they provide a direct connection among numerous medium-to-high density areas around city centre (inner ring) (figure 2-3-D). Second, they can be effective distributors for radial lines. As an illustration, the circle line of London Underground connects nine British Rail stations (London Underground website, 2007).

Please note that all of service lines illustrated in figure 2-3 could be observed in non circular cities as well. For instance, in a city with the grid network pattern, there are always possibilities to establish service line with a radial shape pattern to / from CBD.

The *service network type* expresses the spatial structure of the service network. The spatial specifications of the service lines create networks that can be classified dominantly in 2 different geometric forms as follows:

- Radial service network pattern;
- Rectangular or grid network pattern.

When service lines are radial or transversal focusing on a small area in the city centre, they form a radial network (figure 2-4). Generally speaking, in comparison with road networks, in public transportation, radial networks are dominant. This is especially true for urban areas. The main reason for this phenomenon is that public transport is most efficient when large numbers of trips can be served. Basically, radial networks have some advantages as follows:

- Lines follow major travel directions, thus maximum ridership per kilometre operated service line is achieved;
- Many of the served trips do not require any transfer.

In the radial network type, non CBD oriented trips can be made via a transfer. Rail networks that follow the radial pattern are used in many European cities such as London, Paris, and Munich (Urban Rail.Net 2009). Meanwhile, radial networks have some disadvantages as outlined below:

- Radial networks promote extreme consolidation of service lines in the city centre;
- Radial networks provide low level of service for trips those are non centre oriented and require indirect travel via CBD with a transfer.

Combination of a non passing CBD line, for example a circle line/ ring line, with radial network forms a radial arc service network type. In this service network type, depending on location of the ring line, a number of suburban oriented trips would be made via ring line without transfer.

Rectangular networks consisting of a grid of service lines can provide uniform area coverage (figure 2-4). Trips between any two points are never excessively circuitous and require at maximum one transfer as in radial networks. They are suited for urban areas with a predominantly even density of activities and do not stimulate development of highly concentrated areas such as CBD (Vuchic & Musso 1991).

Note that service network formation depends on the infrastructure network as well. In many cases, no regular geometric form of the network can be distinguished. As an example, we can point out the irregular public transport network that exists in the Canadian city of Montreal. Hence, in designing transport service networks the planner may face limitations which are mostly originated from the infrastructure layer. These limitations can cause adaptations in the service network design and shift the service network pattern from a classical pattern such as the radial network to an irregular pattern.

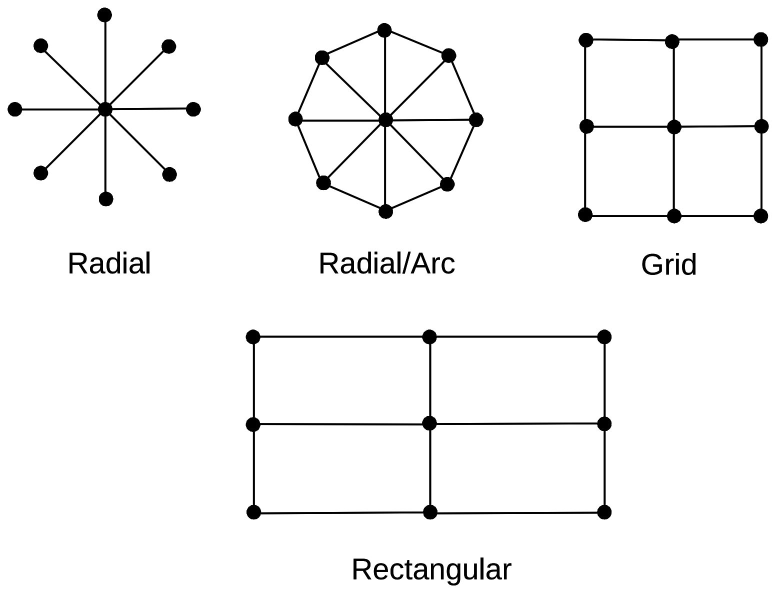

Figure 2-4: Example of network types

A conclusion from the above discussion is that in designing public transport service networks at the strategic level of planning, several aspects such as network hierarchy, the line type, and the network type need to be determined. These aspects make service network design a more sophisticated problem compared to road networks. In the next section the public transport network design problem at the strategic level is elaborated.

2-5 Public transport network design problem

This section defines the approach for the public transport network design problem that will be used in the several parts of this thesis. Firstly, a choice will be made with respect to the problem type. Given the selected case, corresponding complexities and dilemmas that the network designer has to deal with are discussed. Then, a brief review of existing methods found in the literature and addressing the network design problem are presented. By reviewing existing methods in public transport network design, a distinction can be made with respect to network design objectives. Hence, in this section a discussion regarding commonly used network design objectives are presented as well. To formulate network design objectives mathematically, in this section we express a general formulation of the resulting design problem. This section will conclude with formulating the commonly used network design objective functions mathematically.

2-5-1 Design problem type

The topic of public transport network design implies that different network layers should be considered in the design scope, and thus the approach should cover both service networks and infrastructure. Also, the service network could be multimodal consisting of several layers. Due to the complexity of the network design problem to be discussed in the next subsection and also the objectives of this research already discussed in chapter 1, we limit the network design approach to unimodal transport service networks.

2-5-2 Public transport network design complexities and dilemmas

There are three aspects making the public transport network design a complex problem. The first follows from the conflict between the viewpoints of the traveller and the investor or operator (Van Nes & Bovy 2000; Van Nes 2002). The travellers prefer direct connections between any origin and destination, while the investor or operator favours a minimal network in space and in time, thus reducing investment costs (figure 2-5). In order to deal with this conflicting point of view of the authority as well as travellers, transit planners commonly opt for design objectives that incorporate both opposing objectives. In the next section we elaborate on this issue.

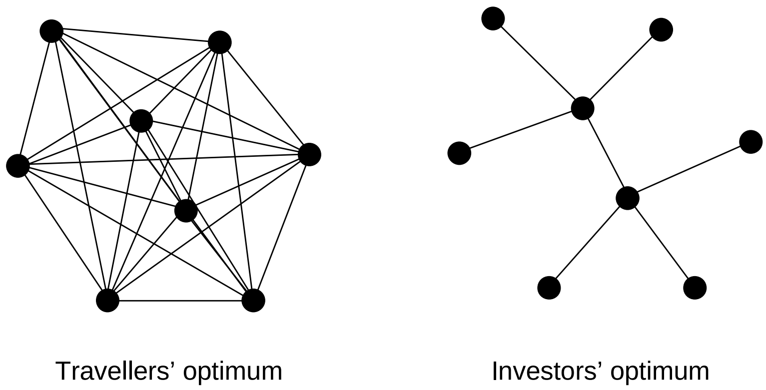

Figure 2-5: Illustration of the difference in optimal network structures between the travellers' and the investors' point of view

As the second aspect determining service network accessibility in time and space implies four design dilemmas from the travellers' perspective. Table 2-1 summarises these design dilemmas and the corresponding trade-offs causing these dilemmas.

In the first trade-off, short access time versus short in-vehicle time is determined. Many stops per square kilometre result in short access distance. On the other hand, the services have to stop at every stop leading to slow speeds and thus long in-vehicle time.

In the second trade-off, short in-vehicle time versus short waiting time need to be weighed. Higher *network density* that is the total length of links used by public transport per square kilometre, lead to direct routes and thus short in-vehicle time. On the other hand, the number of services per link will decrease, resulting in low frequencies and long waiting time.

In the third trade-off, minimisation of transfers versus short waiting times needs to be determined. High *line density* that is total line length per square kilometre, results in a minimum number of transfers, but at the same time to low frequencies per line and thus to large waiting times.

In the fourth trade-off, minimisation of transfers versus short travel times is at stake. Distinguishing different service network levels results in short travel times as each network will be more suited for specific trip lengths. At the same time, however, different network levels lead to transfers between network levels.

The first three design dilemmas are applicable to unimodal networks; however, the key design variables for urban public transport networks are stop and line spacing. In assessing optimal relationships for stop and line spacing for urban public transport networks, only the design dilemmas 1, stop spacing, and 3, line spacing, are relevant.

Table 2-1: Classical public transport network design dilemmas

Yielded Design dilemma	Corresponding Trade-off
Service networks with higher stop density (shorter stop spacing) and shorter access time vs. Service networks with lower stop density (longer stop spacing) and longer access time	Short access times vs. Short in-vehicle times
Service networks with higher network density and lower service frequency vs. Service networks with lower network density and higher service frequency	Short in-vehicle times vs. Short waiting times
Service networks with higher line density (shorter line spacing) and lower service frequency vs. Service networks with lower line density (longer line spacing) and higher service frequency	Minimisation of transfers vs. Short waiting time
Larger number of service networks with larger number of transfers vs. Smaller number of service networks with smaller number of transfers	Minimisation of transfers vs. Short travel times

The third aspect that makes the public transport network design problem a complex one, is the fact that travel behaviour and public transport supply are strongly interrelated. Changes in the public transport network such as service line, timetable, and service reliability lead to changes in traveller's behaviour. As such, the network design problem is often seen as a Stackelberg game in which one decision maker, that is the network designer, has full knowledge of the decisions of the second decision maker, that is the traveller, and uses this knowledge to achieve his own objectives (Gibbons 1992; Cascetta 2001). Figure 2-6 illustrates this relationship.

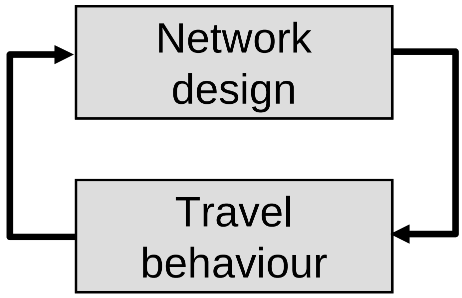

Figure 2-6: Bi-level scheme in public transport network design

In a Stackelberg game two problem types can be distinguished. The upper problem is the actual design objective in which optimal network characteristics are determined given usage of the network by the travellers, while the lower problem describes traveller's behaviour given the network that is supplied. In this approach the network design problem is in fact the upper level problem.

The lower level problem usually deals with route choice only while assuming a fixed level of demand; however, other travel choices (e.g. departure time choice, mode choice, destination choice) need to be considered as well. However, the upper level of the aforementioned framework deals with actual network design dealing with for example, the network type, the line type, stop spacing, line spacing , and service frequency at the strategic level of planning.

2-5-3 Literature on the network design problem

Given the complexity of the network design problem there is a tremendous number of literatures on this subject from different fields such as mathematics, transportation science, and economy. The approaches that are widely found in the literature may be classified into:

- Optimisation models for public transport service network design;
- Design methodologies for public transport networks;
- Decision support systems.

Optimisation models focus entirely on designing new networks in which the design objectives are traveller oriented (Lampkin & Saalmans 1967; Dubois et al, 1979; Hasselström 1979; Ceder & Israeli 1998; Van Nes et al, 1988; Martins & Pato 1996; Pattnaik et al, 1998; Bielli et al, 2002; Chakroborty 2003; Fan & Machemehl 2006; Yang & Yu 2007).
Lampkin & Saalmans (1967) adopt a four-step procedure consisting of skeleton, lines, line selection, and frequencies for designing lines and associated frequencies in unimodal public transport networks. Their objective function is minimising travel time given fleet size and vehicle size. Hasselström (1979) applies a 3-step procedure consisting of link generation, line generation, lines selection and associated frequencies determination in unimodal public transport networks. His objective function is maximising elimination of transfers given a budget. Ceder & Israeli (1998) use a 7-step procedure consisting of line generation, path generation, line selection, demand assignment, frequencies determination, interchange application, and evaluation for designing service lines and frequencies of unimodal public transport networks. Their objective function is minimising travel time plus empty seat hours.
The aforementioned formulated problems have normally a non-linear objective, linear constraints and a great number of variables. These characteristics make the network design problem as a sophisticated problem. Due to complexity of the network design problem, heuristic methods are widely used to cope with this complexity in last two decades. For instance, Van Nes et al. (1988) apply a heuristic method using Newton-Raphson technique for analyses of a simple network. In the first step a large set of lines is generated using several techniques: manual, using a shortest path algorithm, using multiple routing and by chaining line – segments at major transfer nodes. In the second step a heuristic algorithm is used to select lines and assign frequencies simultaneously. Their objective is maximising number of passengers having no transfer, under the constraint of an available fleet size and a limited set of possible frequencies.
Bielli et al, (2002) propose a heuristic approach (genetic algorithm) to solve the transportation bus network optimisation problem. Starting with a set of predefined bus lines with associated service frequencies; their proposed scheme tries to obtain new bus networks with optimal service performance. They use a multi-criteria objective. In addition to Bielli et al.’s genetic algorithm technique, there are several researches applying heuristic optimization techniques such as ant colony algorithms and simulated annealing (Martines & Pato 1996; Pattnaik et al, 1998; Chakroborty 2003; Fan & Machemehl 2006; Yang & Yu 2007).

Compared to the optimisation models, design methodologies have less clear definitions of the objectives and design variables. Design methodologies are used for physical networks as well as for the transport service networks. Many methodologies distinguish different network levels and are traveller oriented. As an example of this approach we can mention Immers et al, (1994). They apply a stepwise procedure consisting of criteria setup, determining access nodes, determining link network, and finally evaluating the network. Their design variables are the links and their objective function is minimising travel time.

Decision Support Systems are all related to the design of single-level (urban) public transport networks. In this case no explicit objective is defined. It is up to the planner to decide whether to focus on the traveller's or on the operator's interests (Van Nes 2002). The main issue in this approach is to provide feedback on a specific network design according to demand assignment and general design rules. Baaj & Mahmassani (1991) apply the Decision Support Systems methodology with a multiple design objective function in public transport network design. Their method consists of network design via computer aided engineering, and transit demand assignment. Given assignment feedback, they apply a line improvement procedure to yield an optimum network. As another example we can point out Shih et al, (1998). They adopt a multiple network design objective to design service lines and associated frequencies too. Their methodology contains network design (computer aided), determining transfer nodes, and demand assignment. Given the design assignment results, they apply a service line improvement method to enhance design objective. In both methods, design variables containing lines and frequencies are initially determined and then an improvement procedure for lines is implemented to achieve a service network with better performance ultimately.

2-5-4 Public transport network design objective

Basically, the main challenge in the traditional public transport network design is to determine a network with an optimal performance given a specific design objective and possible constraints.

As a commonly used method we opt for objectives that incorporate both opposing points of view from the authorities' perspective as well as travellers' perspectives. In that way an identical objective can be used for physical networks and for transport service networks. Typical examples of such objectives found in the literature, that are suitable for both types of networks are:

- Minimising total costs: minimising the sum of the costs involved in travelling, that is the total door-to-door travel time which is monetised using the value of time, plus the investments, maintenance and operating costs (see e.g. Wirasinghe and Vandebona 1999; Van Nes 2002);
- Maximising social welfare: maximising the sum of consumer surplus and producer surplus. (see e.g. Yang & Bell 1997; Van Nes 2002).

The objective of maximising social welfare gives the most comprehensive description for the balance between the travellers' and the investors' objective from an economic point of view (Berechman 1993; Yang & Bell 1997). It incorporates a description of the changes in demand as a result of the changes in the service level that is supplied. This description of the relationship between supply and demand, however, makes it also more complicated than the objective of minimising total cost in which it is possible to assume a fixed level of demand. It can even be shown that incorporating a demand model in the objective of minimising total costs might lead to the trivial solution of offering no services at all, resulting into no travel costs and no investments, maintenance, and operational costs. In the case of the urban public transport network design, it has been shown that given proper assumptions both objectives yield similar outcomes for the resulting optimal designs (Van Nes 2000).

2-5-5 General formulation

Given the aforementioned network design objective functions, the following design problem for the unimodal public transport network can be formulated. For the objective function of maximising social welfare total travel time in the network is determined *(T)* given service network characteristics *(N)*: (e.g. a set of binary variables indicating whether service lines include in the service network, service frequency, etc). Travel time is converted to generalised travel cost *(C)* by using value of time, transport fare and a PT mode preference term. Since generalised travel cost is considered to be the main determinant in mode choice, it determines patronage *(P)*, which determines the revenues *(R)* consequently. Please note that fares are assumed to be fixed. Given the level of demand, the benefits for the traveller are found by the consumer surplus term *(CS)*. In terms of costs, operators pay for operating costs and infrastructure providers/public authorities pay for investment and maintenance costs. These aforementioned costs together with revenue yield producer surplus *(PS)* that together with consumer surplus define the level of social welfare *(SW)*. Figure 2-7 illustrates these relationships graphically.

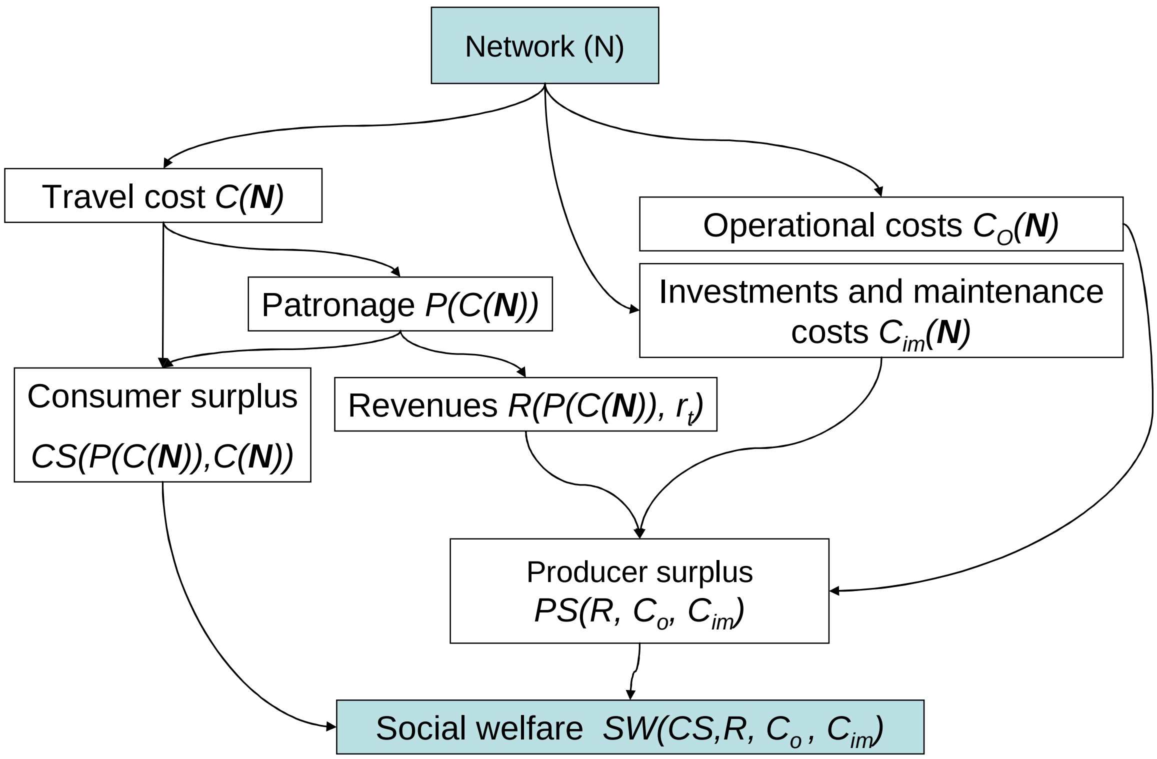

Figure 2-7: Conceptual model of the relationships between the basic network variables and the objective of maximising social welfare

For the objective function of minimising total network costs (C_n) given a fixed level of demand, patronage will be constant consequently. The total network costs consist of travel costs given travel time and patronage, operating costs, investment and maintenance costs. Figure 2-8 illustrates this scheme.

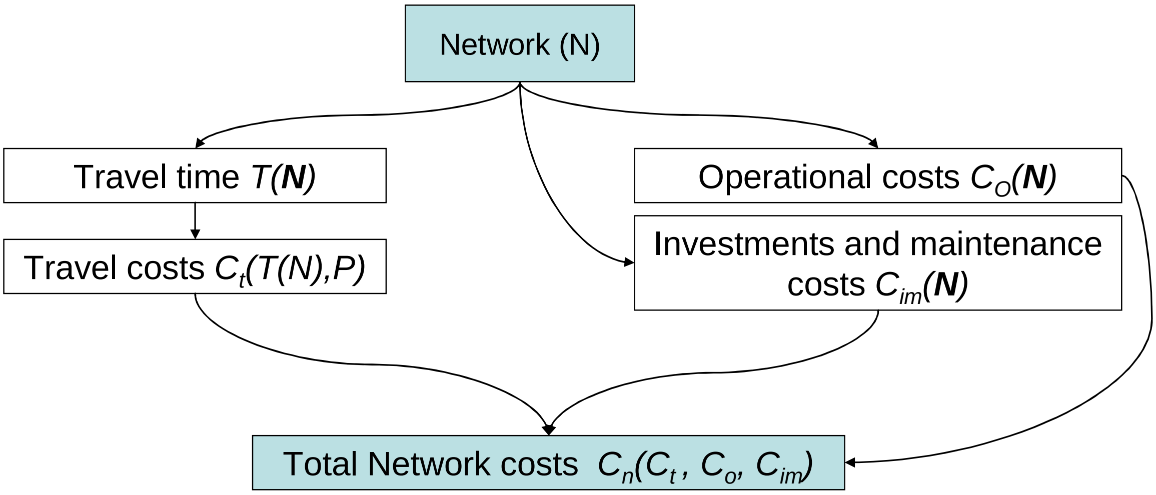

Figure 2-8: Conceptual model of the relationships between the network cost components and the objective of minimising total network costs

2-5-6 Formulating network design objective functions

The aforementioned design objectives can be formulated mathematically as function of a set of variables. In this section we formulate both objective functions (maximising social welfare, and minimising total network costs) mathematically.
Maximising social welfare can be written as the sum of consumer surplus and revenues minus operational costs and infrastructure costs/maintenance costs at an aggregate level:

$$Max\{SW\} = MAX\{\sum_j \sum_k CS(C_{jk}(N)) + \sum_j \sum_k R_{jk}(C_{jk}(N)) - C_o(N) - C_{im}(N)\} \quad (2\text{-}1)$$

Where:
SW= Social welfare
CS= Consumer surplus
C_{jk}= Generalized door-to-door travel costs in the network between origin j and destination k
R_{jk}= Operator's revenues from providing the service between origin j and destination k in the network
C_o= Total operational costs in the network
C_{im}= Total infrastructure and maintenance costs in the network

The approximate consumer surplus CS is a function of total generalised door to door travel cost (C_{jk}) and patronage. It can be approximated by equation (2-2) as follows:

$$CS(C_{jk}(N)) = \int_{C_{jk}(N)}^{\infty} P(x)dx \quad (2\text{-}2)$$

Where:
P= Patronage as a function of generalised costs x

The consumer surplus is the travellers' component in the objective of maximising social welfare. It represents the benefits of travellers who can make their trip with lower costs or shorter travel times compared to their maximum acceptable travel costs or travel time.

Generalised travel cost $C_{jk}(N)$ is a function of travel time components and is formulated as follows (for clarity sake we exclude the indices *(jk)* and *N* in the formulas below):

$$T = \beta_a t_a + \beta_w t_w + \beta_{in} \sum_{y=1}^{n_t+1} t_{in,y} + \beta_{nt} n_t + \beta_t \sum_{z=1}^{n_t} t_{tz} + \beta_e t_e \tag{2-3}$$

$$C = T \cdot VOT + r_t + \alpha =$$
$$(\beta_a t_a + \beta_w t_w + \beta_{in} \sum_{y=1}^{n_t+1} t_{in,y} + \beta_{nt} n_t + \beta_t \sum_{z=1}^{n_t} t_{tz} + \beta_e t_e) \cdot VOT + r_t + \alpha \tag{2-4}$$

Where:
T= Generalised travel time
t_a= Access time to the public transport service
t_w= Waiting time for boarding at the first stop
t_{in}= In vehicle time in the public transport (scheduled)
n_t= Number of required transfers between service lines
t_t= Transfer time (scheduled)
t_e= Egress time from public transport to the destination
β_x= Weight for travel time components
VOT= Average value of time for passengers
r_t= Fare paid by travellers
α= PT mode preference constant

Weights *(β)* account for the fact that travellers have different valuations for the different trip time components. α expressing PT mode preference is used in demand analysis (e.g. mode choice)

Given the patronage function *P* it can determine the revenues for the operator as such:

$$R(N) = \sum_j \sum_k R_{jk}(C_{jk}(N)) = \sum_j \sum_k r_{jk} \cdot P(C_{jk}(N)) \tag{2-5}$$

Where:
R= Total revenue for the transit operator
r_{jk}= Fare paid by travellers per trip between origin *(j)* and destination *(k)*

Producer surplus (*PS*) states benefits for the investor or the transit operator and can be determined as follows:

$$PS(N) = \sum_j \sum_k R_{jk}(C_{jk}(N)) - C_o(N) - C_{im}(N) \tag{2-6}$$

The indicated objective function may have constraints (e.g. budget). A budget constraint can be formulated as:

$$C_O(N) \le B_O \tag{2-7}$$

Where:
B_O= The operational budget

The alternative objective of minimising total network costs is the sum of travellers' costs, operational costs, and infrastructure and maintenance costs. It can be formulated as follows:

$$Min\{C_n\} = Min\{\sum_j \sum_k P_{jk} C_{jk}(N) + C_o(N) + C_{im}(N)\} \tag{2-8}$$

Where:
C_n= Total network costs
C_{jk}= Generalized door to door travel costs in the network between origin *j* and destination k
P_{jk}= Patronage between origin *j* and destination k
C_o= Total operational costs in the network
C_{im}= Total infrastructure and maintenance costs in the network

2-5-7 Synthesis

Given the discussion presented in the previous sections, we conclude that firstly the public transport network design problem is indeed a sophisticated problem. However, there is ample literature addressing the problem by using several techniques such as genetic algorithms. The design approaches that are introduced in the literature are classified into optimisation models, design methodologies, and decision support systems. In all of these approaches, the main assumption is that public transport network characteristics are static and do not vary over time Thus, classical design methodologies do not consider uncertainties in service attributes due to random variations and accordingly service reliability is not a factor in the design procedure.
Furthermore, the existing models predominantly focus on service network design with a given infrastructure. So, the infrastructure network design is not the topic of the classical public transport network design models.

2-6 Summary and Conclusions

This chapter focused on main definitions and fundamental characteristics of classical public transport network design. These definitions and fundamentals are essential to provide the theoretical framework for analysing public transport networks considering reliability. The findings of this chapter will be used mainly in chapter 5 of this thesis for incorporating reliability into the network design problem.

In order to identify the scope of this research with respect to public transport network design we made a distinction between public transport planning levels by categorising network design and planning into three different levels: the strategic level, the tactical level, and the operational level. The focus of this thesis will be on the strategic level and especially the network design problem, however, considering reliability thus implies that operational measures should be incorporated in the analysis.

This chapter also elaborated on the subject of the classical public transport network design problem in general. Simple transport network design was shown to be already a complicated problem. We showed complexities are caused due to several reasons:

- the conflict between view points of the public transport operator and authorities, and travellers;
- design dilemmas raised by accounting for service accessibility;
- the strong interrelationship between travellers' behaviour and network design.

The commonly used objectives for the public transport network design problem dealing with conflicting viewpoints of travellers and operators /invertors are maximising social welfare, and minimising total costs. The former balances the interest of travellers against those of the investor or the operator using the economic principle of social welfare. The second objective focuses on minimising all involved cost components in the network forming total network costs. For both objective functions, there might be some constraints such as operating budget as well.

To deal with the strong relationship between travellers' behaviour and network design, a conceptual bi-level framework according to game theory is used. This bi-level framework is based on an economic perspective. It includes travellers' behaviour and their feedback into network design to improve network performance and to achieve the optimal network.

The bi-level framework, which will be used throughout this dissertation, is a suitable framework for elaboration. In the classical models, there is ample literature to solve the network design problem, whilst the lower level (traveller behaviour) is not discussed completely (Joksimovic 2007; Li et al, 2008 & 2009). Therefore, neither is there descriptive analysis nor is objective regarding travel behaviour in the classical design models.

In the context of public transport network design there are three models addressing the public transport network design problem namely: optimisation models, design methodologies, and decision support systems. In the optimisation models the focus is entirely on designing new networks in which the design objectives are traveller oriented. However, in the design methodologies there are less clear definitions of the objectives and design variables. In the decision support systems model the main issue is to provide feedback on a specific network design based on an assignment of the demand and general design rules.

In all of these models, the main assumption is that public transport network characteristics are constant and do not vary over time. Given the high value of reliability placed nowadays by travellers on travel services this is not a realistic assumption anymore. Public transport networks suffer from variations arising from different sources such as vehicle and devices breakdown, personnel no show, police control, traffic jams in rush hours, diverse driver behaviours and styles, maintenance works, incidents, adverse weather, public events, and calamities.

Besides public transport network variations, public transport demand also varies. Regular sources such as traveller's behaviour and regular demand pattern alterations cause demand variations. Also, there are demand fluctuations caused by external sources such as bad weather, and public events. Thus, the classical design methodologies do not pay attention to random variations and consequently certain degrees of unreliability in upper and lower levels of the bi-level framework.

Regarding these variations, the question is how these need to be considered in public transport network design and assessments? As mentioned in this chapter, the public transport network design methods in classical forms do not consider such variations at all. Hence, in the rest of this thesis we look at public transport network design and assessment more realistically by considering impacts of random variations on transport service network, infrastructure, and public transport demand. These variations are included in the network design problem framework. This inclusion results in a stochastic perspective of public transport network design and assessment.

Therefore, in upcoming chapters 3 and 4 impacts of stochastic variations on public transport networks and consequently network performance will be discussed respectively. Given these effects, the extended public transport network design and assessment scheme with capability of dealing with impacts of random service variations in public transport networks will be described in chapter 5.

3 STOCHASTIC EVENTS IN URBAN PUBLIC TRANSPORT NETWORKS

3-1 Introduction

The design of public transport networks as described in chapter 2 is usually based on a deterministic point of view. All types of input in the traditional design process are assumed to be known exactly and to be constant over time. These are clearly unrealistic assumptions since transport supply varies between hours and over days, while transport demand varies as well. In reality there are a large number of regular and irregular variations influencing trip demand, the public transport service network, and infrastructure.

In order to assess the influence of such variations on public transport networks, in this chapter we identify possible variations and their sources in all transport network layers containing travellers' behaviour, transport service networks, and infrastructure networks. These variations and sources are identified in each layer by means of conceptual frameworks and using empirical findings. For instance, for the travellers' behaviour layer we identify all sources of variations containing choice behaviour variations, demand variations, and demand fluctuations by using an empirical study in the Randstad area in the Netherlands. For the transport service network layer, results of public transport service quality analyses that are recently obtained in the Dutch city of The Hague are studied. For the infrastructure layer we synthesise impacts of variations in infrastructure on transit service performance from a case study in Norway.

With respect to impacts of events on all layers of transport systems, understanding characteristics of random events and ways how they affect network layers is essential. Therefore, we study such events' characteristics qualitatively and categorise events based on key criteria such as time interval, regularity, and predictability.

Due to events' impacts on transit operations there might be remedial adjustments in operation to cope with disturbances and maintain service quality. Depending on the event type and the way it might affect a transit network, operational adjustments may be different. Therefore, in this chapter we study and classify commonly used adaptive strategies that transit operators apply to cope with disturbances in public transport networks regarding the event type. Noticing possible operational adjustments applied by transit operators will enable transport planners to propose appropriate measures at the strategic level of network design for facilitating operating adjustments and improving service performance and reliability.

By recognising the network situation in real conditions when all kinds of events might impact travellers' behaviour, the transport service network, and the infrastructure network, it is possible to assess actual network performance and service quality offered to travellers. Thus, the outcomes of this chapter will provide a valuable basis for determining public transport service quality and network performance in real situations which is the topic of chapter 4.

3-2 Identifying variations in transport networks

As indicated in the introduction, it is a clearly inappropriate assumption to consider all types of input consisting of infrastructure facilities, transport operation characteristics, and travellers' demand as being constant. In this section we identify causes of variations and possible relationships between variations in public transport demand and public transport supply containing service network and infrastructure.

Variations on the demand side and the supply side cause disturbances for travellers and operators in transportation networks. Many sources contribute to these variations. Basically, they might be classified as follows:

- Variations in travellers' behaviour (the demand side);
- Variations in infrastructure quality and availability (the infrastructure supply side);
- Variations in operator's performance (the service supply side).

The above rank order and priority of infrastructure to the service network is due to the fact that infrastructure failure itself could impact service network variations. Figure 3-1 illustrates these variations where a distinction is made between external and internal sources of disturbances.

In the above figure stochastic choice behaviour and demand alterations cause variations on travellers' behaviour. We explain these notions extensively in the next subsection.

Infrastructure supply is impacted by disasters, maintenance activities and external sources of variations. We define *external sources* as factors beyond a public transport operating system causing service alterations from plan. We elaborate on such variations in the infrastructure network in subsection 3-2-2.

In addition to travellers' behaviour and infrastructure supply, the transport service network quality varies due to travellers' behaviour, infrastructure quality, external sources of variations and *internal sources* of variations. *Internal sources* of disturbances are defined as factors inside a public transport operating system causing service alterations from plan. We discuss more on these variations in the transport service network in subsection 3-2-3.

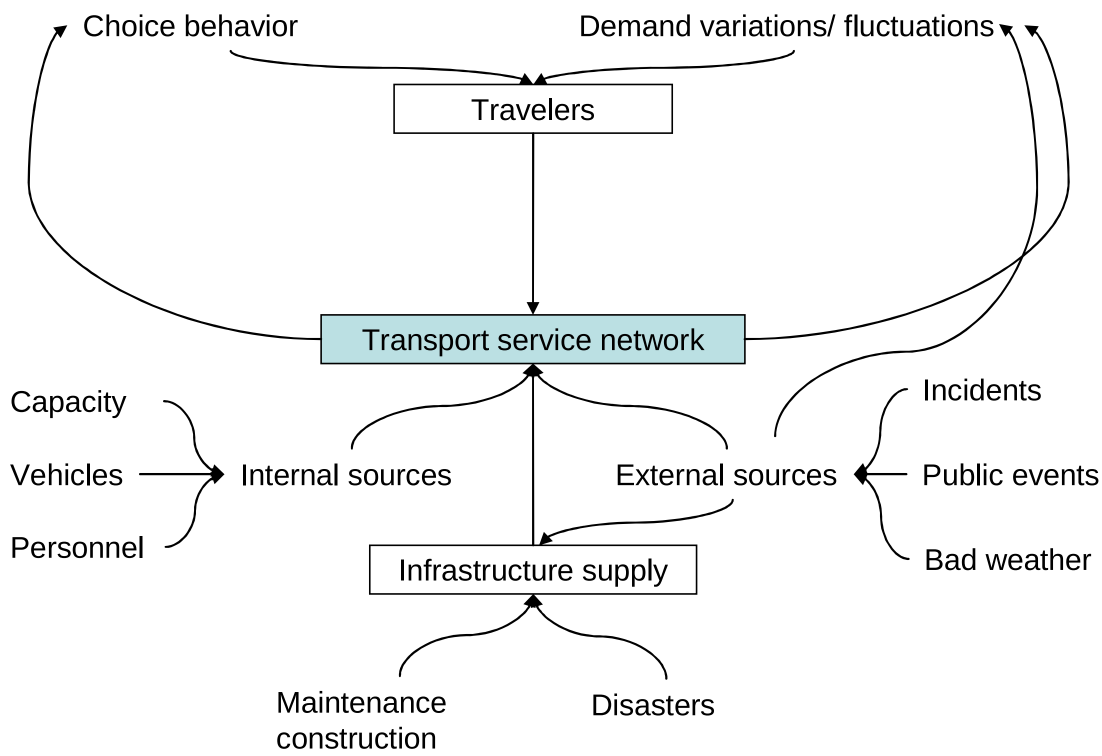

Figure 3-1: Stochastic forces acting on key elements of public transport systems

3-2-1 Variations in traveller's behaviour

The stochastic nature of travellers' choice behaviour is a source of demand variations. Normally, there is randomness in traveller behaviour which can be observed in the departure time choice, mode choice and route choice (Bovy 1996; Nielsen 2000). Of course, these variations in public transport demand will definitely influence public transport quality and its level of services.

Figure 3-1 shows that travel demand is influenced not only by choice behaviour alteration, but also by:

- *Regular travel demand variation;*
- *Irregular travel demand fluctuations.*

We define *regular travel demand variations* as variations that follow predictable patterns whilst *irregular travel demand fluctuations* are defined as variations of which location and time are non-predictable, which are usually caused by external sources such as bad weather. The latter might lead to a huge change in public transport demand level.

Regular travel demand variations over periods of the day, days of the week, and seasons of the year are expected. The validation of these time-based variations is demonstrated using the Dutch Travel Survey and cluster analysis techniques (Everitt et al 2001), despite of the fact that there might be irregular travel demand variations in the survey's database as well. Figures 3-2 to 3-4 show the result of an analysis of public transport demand variations in the Randstad area in the Netherlands. This urbanised area consists of four major Dutch cities: Utrecht, Rotterdam, The Hague, and Amsterdam. It is considered as the Dutch core economic and industrial zone. This analysis has been conducted based on available data for the period between the years 1999 to 2005. Also, a distinction is made between traveller types such as:

- Commuters;
- Shoppers;
- Students;
- Other travellers;

Figure 3-2 illustrates hourly variations in public transport demand in the month of November for working days. This month is chosen intentionally since educational trips are completely made in this month as well. It shows the percentage of hourly demand to the average hourly demand for each user class. The horizontal axis indicates the departure time of trips. As it is obvious, during morning and afternoon peak hours demand for commuting and educational trip purposes increases dramatically, whereas shopping trips often take place during off peak hours.

Figure 3-3 shows daily variations in public transport demand in the month of November. It shows the percentage of daily demand to the average working day demand. Similarly, the outcomes demonstrate that there are some significant variations in public transport demand day by day and especially for shopping and educational trip purposes. Of course, daily variation is quite smaller than hourly variation.

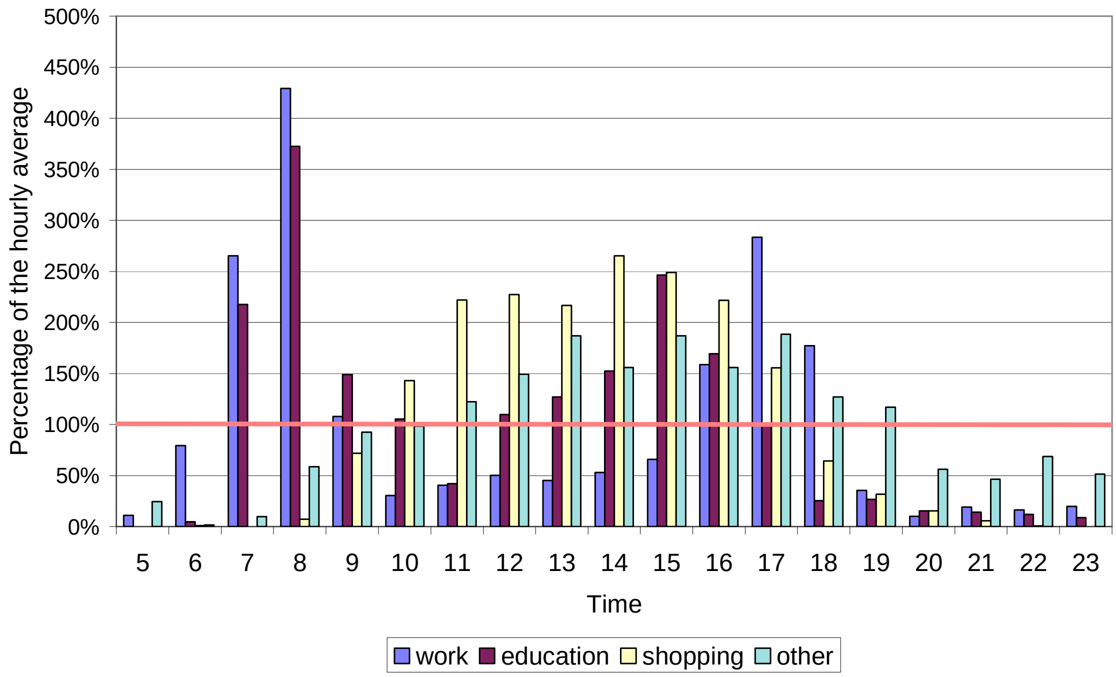

Figure 3-2: Hourly variations in Public transport demand (Randstad Area, 1999-2005)

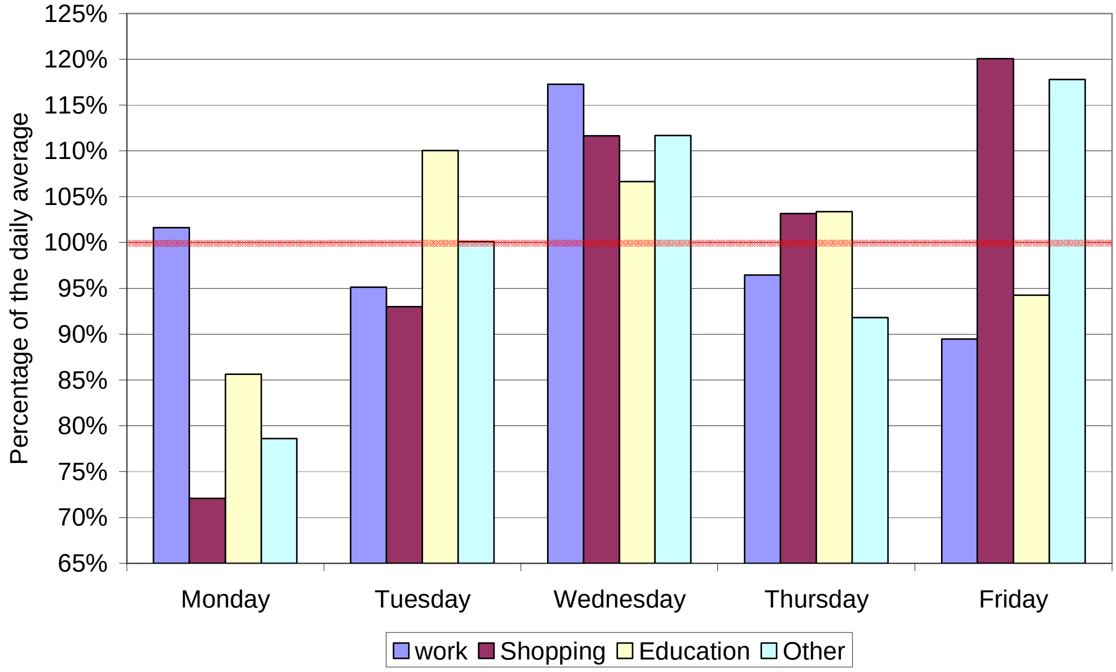

Figure 3-3: Daily variations in public transport demand (Randstad Area, 1999-2005)

Figure 3-4 illustrates seasonal variations in public transport demand. It shows the demand percentage in each season to the seasonal average demand for each travel purpose. The results demonstrate that there are some sensible differences in public transport demand seasonally especially for educational and other trip purposes. Given these results, it is obvious that seasonal variation is higher than daily variation since it reaches up to 150% of average trip demand.

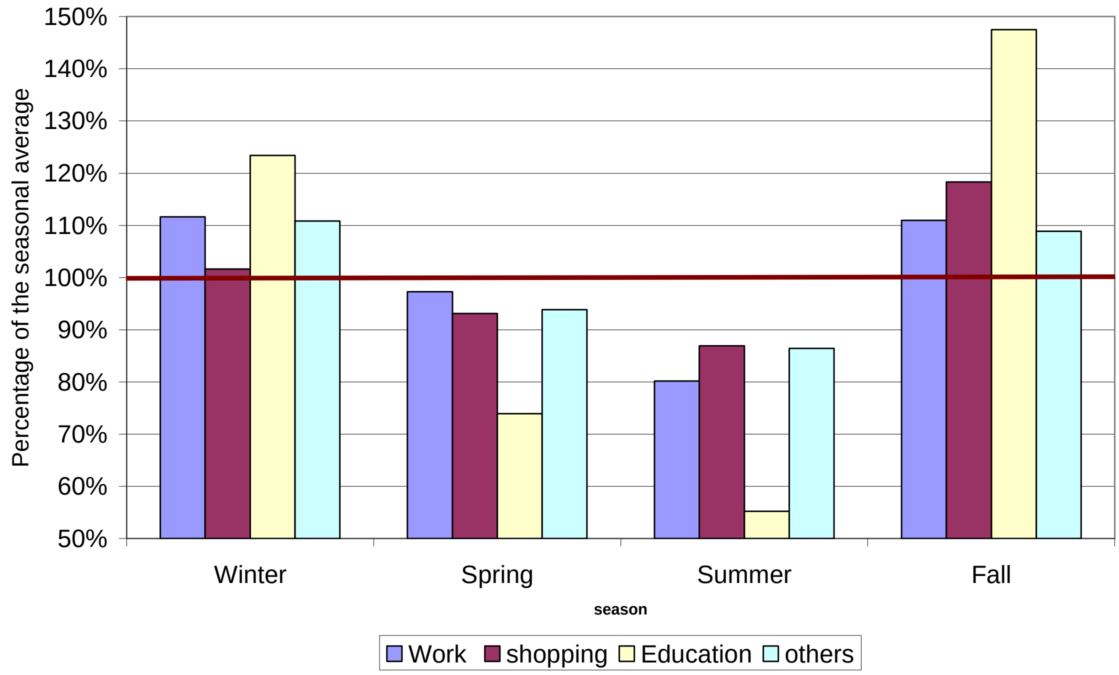

Figure 3-4: Seasonal variations in public transport demand (Randstad Area, 1999-2005)

As mentioned previously in studying trip demand variations irregular demand fluctuations that arise due to some external events are a source of travellers' behaviour variations. Demand fluctuations are irregular demand alterations which do not follow an expected regular pattern. For instance, some events such as bad weather and public events influence traveller's mode and route choice decisions and cause significant increase or decrease in public transport demand at the time of happening. In case of bad weather, cyclists normally shift to either their private cars or public transport. Thus, the demand of public transport increases accordingly. If a metro network is available, in case of bad weather the other travellers might use it temporarily due to more convenient and reliable services. Hence, there is huge rise of metro network demand. Also public events, such as festivals, carnival, and ceremonies attract many people to certain locations that obviously increase transport demand as well (Hendren 2006). In cases such as public events, the public transport network might be an attractive option because of the lack of traffic jams and parking problems. This increases public transport demand.

These examples demonstrate that public transport demand is expected to suffer from variations usually caused by external phenomena. However, there are empirical evidences emphasising this idea too.

An empirical study by Khattak & Le Colletter (1994) investigates the propensity of auto commuters to switch to public transportation in response to unexpected traffic congestion in the Golden Gate bridge corridor in San Francisco. Their study shows that unexpected situations increase public transport demand especially when travellers are already aware of events consequences. As many as 18.3% of respondents stated that they would switch to public transportation, if suggested to do so by a pre-trip notice. Potential switchers were found to be more frequent transit users than others, have no highway to divert to as an alternate route, experience more recurrent congestion at the entrance of the Golden Gate Bridge, and have shorter transit travel times. The cause of the unexpected congestion also influenced the propensity to switch to transit, accidents inducing less people to switch than adverse weather. Table 3-1 outlines the shift rate to public transportation by the event type.

Table 3-1: Percentage of stated diversion to public transportation in Golden Gate corridor, San Francisco (Source: Khattak & Le Colletter 1994)

Irregular event type	Stated propensity for diversion to public transport
Construction / Road work	14.7%
Accident	15.9%
Bad weather	25.5%
Other / unknown	23.7%

The stated propensities are rather naive and might not be quiet correct, since the capacity of public transport networks has not been considered. The question is how much is relative increase in public transport ridership feasible considering limited capacity of public transport in US?

Although this stated choice data is not very convincing and also might not be applicable for European cities, it justifies that transit demand suffers from alterations caused by three factors, namely travellers' behaviour, regular transit demand variations, irregular transit demand alterations. Therefore, transit planners should consider these factors in order to have a realistic perception of transit demand.

3-2-2 Variations in infrastructure networks

An implicit requirement in public transport network evaluation studies is that the necessary infrastructure is available with appropriate quality. Here, transit infrastructure might consist of equipments such as ticket machines, traffic control and monitoring systems, tracks, vehicles, switches, interlocking systems and other safety devices. Additionally, public transport services often share infrastructure with other modes, while in the case of dedicated infrastructure there are still crossings with other traffic.

If infrastructure elements fail due to events, the transport service network can no longer use the failed infrastructures and consequently service operation might be temporarily halted. There is scarce evidence about impacts of infrastructure failures on service quality for urban public transport networks. Veiseth et al (2007) performed an analysis for the interurban rail network in Norway. They show that infrastructure faults are a major source for delayed and cancelled trains. More than 30% of the total amount of delay hours in Norwegian trains in 2005 was caused by infrastructure failures. This number can be split into five subcategories: track, signal (including safety and communication systems), power supply, planned work, and blocked tracks, as shown in table 3-2.

Table 3-2: Infrastructure related delay hours registered in Norway in 2005 split by infrastructure failure category (Source: Jernbanverkt 2005)

Infrastructure failure type	Delay (Hours)
Track	552
Signal	1911
Power supply	624
Planned work	753
Blocked track	278

Infrastructure may suffer from impacts of external events. Thus, it is possible that some part of infrastructure is blocked for a while due to an external event. By referring to figure 3-1, external conditions such as bad weather, incidents, and public events are factors which may block the right of way or increase the probability of infrastructure failures (Schmocker & Bell 2002; Yin & Ieda 2001; Immers et al 2004, 2009). For instance, storm can hit the transit power supply, ice can hamper interlocking system performance and a heavy snow can block tracks and roads. In these conditions, rail bound transport networks might not use the affected infrastructures until repairing activities are done.
Another 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 e.g. sewers, cables, et cetera. Please note that it is possible to schedule these kinds of maintenance activities in such a way that their impacts on transportation networks are minimised in terms affected service frequency (Higgins et al 1999).

In case of right of way blockade due to external conditions such as snow or incidents a bus network can also be affected. However, there is a difference between infrastructure failures in road bound transport and rail bound transport. Infrastructure failures may affect a road either partially or completely. For instance, the capacity of a two lane road might be halved, if one lane is blocked due to road maintenance. This causes traffic congestion and delays in a part of road network; however, it does not cause a full road shut down. Thus, the impacts on private car users as well as road bound public transport (e.g. bus) might be limited.

However, in rail bound public transport the situation is different since track blockades take place completely. If there is a blockade in a part of the rail network, the affected track is out of service fully. Thus, those service lines of the public transport service network using that link shut down until it retrieves. Therefore, rail bound public transport using the affected link(s) might no longer be operated and thus the influence of infrastructure failures are relatively more severe on rail bound public transport than on road bound public transport.

3-2-3 Variations in transport service networks

In addition to variations in infrastructure, the transport service networks might be affected by events as well. Different sources of disturbances consisting of internal sources and external sources may affect transport service networks.

In general public transport services have their own variations in service quality. Different driver behaviour, equipment breakdown, fleet or staff shortage, and staff no-show are main internal sources of service variations (Muller & Knoppers 2005; Van Oort & Van Nes 2006). For example, consider the London public transport system. London Underground Limited reports that they cancel on average 5% of all services almost every day caused by internal disturbances and this rate is even higher during the morning peak period (Shimamoto 2007). At national level the Norwegian study by Veiseth et al, (2007) shows that 5820 hours delay registered in Norwegian trains in 2005 are caused by operational variations and failures. This rate is about 37% of total delays due to all kinds of delay causes in Norwegian trains.

External sources are factors affecting service operations that are beyond the control of the public transit operating system. Referring to figure 3-1 once again, we can observe that external factors such as incidents and bad weather not only impact infrastructure, but they may influence also the transport service network. Bad weather may reduce trains and buses' speed. Otherwise, tubes suffer less from bad weather consequences compared to other transit modes. Incidents are other external factor causing variations in service network quality. For instance, the same study in London Underground shows that more than 50% of the services are cancelled in case of a major incidents (Shimamoto 2007).

Road traffic jams during rush hours are the other external factor causing transit service variations. Van Oort & Van Nes (2006) measured running times of bus lines in city of The Hague in the Netherlands. They found that during rush hours travel times of a tangential bus line with 6% exclusive right of way increases around 12 % and travellers suffer from 43% increase in average waiting time. For a transversal tram line with similar length and 100% exclusive right of way, these values decrease down to 5% and 21% respectively. Furthermore, the length of the service line is a decisive factor influencing impacts of external events on services. In other words, longer service lines which normally consist of longer and larger number of links are more vulnerable for external conditions than shorter lines. This is an obvious phenomenon since long lines are highly in exposure of events' consequences compared to short lines.

3-2-4 Synthesis

The aforementioned discussions show that stochastic events consisting of internal sources and external sources of disturbances may affect the entire public transport system containing travellers as the demand side, and transport service networks and infrastructure as the supply side. Impacts of events on infrastructure can affect the transport service network as well. In case of infrastructure failures, transport services might face disturbances and loss of quality.

So far we identified probable variations that influence public transport networks. In analysing variations in transport network layers (travel demand, the transport service network, infrastructure supply), the important issue is that disturbances and consequent level of service variations depend on event type. Each type of event with its own specific characteristics may affect transport networks differently.
Therefore, it can be concluded that understanding the characteristics of stochastic events and classifying them according to their characteristics are key aspects to assess public transport network performance in the stochastic perspective. In the next part stochastic events are classified based on their principal characteristics.

3-3 Classification of stochastic events

In order to measure impacts of stochastic events on public transport services and distinguish remedial solutions applied by transit operators to mitigate disturbances, the influential characteristics of events should be determined. There are ample literature describing disturbances in transport networks (Garib et al, 1997; Chattopadhyay 2005; Muller & Knoppers 2005; Schreuder et al, 2007); however, scarce studies distinguish and classify events according to their impacts on public transport services. Therefore, in this section we categorise stochastic events explicitly according to their impacts on public transport networks and the ways transit operators mitigate their consequent disturbances.
Our classification is built up from the following three dimensions (axes), namely:

- Event’s frequency;
- Event’s predictability;
- Event’s regularity.

In addition to the above dimensions, *severity* and *spatial extensions* are other criteria which could make distinction between events. However, these two criteria are not applicable for all kinds of events. They are mostly suitable for events with low degree of regularity. Events can also be categorised according to their sources. However, such categorisation does not express ways they impact transport networks and therefore is not relevant very much.

Event’s *frequency* is defined as the number of occurrence of a repeating event per unit time. Our categorisation is as follows:

- Frequent events;
- Semi-frequent events;
- Low frequent (occasional) events.

Some events take place frequently (e.g. once per day) in transport systems such as traffic jams during rush hours or vehicles breakdown, whereas other events such as calamities or major incidents happen occasionally (e.g. once per year). Also, there are events that take place semi frequently (e.g. once per month) in the network such as minor incidents or traffic light failures (Schreuder et al, 2007).

Additionally, events can be distinguished based on their degree of *predictability*. *Predictability* refers to the degree that a correct prediction or forecast of a system’s state reasonably can be made either qualitatively or quantitatively. Events classification based on the degree of predictability is:

- Predictable events;
- Unpredictable events.

Some events are reasonably predictable with a high degree of accuracy. *Accuracy* is defined as the degree of closeness of a measured or calculated quantity to its actual value. In weather forecast the perception of times that the forecast made a perfect prediction as to what the weather would be, determines the forecast accuracy. Hansen & Hansen (2007) studies the internet weather forecast accuracy. They classify commonly used web based weather forecasters according to the prediction accuracy and the time of prediction in advance (Table 3-3).

Table 3-3: Accuracy rank groupings for short (0-4 days previous), mid (5-6 days previous), and long term (7-9 days previous) weather forecasts (Hansen & Hansen 2007)

Online Weather Channel	Average accuracy rank grouping		
	0-4	5-6	7-9
The National Weather Service	4	3	
BBC Weather	10		
The Weather Channel	1	4	1
The Weather Underground	7		
IntelliCast	5	6	2
CNN Weather	2		
MSN Weather	9	4	4
The Weather Network	8		
Unisys	3	1	
Accuweather	6	2	3

Finally events can be categorized based on their level of *regularity*. We define regularity of an event as normal manner of events affecting transport networks. In other words, regular events which take place quite often relate normal or inherent behaviour of transport systems. Regular events cause minor disturbance in transport networks which partly deviates from the original plan. Irregular events are events that take place abnormally in transport systems in terms of pattern and occurrence expectation and generate large disturbance in transport networks which deviates substantially from the original plan. Depending on events' degree of regularity, we divide the consequent disturbance into:

- Minor quasi continuous ongoing;
- Major discrete.

Some variations in public transport services arise due to regular events such as regular demand variation, and traffic jam. They cause reasonably expectable varying conditions. For instance, regular travel demand variations, and regular traffic jam during rush hours are examples of regularly expected variations. We define *minor quasi-continuous ongoing events* as regular ongoing events which take place in pre-defined patterns and cause minor variations in public transport networks.

Minor variations in the transport supply layers as well as transit demand may be dealt with by responsible authorities. These variations take place continually and cause usually slight variations in service performance. For instance, minor events such as minor incidents or traffic jams cause small variations in infrastructure quality or services that can tackled by public authorities or operators respectively.

Besides minor continuous ongoing events, there are major distortions that arise due to *major discrete events*. We define major discrete events as events that take place in transport networks normally without any predefined pattern and cause major distortions in the network.

For instance, a major accident is a specific type of incident that normally involves human injury or casualty. A major traffic accident may cause an unexpected situation in the network such as huge traffic jam behind the location of the accident. It is not a planned closure of a road nor a special event; therefore, there is no in advance notice. Other incidental phenomena include vehicle breakdowns, natural disasters, extreme bad weather, vast failures of traffic control devices for example due to electricity outage , and those caused by humans (e.g. public events).
Major discrete events can cause large variations in network performance. For example, extreme bad weather or major accidents cause inevitable distortions in the network. This is the case for the demand side as well. Transit operators usually plan services to deal with regular demand variations. For instance, they increase service frequency during peak hours. However, in some cases such as a huge rise in transit demand (e.g. due to a public event), the transit operator may not be able to cope with events' impacts.

Given the above discussion, it is concluded that regularity of events play the key role in determining impacts of events on transport networks, albeit other criteria consisting events' frequency and events' predictability influence as well. Table 3-4 categorises several common events based on all aforementioned criteria. In order that this table is digestible, we show quantitative indications for some events. The results of an experiment study (Tahmasseby et al, 2007) show that on average the frequency of minor incidents is approximately 450 times per year (1.2 times per day); whilst, it drops to 50 times per year (0.13 times per day) for vehicle breakdown. For major construction activities it decreases to 4.2 times per year. Hence, we can see that dissimilar events with diverse level of predictability and frequency impact transport networks differently.

Table 3-4: Event classification based on severity, time intervals and predictability

<table>
<tr><th colspan="2">Minor ongoing continuous events</th><th colspan="2">Major discrete events</th></tr>
<tr><th>frequent events</th><th>semi frequent events</th><th>Semi frequent events</th><th>occasional event</th></tr>
<tr><td>Traffic congestion during rush hours*</td><td>Minor maintenance works</td><td>Irregular transit demand fluctuations</td><td>Major incidents</td></tr>
<tr><td>Bad weather conditions: Heavy rain, Fog, Light Snow, Heavy Wind</td><td>Police control</td><td>Failure in rail traffic control devices</td><td>Calamities</td></tr>
<tr><td>Regular transit demand variations</td><td>Failure in traffic lights</td><td>Vehicle breakdown</td><td>Extreme bad weather condition: Heavy snow, Storm, Ice, Thunderstorm</td></tr>
<tr><td rowspan="2">Minor incidents</td><td rowspan="2">Lateness of personnel</td><td rowspan="2"></td><td>Major construction activities</td></tr>
<tr><td>Public Events</td></tr>
</table>

**Gray cells indicate higher level of events' predictability in terms of accuracy*

3-4 Major discrete-event characteristics

In analysing public transport service quality regular quality variations caused by minor continuous ongoing events are generally implicitly accounted for. Public transport operators are aware of slight service quality variations and transit demand and therefore they usually consider spare capacity in operational aspects (e.g. timetable). However, impacts of large variations in infrastructure, service quality and transit demand due to major discrete events should be studies explicitly. The characteristics of events and ways they impact transit networks including infrastructure are two important aspects to determine service quality variations. In this part, the characteristics of some major discrete events and ways how they impact on public transport networks are discussed.
Service quality variations caused by major discrete events in public transport networks depend on the characteristics of the events. The main characteristics in addition to time interval and predictability are duration and location and severity. Depending on these characteristics, ways events influence transport networks and generate disturbances are identified, and thus impacts of an event on transport networks can be found out.
We define event's *duration* as the time period between the occurrence and clearance of disturbance caused by an event. Events' *severity* is defined as the quality or condition of events being sever specifically strictness. Basically, events' degree of severity is diverse even for the same type of an event. For example, the severity of storm (hurricane) is determined by the Saffir-Simpson scale (US National Weather Service 2009). It is a 1-5 rating based on the hurricane's present intensity. This is used to give an estimate of the potential property damage and flooding. Wind speed is the determining factor in the scale. The severity of incidents is basically determined by two factors: injuries and fatalities. Depending on whether an incident leads to injuries or fatalities, the time for eliminating the blocked caused by the incident varies. Also, when the police report is required for an incident, the incident position must not be changed which increases the blockade time.

Thus, the criteria that determine impacts of major discrete events on public transport service performance are:

- events' time interval (frequency);
- events' duration;
- events' location;
- events' predictability.

Excluding special events causing calamities (e.g. earthquake) there are some major discrete events that can take place in several types of public transport network and can result in irregular disturbances in the network. These types of events are listed as follows:

- major incidents (e.g. accidents, infrastructure failures);
- extreme bad weather conditions such as storm, ice, snow, and thunderstorm;
- public events;
- vehicle failures;
- traffic control devices failures;
- road works.

Table 3-5 classifies these events according to the aforementioned criteria. Since events' severity is not fixed even for the same event type, it is excluded from the classification. But, disturbance location expresses events' severity indirectly. When the disturbance location is vast, for some types of events such as incidents may show that the event is sever.

Table 3-5 shows that incidents, bad weather, vehicle failures and road works have clearly different characteristics in terms of frequency, duration, location, and predictability. For instance, failures in transit vehicles and traffic control devices might occur with shorter time interval compared to other events. Table also shows that the duration of road works is longer than other events.

Table 3-5: Classifications of common major discrete events according to principal criteria

Event type	**Frequency**		**Duration**			**Location**			**Predictability**	
	High	Low	1 or 2 hours	Daily period	Days or weeks	Link/ crossing	A part of transport network	Whole transport network	Yes	No
Major Incidents		✓	✓			✓	✓			✓
Storm		✓		✓				✓	✓	
Black ice		✓		✓				✓	✓	
Snow		✓		✓				✓	✓	
Thunderstorm		✓		✓			✓		✓	
Public events		✓		✓		✓	✓		✓	
Vehicle failures	✓		✓				✓			✓
Traffic devices failures	✓		✓			✓	✓			✓
Road works		✓			✓	✓	✓		✓	

Events might be correlated in time or space. Local circumstances influence incidents (Schreuder et al 2007). For instance, the probability of incidents may increase during bad weather conditions. This relationship is not straightforward; the weather influences the frequency of road accidents by affecting both the volume of traffic, and therefore the number of road users exposed to risk, and the risk per unit of travel (Codling 1974). The adverse weather influences public transport incidents as well. Although there is scarce source of weather related incidents in level of urban transport, in the national level the WIST Report (2006) expresses that between 1995 and 2005, 865 weather-related accidents or incidents occurred on America's railways, causing 8 deaths, 1,242 injuries, and property damage costs of more than $189 million. The correlation between bad weather and road works is the other issue of events correlation. The probability of road works increases substantially after extreme weather conditions such as snow or storm due to damaged infrastructure.

Other than frequency and duration of events, the events' location is an important factor determining the severity of disruptions. Depending on types of events there is a distinction between the areas that are affected. Some events such as incidents, thunderstorms, public events, and vehicle failures affect network partially, while other type of events such as snow and storm might influence the entire network. Incidents, with a limited influenced area usually obstruct a link and thus cause minor disruption in the network for a short time. Although, depending on the location of the incident consequences might vary and even be vast. If the area in which an incident happens is a key location in terms of transportation such as a terminal, it is possible that many lines are no longer able to be operated.

Meanwhile, in terms of events impacts, there are some differences among areas. Some areas are more vulnerable for particular event's occurrence such as the incident, bad weather, and road work. Thus, the probability of events may rise for them. For instance, junctions that are designed without fulfilling engineering safety guidelines usually suffer from larger number of accidents compared to well engineering designed junctions. Also, bad weather such as flood, ice and snow has severe impacts on transportation at bridges tunnels, and curves. Since these structures require to be checked frequently, probability of construction and maintenance (e.g. lighting, sanitary facilities, etc) is higher for them compared to other network parts.

Finally, major discrete events can be distinguished based on their level of predictability. Adverse weather is usually forecasted beforehand at detail level (e.g. daily and in scale of towns). For instance, Yahoo Weather can forecast the weather condition for five days in advance in city of Delft in the Netherlands. Public events are also predictable since their program is announced in advance (e.g. several months ago). For major road works, the constructor asks the public authority for permit beforehand and accordingly the plan is publicised for public for example by using billboards near the construction zone. Thus, for predictable events transit operators can coordinate and manage services accordingly. This leads to reduction in events' impacts on transit operation.

In summary, three conclusions are drawn from the above discussions:

- Different event types impact differently on public transport networks including infrastructure;
- Different locations have different vulnerabilities to major discrete events;
- Disturbances in different locations may impact public transport network performance differently;
- Some events are reasonably predictable and thus it is possible to weaken their impacts on transit operation by using appropriate preparations.

3-5 Estimating time interval and duration of events

In order to assess impacts of major discrete events on service quality and network performance realistically, the time interval as well as events' duration in each part of the network should be determined correctly. Time interval and duration of events can be estimated based on statistical information. Obviously, positive time distributions have to be chosen to estimate time interval and duration of events. Some typical patterns are Poisson distribution, Exponential distribution, Gamma distribution, and Log normal distribution. The Poisson distribution is a discrete probability distribution that can expresses the probability of a number of events occurring in a fixed period of time, whilst the other probability distributions are a class of continuous probability distributions that can describe the time interval and duration of events. For instance, the exponential distributions are a class of continuous probability distribution describing the times between events in a Poisson process i.e. a process in which events occur continuously and independently at a constant average rate.

There are ample empirical evidences demonstrating that time intervals of events can be fitted to exponential distributions. Tsakiris & Agrafiotis (1988) show that the time interval between successive snow and rain fall follows an exponential distribution. Chattopadhyay et al, (2005) focus on identifying the factors influencing rail degradation, developing models for rail failures. They also model the time interval between rail breakdowns. Their model clearly shows that the time interval between rail breaks adequately can be simulated by using exponential distributions.

Similarly, empirical evidences show that event durations may be fitted to lognormal distributions. Golob et al. (1987) analysed data from over 9,000 accidents involving large trucks and combination vehicles collected over a two-year period on freeways in the greater Los Angeles area. They found that accident duration fitted a log-normal distribution. Their findings have been confirmed by Giuliano (1989). She extended the research of Golob et al. by applying a log-normal distribution in the incident duration analysis of 512 incidents in Los Angeles. Other papers that present complementary statistical analyses of incident duration include Wang (1991), Sullivan (1997), Cohen & Nouveliere (1997), Garib et al. (1997), Smith & Smith (2000), and Fu & Hellinga (2002).
Wu et al (2006) simulate bad weather event sequences such as rainstorm by stochastic models using spatial and temporal statistical properties of rainfall process extracted from available records. Their model demonstrates that a log normal distribution is a relevant option for representing bad weather durations. Similar findings had already been stated by Heneker et al, (2001).

3-6 Events’ impacts on public transport operation

In this part we study impacts of different types of events on transit operation. Recognizing the impacts of events on transit operation will enable the transit planner to distinguish adaptive operational adjustments usually applied by transit operators for tackling disturbances in the network and thus to consider suitable measures in network design to facilitate adjustments.

Generally, not all types of events may lead to problems for transit operation. Depending on the event type, the disturbance level varies. In case of minor ongoing quasi-continuous events, service disturbances usually are limited to service running time variations as well as to timetable variations. Variations might arise due to alterations of speed as well as dwell time. Different driver behaviours and driving styles may lead to slight changes in service run times. Most of traffic accidents are minor and their impacts on service running time are minor, since link blockades could be easily and quickly eliminated from the network. An interview with the HTM, public transport service provider in The Hague, showed that bus services suffer from 2,500 accidents per year, of which only 12% have quite a long duration because of bodily injuries (HTM 2004).
In case of minor ongoing quasi-continuous events the actual timetable also might be different from the planned timetable. Service variations in headways, dwell times, layover times, departure times, and arrival times are expected in such conditions. These variations can be measured by criteria such as punctuality and irregularity, although impacts of major discrete events might be included in these criteria too. We will elaborate more on this issue in chapter 4 of this dissertation.

However, in case of major discrete events service disturbances are observed not only in service running time variations, but also in the service line itinerary as well as the associated service frequency. During adverse weather conditions drivers run vehicles carefully and proceed slowly. Moreover, due to high increases of transit demand, dwell times take longer. Thus, service running time increases substantially which might lead to missing the service schedule and decreasing service frequency. In case of right of way blockade due to for example incidents or road works, services might be operated via a detoured path to avoid blocked paths. Or the service line might be split into two parts. Consequently, some stops might not be served. In section 3-7 we elaborate more on service adjustments applied by transit operators.

With respect to these phenomena, it can be concluded that determining the impacts of major discrete events on transport networks needs exclusive models in which location, time interval, duration, severity of events and possible correlations among these are accounted for. Due to existing complexities and disturbance correlations, simulation could be a suitable technique to deal with such types of service variations.

There is a clear difference between vulnerability of different public transport types to events. For instance, tram services have more dedicated infrastructure and have a smaller infrastructure network than bus services. Thus, the number of disruptions is clearly lower for tram service networks; however, the impact might be more severe.
Bus networks benefit from more flexibility since most of the road network could be used in case of emergency. This characteristic of transport networks is named "*Network Flexibility*" (Immers et al 2004, 2009). Network flexibility is defined as the capability of the transport system to carry out more and other functions than it was originally designed for. Flexibility then is the property enabling a system to evolve with new requirements. We will elaborate more on this issue in chapter 5. Table 3-6 outlines the sensitivity of different public transport networks to some major events as judged by us. The table shows that uncovered urban public transport networks such as bus and tram are more vulnerable to common events than covered urban public transport networks such as metro and interurban public transport networks such as train networks.

The discussion above demonstrates that changes in transit operation and thus service quality are more critical for the urban public transport networks than for other public transport networks. This motivates transit planners to evaluate urban public transport service performance under disturbances caused by major discrete events when service reliability is concerned. In the following section we will discuss how transit operators mitigate transit services according to the disturbance type. Thus, we will categorise the strategies which are applied by transit operators to cope with events' impacts

Table 3-6: Vulnerability of Public transport networks to events

Event type	(shared ROW) Bus, Taxi	(Partial Exclusive ROW)Tram, Trolley Bus	(Fully Exclusive ROW) Metro (tunnel)	(Fully Exclusive ROW) Train
Bad weather	(+) Delays due to traffic jams, and applied detours	(+) Delays due to probable detours, and speed reduction	(O)	(+), speed reduction
Extreme bad weather	(+) Delays due to traffic jams, and applied detours	(+) Delays due to probable detours, and speed reduction	(O)	(+)
Calamities	(+) Delays due to traffic jams, and applied detours	(+) Delays due to probable detours, and speed reduction	(+) out of service	(+)
Public events	(+) Delays due to traffic jams, and applied detours	(+) Delays due to applied detours	(O) if they are in operation	(O)
Road works	(+) Delays due to traffic jams, and applied detours	(+) Delays due to applied detours, if they are in operation	(O,+) if they are in operation, possibility of frequency reduction	(O,+) if they are in operation, possibility of frequency reduction
Failure of traffic control devices	(+) Facing traffic jams, buses may miss the prioritizing system	(+) Missing the prioritizing system	(+) out of service	(+) out of service
Failure of road traffic signal	(+) Facing traffic jams, missing prioritizing system	(+) Missing the prioritizing system	(O)	(O)
Vehicle breakdown	(+) On board passengers can alight and wait for the next service	(+) Delays, The services using the affected segments will be stopped until the broken-down vehicle is removed	(+) Delays, The services using the affected segments will be stopped until the broken-down vehicle is removed	(+) Delays, The services using the affected segments will be stopped until the broken-down vehicle is removed
Accidents	(+) Delays due to traffic jams, and applied detours	(+) delays due to probable detours	(O)	(O)
Irregular demand fluctuation	(+) Delays due to increasing service running time	(+) Delays due to increasing running time	(+) Delays due to increasing running time	(+) Delays due to increasing running time

Signs descriptions: Affected: (+) Less affected or not affected: (O)

3-7 Transit operator adjustments

With respect to stochastic events and consequent disturbances in transit networks, transit service providers usually try to cope with disturbances and maintain transit service quality as good as possible. In this section we intend to categorise strategies used by public transport operators to deal with impacts of stochastic events.
Generally, transit operators apply service adjustments according to type and consequent impacts of events on the network. Depending on the event type in terms of regularity, operational adjustments are different. In case of minor ongoing continuous events the applied strategies focus on *speeding up* and *slowing down* services (Gifford et al, 2001; Chang et al, 2003; Banks 2004; Van Oort and Van Nes 2007). By applying these strategies the operator tries to adjust the affected services within their running. For instance:

- skipping stops for delayed and/or overloaded vehicles;
- giving priority to delayed public transport services;
- slowing down early vehicles;
- giving delay to early public transport services.

We will elaborate more on these tactics in chapter 5.

In case of major discrete events, transit operators try to maintain services and restore them quickly. As such, it is likely that they attempt to weaken the events' impacts by applying appropriate service remedies. In urban public transport networks remedial solutions are limited to the following options:

- implementing detours;
- applying partial services, splitting the usual line and using short turn;
- skipping services partially;
- halting services temporarily/ skipping runs.

Meanwhile to keep service quality as much as possible compatible with original plan, the operator might execute the following tactics too:

- deploying extra services;
- keeping service frequency as usual by using the extra vehicles.

Implementing detours to avoid a blocked path is a commonly used strategy. Thus, public transport services will be maintained as effectively as possible by diverting the path using the available infrastructure. For bus services such a detour might be easily feasible, while for rail bound transport services the options for detours are likely to be limited. Naturally, due to such detours some stops may not be served during the disturbance.
Applying detours as a remedial solution can affect operating costs as well. Detoured services require additional driving time and thus additional operating costs. Therefore, operational consequences might limit the possibilities for operators. For instance, before applying a detour, operators might consider a detour criterion; for example, a certain maximum for the ratio of the total running time of the line including detours to the normal running time. We will elaborate more on this issue in chapter 7.
Applying partial services is another commonly used solution, especially when there is no possibility for applying a detour. In this case the scheduled services are limited to a shorter service line or might even be split in two different parts, depending on the location of the disturbance. In this case some part of the service line might be skipped due to applying partial services or splitting the service line.

In severe conditions it is likely that some services need to be skipped from the schedule; for instance, in case of multiple disturbances along a service line, or in the case of disturbances due to extreme weather conditions or calamities. In this condition, travellers have no other option than to use a different transport mode or to postpone their trips.
In case of some kinds of events such as public events (e.g. exhibitions, athletic tournaments, festivals, carnivals, etc), operators might establish dedicated extra services to maintain a proper level of service. Normally, these extra services will be operated between the event's location and major points of the city such as the central station and the city centre.
Furthermore, operators might try to keep the regular service frequency. In case of bad weather conditions running speed will reduce, while dwell time at stops will increase as well due to higher public transport demand. This leads to an increase of service running times. A case study in Ireland shows that bad weather increases service running time around 15 % per run (Hofmann & Mahony 2005). In order to keep the service schedule as unaffected as possible, the operator might deploy extra vehicles (if they are available). Please note that this strategy for example in bus services may be applied in case of vehicle breakdown as well. Table 3-7 summarises the operating remedial solutions in urban public transport networks for different event types.

Table 3-7: Operational remedial solutions for major discrete events

Event type	**Operating remedial solution**			
	Line detour	Partial services	Dedicated services	Extra vehicles
Incidents	✓			
Storm	✓	✓		✓
Black ice	✓	✓		✓
Snow	✓	✓		✓
Thunderstorm	✓	✓		✓
Public events	✓	✓	✓	✓
Vehicle breakdown	✓			✓
Traffic control devices failure	✓	✓		
Road works	✓	✓		

Applying the aforementioned remedial solutions by transit operators depend on characteristics of events such as predictability and location. For instance, for reasonably predictable events (e.g. public events), establishing dedicated services is announced beforehand and deploying extra vehicles is planned accordingly. For events with vast impact area (e.g. ice, snow) applying remedial solutions might not be possible, since many parts of the transit network may be affected simultaneously.

Disturbances and the aforementioned adaptive solutions bring in consequences for the public transport operators. In general, remedial adjustments such as detours will increase service running time. Detours require additional driving time, but if the extra time is shorter than the scheduled buffer time for corresponding service lines, actual impact, however, might be limited. In case of applying detours if consequent delays at the end of service lines exceed than layover time, service frequency might drop. To maintain service frequency as original plan, transit operators may deploy extra runs. In case of splitting service line into two or more parts, additional vehicles might be required which increase operating costs too. If service runs are cancelled due to large disturbances, operator's revenue may reduce temporarily. Thus, major discrete events and all adaptive remedial solutions might influence operating costs.

We conclude from the discussion above that given the disturbance type, operational adjustments and remedial solutions, which are commonly applied by transit operators, are distinguishable. In case of minor quasi continuous ongoing events, operational actions are limited to minor service adjustments focusing on slowing down and speeding up affected services. In case of major discrete events actual remedies are applied by transit operators to cope with service disturbances.

3-8 Summary and Conclusions

In this chapter we introduced the stochastic perspective of public transport networks' situations in which transit demand, the transport service network, and infrastructure are not constant but rather vary with time. This condition expresses actually a realistic situation of public transport networks.

Stochastic events will impact transport systems containing demand and supply including infrastructure. The effects of stochastic events on infrastructure can be more critical since infrastructure failures affect the transport service network as well and generate disturbances in the transport system.

For the purpose of distinguishing impacts of events on public transport networks, we classified disturbances in transport networks based on three influential dimensions: time interval, predictability, and regularity. In order to make realistic classifications of events regarding the aforementioned criteria, we used various empirical results from many researchers in several studies such as Dutch, Norwegian, British, and American studies.
The first dimension distinguishes between events according to time interval (frequency). Some events take place frequently such as traffic jam during rush hours, whereas there are events such as the extreme bad weather or incidents which happen occasionally. The second dimension classifies events based on the degree of predictability. Some events such as traffic jams during rush hours, bad weather, major work zones, and public events are predictable with a reasonable accuracy, whilst there are events such as incidents, failure of traffic devices, and vehicle breakdown that are not predictable plausibly. The latter dimension (regularity) leads to a distinction between minor continuous ongoing events and major discrete events causing regular and irregular variations respectively in transport networks.
The regularity dimension is a key aspect due to ways events affect public transport networks. Impacts of minor continuous ongoing events are minor enough that operators normally deal with them. However, impacts of major discrete events are critical for transit operators. In case of major discrete events such as incidents, extreme bad weather, vehicle breakdown and major construction zones, the situation is cumbersome. Transit operators might not already be aware of the event type and its consequences on the system. Furthermore, impacts of some of those events are vast enough to affect several parts of the network simultaneously.

With respect to impacts of stochastic events on transit networks, we categorised the strategies which are applied by transit operators to cope with events' impacts. In case of minor ongoing continuous events, the applied tactics are mainly repairing-oriented. Speeding up and slowing down services are two main tactics that are carried out to keep service schedules as close as possible to the planned schedule. In case of major discrete events, strategies are remedial-oriented to cope with disturbances and to weaken their impacts on services. Applying detours and running partial services are two commonly used techniques considered by transit operators in case of major disturbance in the transit network.

As an important conclusion drawn from this chapter, we showed that random variations in transport systems caused by various types of events can be distinguished, and classified based on several criteria such as the event's source, event's frequency, event's location, event's predictability and event's regularity. As indicated before, events' regularity is the most important criterion; because it leads to a distinction in ways they impacts transport systems.

Given discussions of this chapter, we can conclude that transit service variations due to minor continuous ongoing events are limited to service running time as well as timetable variations which are observed as regular service quality variations and are coped with by transit operators. However, consequent transit service distortions caused by major discrete events is more complicated enough not to be simply observed in transit service quality indicators. Therefore, impacts of major discrete events on transit service performance should be studied explicitly by considering events' characteristics and ways they impact service operations. We propose simulation as an appropriate technique to determine the transit network situation in case of major discrete events.

In this chapter we also conclude that depending on the event type transit operators might apply different remedial solutions to mitigate event's impacts on transit services. For minor continuous ongoing events, solutions are limited to some service adjustments, whist in case of major discrete events actual service remedies such as applying detour are implemented by transit operators.

Given stochastic events and their impacts on transport systems, in the next chapter we will study public transport service performance offered to travellers more quantitatively in realistic situations when all kind of variations occur. Stochastic events containing minor continuous ongoing events as well as major discrete events result in variations in service performance and quality of service and thus influence transit service reliability. In the next chapter, we will show how service performance can be measured in the stochastic perspective. Also what is the impact of service variations which is perceived in the long term by service reliability criterion on travellers' behaviour?

4 IMPACTS OF STOCHASTIC EVENTS ON PUBLIC TRANSPORT NETWORK PERFORMANCE

4-1 Introduction

As shown in chapter 2, the main assumption in the classical public transport design problem is that all transport system components perform perfectly as expected and do not vary over time. We demonstrated in chapter 3 that this assumption is not very realistic, since transport demand and supply characteristics are not fixed. In other words, public transport demand, the transport service network, and infrastructure quality vary over time due to minor continuously ongoing events and major discrete events. In case of minor disturbance remedial tactics applied by transit operators are adjusting-oriented, whilst in case of major disturbances actual remedies are implemented such as applying detours.
Regarding the layer model of the transport system illustrated by figure 2-1, now the question is raised: what the impacts are of stochastic variations and operational adjustments on public transport service performance offered to travellers? The purpose of this chapter is addressing this question which is essential to assess public transport network performance in the stochastic perspective.

In the first part of this chapter we study quantitavely impacts of network variations on public transport service performance. We will determine how variations and disturbances in transit networks caused by minor ongoing continuous events and major discrete events respectively, affect public transport network performance. Empirical methods supported by scientific theories and techniques are discussed to quantify impacts of stochastic variations on public transport service quality and performance. Moreover, relevant measures regarding service performance variations are introduced such as *service running time variations*, *punctuality*, *and regularity.*

The second part of this chapter deals with impacts of service performance variations on trip time of transit travellers. Given the level of service offered by the operator, transit travellers may suffer from variations in their trip quality. The main indicators that are studied are *travel* *time variations* and *the number of cancelled trips*. These are appropriate criteria applied to appraise service reliability of a public transport system for travellers.

The third part of this chapter deals with travellers' behaviour influenced by service reliability. As explained in chapter 2, the network design problem can be modelled by a bi-level relationship existing between network design and travellers' behaviour. Service reliability affects travellers' behaviour and plays a significant role in their travel choices. Thus in this part, impacts of service reliability on travellers' behaviour are studied based on empirical studies.

The findings of this chapter will provide ample background for developing the network design problem concerning reliability where both network design and travellers' behaviour are impacted by service reliability. This will be the topic of chapter 5.

4-2 Impacts of public transport network variations on service performance

In this part, impacts of stochastic events on public transport service performance are studied. We showed in chapter 3 that actual public transport operations may be different from the original plan due to variations caused by stochastic events. Three aspects of service performance are considered:

- *Service running time variation;*
- *Punctuality;*
- *Regularity.*

These criteria are the main service performance indicators for line bound public transport (Van Oort & Van Nes 2006, 2007).

Service running time is the amount of time that for a public transport service takes to travel along its route. Service running time may vary for each service run. This is usual due to impacts of minor ongoing continuous events. Empirical evidence shows that service running time may sufficiently be described by a Normal distribution albeit by nature it cannot be an exact Normal distribution because it never can be negative, and because longer times are more probable than shorter times than planned (Jenkins 1976; Abkowitz et al, 1987; Seneviratne 1990; Strathman et al, 2002). There are alternative statistical distributions representing service running time variations. Table 4-1 outlines other probability distributions for the running time variations in past studies.

Table 4-1: Transit running time distributions from previous studies

Authors	Distribution function
Jenkins 1976	Normal
Andersson et al, 1979	Lognormal
Turnquist & Bowman 1980	Gamma
Abkowitz et al, 1987	Normal
Seneviratne 1990	Normal, Gamma
Lee and Schonfeld 1991	Gumbel
Wirasinghe & Liu 1995	Gamma
Strathman et al, 2002	Normal

In case of major discrete events, there are some jumps in the right tail of the running time distribution causing large variations. In order to assess impacts of major discrete events on service running time variations, we have performed an experimental analysis in a hypothetical public transport line involving two end terminals and seven middle stops. The details of this case study are presented in appendix 2. We considered all major discrete events mentioned in chapter 3. The outcomes of this study for a 20 year time window demonstrate that major discrete events do not affect the mean travel time significantly (+2%), whereas they increase service running time variations substantially around 20%. This experimental study demonstrates that impacts of major discrete events are significant enough to be considered in quantifying service performance.

There are empirical evidences demonstrating that the level of service running time variations depends on service running time itself (Abkowitz and Engelstein 1984; Van Oort & Van Nes 2006). The relationship between the standard deviation of running time and the mean running time for a service line is assumed as follows:

$$STD(t_{rn}) = \varphi\sqrt{t_{rn}} \tag{4-1}$$

Where:

t_{rn}= Running time

φ= Proportionality constant

Van Oort & Van Nes (2006) measure running time variations of bus and tram lines in the city of The Hague in the Netherlands considering impacts of minor continuous ongoing and major discrete events. They found that during rush hours the running time of a tangential bus line with 6% exclusive right of way increases by around 12 %. For a transversal tram line of the same length and 100% exclusive right of way, this value reduces to 5%.

Figure 4-1 shows the standard deviation of begin-end running time in each direction for tram line 1 and bus line 23 in The Hague as a function of the trip distance from the begin stop. The standard deviation of running time has been computed and averaged over peak hours in a whole month. These two lines are relatively long and connect a large number of regions in the city. To estimate the standard deviation of running time, a morning peak hour during a month has been chosen. As to be expected, the monthly standard deviation of running time over these two lines generally increases along the line. Contrary to the tram line, the standard deviation of running time of the bus line sometimes decreases. This is because of operational measures like holding vehicles ahead of the schedule at a stop. Despite these measures, the variation of bus running time is still larger than that of tram. This is probably because of the low proportion of the bus line having its own right of way. For the tram line the average increase of the standard deviation is 11.1 s/km. For the bus line this increase is larger: 17.6 s/km.

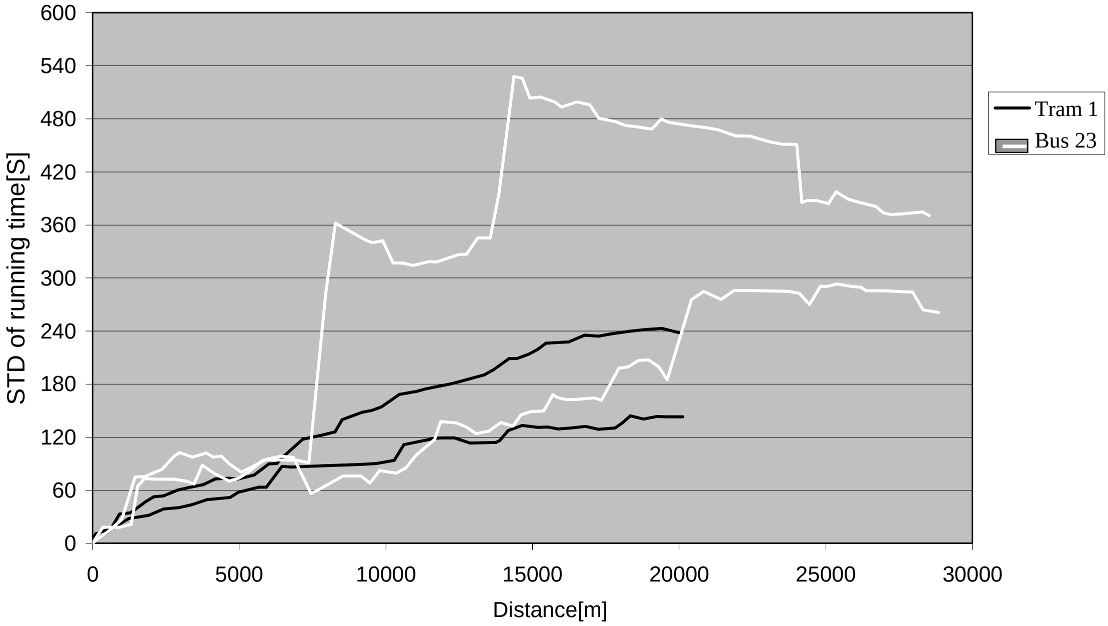

Figure 4-1: Standard deviations of bus and tram running time for each direction by increasing trip distance (Van Oort & Van Nes 2006)

Shalaby et al, (2001) show that running time variation not only depends on service running time (or trip length) itself, but also it is affected by number of stops made, the number of signalized intersection passed, and the measured vehicles /hour/lane. Abkowitz and Engelstein (1984) found that mean running time is affected by line length, passenger activity, and number of signalized intersections. Most researchers agree on the basic factors affecting bus running times (Abkowitz & Engelstein 1983; Levinson 1983; Abkowitz & Tozzi 1987; Strathman et al, 2000). Table 4-2 contains a summary of factors affecting service running times in regular situations (minor continuous ongoing events).

As indicated in chapter 3, service running time variations affect operator's costs as well. However, if the extra time is shorter than the scheduled buffer time for corresponding service lines, actual impacts, however might be limited. In case of major variations caused by major discrete events, not only service running time varies, but also there might be changes in service line itinerary and more. Even, it might lead to service cancelation. Service cancelation usually affects operator's revenue. During service cancelation, public transport customers might use other modes or cancel planned trips. This leads to a reduction in patronage and thus operator's revenue.

Table 4-2: Factors influencing service running time variations

Variables	Description
Distance	Segment length
Intersections	Number of signalized intersections
Bus stops	Number of bus stops
Boarding	Number of passengers boarding
Alighting	Number of passengers alighting
Time	Time period
Driver	Driver experience and style
Period of service	The duration that the driver has been on service
Stop delay time	Time lost in stops based on bus configuration (low floor , etc)

The other aspect of public transport service performance dealing with timetable is *punctuality*. It is defined as the time difference between planned (e.g. according to the timetable) and actual moments of either arrival or departure. In other words, punctuality of a line shows the average deviations from the schedule (Muller & Furth 2000). Formula 4-2 shows how to calculate departure punctuality of a line averaged over its stops (Muller & Furth 2000):

$$\bar{p} = \frac{\sum_{j=1}^{n_j} \sum_{i=1}^{n_i} \left| t_{i,j}^{real} - t_{i,j}^{planned} \right|}{n_i . n_j} \qquad (4\text{-}2)$$

Where:

$\bar{p}$ = Average punctuality of the line

$t_{i,j}^{real}$ = Real departure time of vehicle *i* at stop *j*

$t_{i,j}^{planned}$ = Planned departure time of vehicle *i* at stop *j*

n_i = Number of runs

n_j = Number of stops

i = Line number

j = Stop number

Please note that this formulation doesn't indicate whether vehicles depart too early or too late. Van Oort and Van Nes (2006) compute the average *punctuality* of four service lines in city of The Hague given the formula above. The service lines are tram and bus lines of a different type such as radial, tangential, and transversal lines. Figure 4-2 shows the distribution of the punctuality of all lines. The vertical axis expresses the percentage of service lines that match with punctuality ranges. The figure shows that the punctuality distribution is skewed to the right which indicates that the probability of various long delays than the average. The right skewness is due to computing punctuality in absolute value.

A further important service performance criterion is *regularity*. It is calculated as the average ratio of the absolute difference of the real service and the planned service intervals to the planned interval at a certain location(s) of a service line (Muller & Furth 2000). Empirical evidences show that when service frequencies are higher than 5 or 6 times per hour, travellers arrive at a stop randomly (Seddon 1974, O'Flaherty 1970). In this case regularity is more important than punctuality: headways between successive vehicles ideally should all be equal. A mathematical formulation for irregularity is as follows:

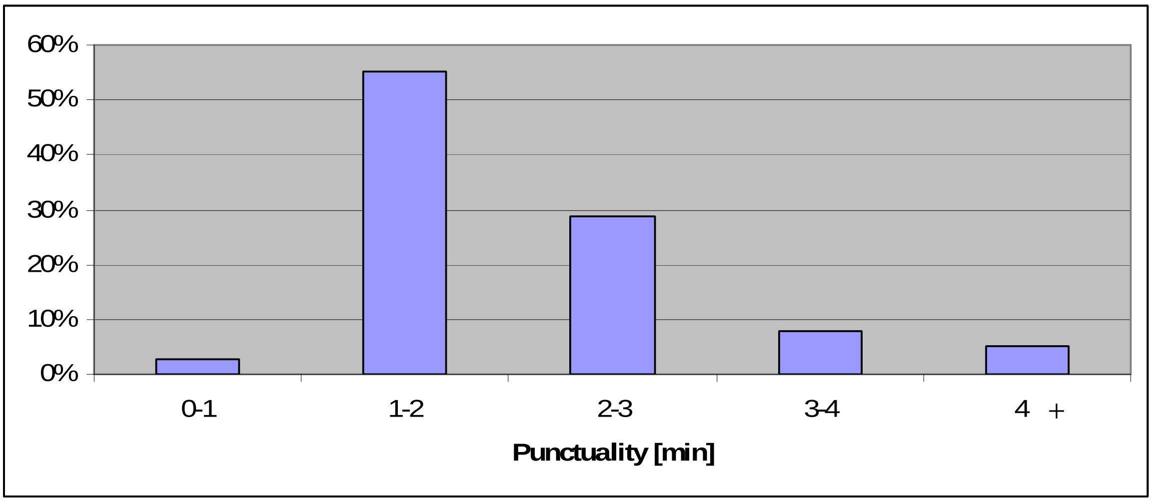

Figure 4-2: Average punctuality of four transit lines in city of The Hague (Source: Van Oort & Van Nes 2006)

$$PRDM_j = \frac{\sum_{i}^{n_{ij}} \left| \frac{hp_{i,j} - ha_{i,j}}{hp_{i,j}} \right|}{n_j} \qquad (4\text{-}3)$$

where:

$PRDM_j =$	Irregularity of service at stop *j*
$hp_{i,j} =$	Planned headway of vehicle *i* at stop *j*
$ha_{i,j} =$	Actual headway of vehicle *i* at stop *j*
$n_j =$	Number of vehicles at stop *j*

To provide services with high regularity, exact departure times are less important. In case of equal headways the average waiting time is minimised and the distribution over vehicles is optimal, which prevents overcrowding (i.e. under the assumption of a uniformly distributed arrival pattern). Van Oort & Van Nes (2006) show that usually the regularity at the beginning of the line is better and it decreases along the line. At the end of the line, regularity is worse than the average value.

Given the discussion above, a conclusion can be made that public transport service performance is impacted by stochastic events in aspects of service running time, and schedule.

4-3 Impacts of service performance variations on travellers' trips

So far we have shown how stochastic events impact public transport operation and the offered services to travellers in terms of running time, punctuality, and regularity. Given the

variations in the level of service as commonly measured by time indicators the question is: what the impact is on trip time of public transport users?
Service running time variations, punctuality, and irregularity in public transport networks influence the level of service offered to travellers. Basically, the door to door travel time of a public transport user consists of:

- access time;
- waiting time(s);
- in-vehicle time(s);
- transfer time(s);
- egress time.

A door-to-door travel time of travellers excluding access time and egress time consists of waiting time, in-vehicle time(s), and transfer time(s). In order to quantify travel time variations in a passenger’s route, all travel time components should be included in the calculation. We assume the access and the egress time variations are negligible and therefore can be neglected in the trip time variance calculation. Thus, travel time variations can be estimated statistically by including variations of all travel time components. Equation 4-4 formulates the variance of the total travel time in a route assuming independence among the links constituting the route:

$$Var\{t_r\} = \sum_{n_{\hat{j}}} Var\{t_{in}\}^{\hat{j}} + \sum_{n_{\hat{k}}} Var\{t_w\}^{\hat{k}} + \sum_{n_{\hat{z}}} Var\{t_t\}^{\hat{z}} \qquad (4\text{-}4)$$

Where
r = Route index
$\hat{j}, \hat{k}, \hat{z}$ = Link indices of in-vehicle links, waiting links and transfer links respectively belong to route r
n = Total number of contributing links of each type
t_{in} = In-vehicle travel time on link j
t_w = Waiting time on link k
t_t = Transfer time on link z
t_r = The total travel time on route r

In the formula above, waiting time and transfer time are expressed by virtual links. Thus, the variances of all travel time components need to be estimated such as e.g. service running time variances using formula 4-1.

For the discussed formula the assumption of independency between link travel time variations is certainly not correct in public transport networks. In reality travel times of successive links depend on each other and are mostly positively correlated to some degree. Ignoring this interdependency between travel time components is a limitation in computing travel time variations, if it is not already captured by proportionality constant φ in formula 4-1. Neglecting this correlation leads to underestimation of trip travel time variance.

Besides travel time variations, it is possible that travellers suffer from trip cancelation. If the transit service is not run due to major discrete events impacts (e.g. a blockade caused by an incident), passengers are forced to use alternative routes, or in the worst case to postpone or to cancel their trips. Obviously, in such conditions they are affected by a higher impact of service performance variations.

The conclusion drawn from the above discussion is that passengers suffer from service quality variations. Variations can affect trip time and its reliability or in the worse condition leads to trip cancelation. Service variation impacts in the long term form a service reliability perception for travellers. This is the topic of the next section.

4-4 Public transport service reliability

The previous section discussed variations in passengers' trip quality caused by public transport service quality variations. Now the question is that how do travellers perceive trip quality variations after a long term performance? This perception influences their travel behaviour.
The observable trip quality variations of travellers in the long time form the service reliability perception for the travellers. The reliability perception as indicated in the introduction plays a significant role especially in travellers' choices. In this section, we describe reliability in public transport networks conceptually.

Basically, the term *reliability* refers to a particular attribute of any system that consistently produces one or more products or services. In transportation, service reliability is defined as the probability that a transport service will perform a required function under given environmental and operational conditions and for a stated period of time (Iida & Wakabayashi 1989). This is a general definition which is applicable for any type of transport system.
Reliability of public transport networks predominantly deals with travel time and schedule reliability as well as connectivity reliability (Turnquist and Blume 1980; Carey 1999; Strathman et al. 1999; Kimpel 2001; Bell 2000; Al Deek & Ben Emam 2006).

Excluding schedule reliability, *travel time reliability* is defined as the range of travel times perceived by travellers based on their experiences during a large number of daily trips. Although there are not ample studies to find out how may travel time reliability be measured for public transport networks, some researchers propose the standard deviation of the entire route travel time as an appropriate criterion for measuring travel time reliability of a particular route (Turnquist & Bowman 1980; Rietveld et al, 2001; Tseng et al 2005). In addition to the standard deviation of route travel time, the coefficient of variation of route travel time (COV), difference between 90th and 50th travel time (90DMP), difference between 80th and 50th travel time (80DMP) are other measures for describing travel time reliability (Turnquist & Bowman 1980; Tseng et al, 2005; Vincent & Hamilton 2008). Tseng et al, (2005) show that these indicators are transformable to each other and transformation rates depend on travel time distribution as well. For instance, they showed that the STD of travel time can be transformed to 80DMP of travel time by a coefficient of 0.843 when travel time follows a normal distribution.

Connectivity reliability is defined as the probability that network nodes are connected and can be reached (Iida & Wakabayashi 1989). Regarding travellers' point of view, connectivity reliability might for example be quantified as the number of trips that over a longer period of time with its varying conditions could not be performed (Bell & Iida 1997; Al-Deek & Ben-Emam 2006).
Connectivity reliability is also studied in the context of public transport supply. On the supply side (the service network), it can be measured as the probability that network nodes are still connected (Bell 2000; Asakura et al. 2001; Kurauchi et al. 2004). The network is successful, if the existing lines are in operation as planned. In case of disruptions in the system, the

probability of service line failures might affect connectivity reliability on the supply side. For instance, it can be quantified as the number of service runs that might not reach their destinations, although all travellers might be able to reach their destinations (after making extra transfers and detours etc). That is an example of the difference between the travellers and the operator’s point of view.

All the aforementioned indicators are quantified based on perceived variation in trips properties in the past, however in a long term window. Thus, reliability of a transport network expresses long term performance recognised by travellers. There is an ambiguity how travellers perceive reliability confronting different experiences. There are several empirical analyses addressing this question. Noland and Polak (2002) focus on travel time reliability perception by studies of individual learning about travel conditions over time. Early work in this area was conducted by Chang and Mahmassani (1988) who performed a series of simulation experiments to analyse how individuals adjust their departure time choice in response to previous experiences. They conclude that travellers’ experience in the long term plays the main role, albeit the most recent information, essentially the previous trip’s travel time is important factor in adjusting the next trip’s departure time.
Iida et al (1992) conducted a laboratory experiment to analyse route choice behaviour and dynamic adjustments over time. Their empirical estimates suggested that more recent travel experiences are more important than less recent travel experiences. They also identified individual variations in the decision making process. They found that some travellers less likely change their frequent routes regardless of their experience, whilst others change them frequently. Polak and Oladeinde (2000) performed a laboratory experiment to examine learning effects when travel times are varying. Their results support the model applied by Iida et al (1992).

We can conclude from the discussion above that service reliability in transportation is a performance criterion expressing long term performance although recent experiences impact more on service reliability than past experience especially for minor continuous ongoing variations. Now the question is how service reliability would influence travellers’ behaviour and their choices such as route choice, departure time choice, mode choice, and destination choice. In the next part this question will be addressed.

4-5 Impacts of public transport service reliability on public transport passengers’ behaviour

In this part we discuss the impacts of public transport service reliability on public transport passengers’ behaviour. The achievements capture influences of stochastic variations on passengers’ choice behaviour.
This section consists of two parts: in the first part we show empirically how public transport users appreciate and value service reliability in their choice behaviour. Moreover, how reliability perception among all other factors such as travel time determines the level of satisfaction of public transportation after long term performance.
In the second part we focus on the role of service reliability in travel choices. Basically, service reliability can affect travellers’ choice behaviour in route choice, mode choice, destination choice, and departure time choice. We will describe among other matters using empirical researches how reliability may be involved in those aforementioned choices.

4-5-1 Reliability appreciation by travellers

For a number of years research projects have shown the importance of reliability factors in the travel decision process, also outside the public transport domain. As indicated in the previous part, there are ample evidences demonstrating that travellers perceive reliability based on a learning procedure in which more recent experiences are dominant. Now the question is how much reliability is appreciated by travellers compared to other influencing factors such as travel time.

In several studies reliability-related attributes have been found among the most important service attributes in a variety of situations (Prashkar 1977; Jackson & Jucker 1981; Black and Towriss 1991). For instance, Prashkar (1977) shows for private mode and public transportation that reliability of searching time for a parking place and waiting time for boarding public transport is more important in the decision than just travel time.

The other important issue is that reliability perception in combination with other factors such as travel time, fares, convenience, safety, correct information availability, and so on will determine a level of satisfaction of public transportation in a long term scale for frequent travellers. This idea is supported by several empirical evidences. Conlon et al, (2001) conducted a study to measure passenger satisfaction after implementation of major changes along a bus route in the Chicago area. The implemented changes led to a decrease in service variation along the studied route. Passengers were satisfied with the service quality in terms of running time, waiting time, route dependability, and on time performance.

Another recent study used a service quality index to quantify passenger satisfaction with bus service in New South Wales, Australia. This study concludes that running time variations and fare are the greatest sources of dissatisfaction, while frequency of service and seating availability had the largest positive impact on passenger satisfaction. The study indicates that access time to bus stops when combined with frequency of service is an important aspect of reliable service from a passenger perspective (Hensher et al, 2003).

In the Netherlands The Hague Public Transport Company HTM regularly monitors customer satisfaction (HTM 2002). Their findings demonstrate that public transport reliable services increase transit patronage. This conclusion is also stated in American research (Vuchic 2005).

Therefore, it can be concluded from the above discussion that service reliability is valued highly by travellers among all other influencing factors and it impacts on their choice travel behaviour.

4-5-2 Impacts of transit service reliability on travellers' choice behaviour

Service Reliability can affect travellers' choice behaviour in many aspects. The logical order of choices based on the time scope (from short time window to long time window) can be:

- Departure time choice;
- Route choice;
- Mode choice;
- Destination choice;
- Trip choice.

For public transportation, the impact of reliability on departure time choice is important especially during peak hours when public transport lines are heavily used. For instance, passengers who like to avoid overloading and probable longer waiting times, depart from their origin normally earlier than expected departing time.

There are several researches including reliability in departure time choice analyses. Some of the earliest choice analyses under travel time uncertainty consider choice of departure time for working trips. The central issues in the choice of departure time concerns travel time reliability for different departure times, the importance of early or late arrival and of minutes late all of which might vary across travellers (Graver 1968; Small 1982; Black & Towriss 1993; Noland & Small 1995; Noland et al, 1998; Lo et al, 2006; Li 2008; Li 2009; van Amelsfort 2009)
In less frequent lines, travellers do not arrive at the station randomly but with some knowledge of the departure time such that they minimise their waiting times. However, Bates et al, (2000) suggest that if travel time reliability is low, then travellers may well ignore the schedules and arrive more or less randomly. They also propose that incorrect perceptions will lead to different disutility since travellers will choose for example “the incorrect” optimal departure time.
The above discussion results in travel time reliability as an influencing factor in departure time choice of public transport travellers in addition to travel time itself.

In addition to departure time choice, the travel time reliability affects route choice too. Route attributes (e.g. waiting time, in-vehicle time, transfer time) in public transport networks may be directly affected by regular variations (e.g. rush hour) and major discrete events such as incidents. It is important to note that waiting time is directly related to the size of the amount of headway variation (Hounsell & McLeod 1998). These variations are observed in a short time window for example daily variations and affect travellers’ choice. In choosing routes travellers consider these variations, although they might perceive reliability differently depending on their attitudes. Risk prone travellers obviously attach lower weight to reliability of a route compared to risk adverse travellers. This is also valid for other travel choices (e.g. mode choice). In an empirical study by Abdel-Aty et al, (1994) travel time reliability was found as one of the most important factors for the route choice, with about 54 percent of respondents in a route choice survey indicating that travel time reliability is either the most important or the second most important reason for choosing their primary commute routes. A British study explores that if delays are often experienced, travellers will re-consider their preferred routes (Schmöcker & Bell 2002).
Thus, we can conclude that service reliability is an influencing factor in route choice behaviour of public transport travellers as well.

Service reliability affects mode choice as well. Peeters (1998) shows that people are likely to change their mode of transport because of changes in reliability. Results demonstrate that reliability has a substantial impact on the mode choice of travellers, depending whether it is an improvement or deterioration. For instance, a positive unit change in service reliability of public transport will increase 9% public transport ridership, whereas a negative change will lead to 17 % decrease in public transport ridership. This shows an asymmetric relationship between public transport service reliability and public transport ridership. Table 4-3 presents the impacts of reliability in the mode choice of travellers. A research done by König and Axhausen (2002) yields similar results. Their study demonstrates that reliability among other influencing factors should be included in mode choice models.

Table 4-3: Effects of changes in PT reliability on mode choice (Source: Peeters 1998)

Change of PT reliability	Regular passengers	Occasional passengers	Non PT users
A Unit Increase	9%	22%	9%
A Unit Decrease	17%	44%	-

Besides departure time choice, route choice and mode choice, destination choice is influenced by service reliability too. Although, there is no empirical evidence regarding the influence of reliability on destination choice, it is natural to conclude from the previous discussions that destinations served by unreliable modes may be less attractive for travellers especially for optional trip purposes such as leisure. However, the impact of reliability on destination choice is not as large as on mode choice. The reason is that destinations are normally served by a variety of modes. Hence, travellers usually have possibility of selecting different kinds of modes with different level of reliability. Therefore, if a mode suffers from a high level of unreliability, it does not mean necessarily that the access to the corresponding destination always face high variations and unreliability (Berdica 2007). Thus reliability is of less concern in the destination choice process.

The discussions above demonstrate that service reliability of public transport networks should be included in traveller's behaviour and their choices consisting departure time choice, route choice, mode choice, and destination choice. The inclusion of public transport service reliability could be achieved by different measures. For instance, in the context of route choice including the standard deviation of travel time or the coefficient of variation of travel time to the route's utility function could be a suitable method. Another important point is the perception of service reliability depends on the trip purpose and the traveller's attitude in term of risk averseness. Albeit as indicated before, the importance of reliability is regarded lower in the destination choice compared to other choices.

4-6 Summary and Conclusions

In this chapter we studied the impacts of stochastic events, which were extensively discussed in chapter 3, on transport network service performance. Due to minor continuous ongoing variations taking place every day (e.g. traffic jams during rush hour, ordinary demand variations, etc) and major discrete events (e.g. incidents), service quality varies. Service quality variations influence traveller's time and cost as well as operator costs and revenue.

In order to evaluate public transport network performance in the stochastic perspective, public transport service quality should be measured when variations are taken into account. In this chapter we proposed inclusion of variations and consequent costs in service performance measures. Service quality variations criteria discussed in this chapter are service running time variations, punctuality, and regularity. In terms of service running time variations, we showed that service running time itself is a decisive factor; albeit, other factors such as driving style and the number of signalized junction affect service running time variations as well. In terms of punctuality the findings demonstrated that the punctuality distribution is skewed to the right which indicates the probability of longer delays than the expected average delay. In terms of regularity, it is normally high at the beginning of service lines, but it decreases along lines. At the end of the line, regularity is worse than the average value.

The conclusion is that public transport service quality is impacted by stochastic events, and thus may deviate from the original plan. Service quality deviation depends on the event type and can be measured by common operating measures such as service running time variations, punctuality, and regularity. Service quality variations impact transit network performance so that travellers suffer from trip time variations and possibly trip cancelations. Both aspects caused by stochastic events impact travellers and consequently impose additional costs to them. Variations in quality of services offered to travellers in the long term form the basis for a service reliability perception in the travellers' mind.

In this chapter we also studied the impact of travel time reliability on travel behaviour as the essential part of the network design problem. We reviewed studies addressing the influence of service reliability on different aspects of travel choice behaviour such as departure time choice, route choice, mode choice and destination choice. Findings showed that service reliability affects all travel choice aspects. The important point in this issue is that travellers perceive service reliability after a long time experience according to their trip purpose and degree of risk aversion, although the most recent experiences are accounted highly especially in case of variations caused by minor continuous ongoing events.

These findings clearly demonstrate that service reliability is an influencing factor on both levels of network design and travellers' behaviour and therefore, it should be included into the network design problem. This inclusion leads to extensions in the traditional bi-level framework previously explained in chapter 2. We will discuss these extensions in chapter 5.

5 URBAN PUBLIC TRANSPORT NETWORK DESIGN AND RELIABILITY

5-1 Introduction

In chapter 2 we described the classical public transport network design problem. Its main assumptions are that network supply and demand are constant and do not vary within time. We showed in chapter 3 that this assumption is not quite realistic since public transport demand, the transport service network, and the infrastructure network all vary within time. These variations may happen due to minor ongoing continuous disturbing events as well as major discrete disturbing events. As defined in chapter 3, minor ongoing continuous events take place quasi continuously in a transport network and can be generated by internal as well as external sources of disturbances. Their impacts in terms of service deviations from planning are usually minor. Major discrete events take place discretely in the transport network. They are also generated by internal as well as external sources of disturbances; however, they are normally without any predefined pattern and cause major disturbance(s) in the service network.
In chapter 4 we demonstrated that variations caused by minor ongoing continuous events as well as major discrete events in a public transport network may seriously affect service performance. For the operator, such variations influence operations, and for passengers they influence travel time (costs) as well as service reliability. Such variations are mostly dealt with at the operational level only, whilst it is yet unknown what the contribution at the strategic level could be to reduce these variations.

In order to incorporate service reliability into network design at the strategic level, however, we need to recognise tactics that are applied at the operational and tactical levels with the intention of improvement of service reliability. These tactics can be classified into prevention-oriented or coping-oriented. Hence, in this chapter commonly used tactics belonging to each of these classes are discussed extensively. Thereafter, dealing with service reliability at the strategic level will be discussed mainly focussing on the service network structure as well as infrastructure.

Accounting for service reliability at the strategic network design leads to extensions of the classical public transport network design problem with respect to the following aspects:

- Network design dilemmas;
- Network design objectives;
- Network design bi-level framework.

All aforementioned extensions of the network design problem will be dealt with in this chapter. The result will be an extended public transport network design scheme at the strategic level in which service reliability will be fully integrated.

5-2 Reliability and Robustness

In this part public transport network characteristics that are related to service reliability are discussed. These characteristics may be used in different planning stages to improve public transport network reliability.
As indicated in chapter 4, service reliability has been recognized as an important feature of transport network performance as perceived by travellers. In transportation analysis, service reliability is quantified as the probability that a transport service will perform a required function under given environmental and operational conditions and for a stated period of time. It is a long term service quality attribute. Generally, in travellers' perception of service reliability, slight variations of transport services are natural and acceptable for the traveller, whilst unexpected variations yield unreliable services in travellers' perception (Immers et al 2004).
We stated in chapter 4 that service reliability as a long term service attribute predominantly consists of travel time reliability and connectivity reliability thereby leaving other reliability dimensions such as arrival time reliability aside. In order to provide reliable services for travellers, the transport service network (supply) should be planned in such a way that it is able to perform always its duty at an acceptable level. Travel time reliability is defined as the range of travel times experienced by travellers during a large number of daily trips, whilst connectivity reliability is defined as the probability that network nodes are connected and can be reached. Regarding connectivity reliability, transport networks should have the capability of maintaining its operation at a minimum acceptable level in case of disturbances caused by major discrete events.
With respect to the discussion in chapter 3, minor continuous ongoing events predominantly impact travel time reliability. Transit operators try to deal with such events and apply several operational measures to improve actual service performance in order to maintain long term travel time reliability at the desired level. However, impacts of major discrete events are much larger and may affect connectivity reliability. In order to apply operational measures to maintain or restore network and thereby maintain acceptable connectivity reliability in the long run, the public transport network has to be sufficiently robust. Thus, connectivity reliability relates to network *robustness*.

Robustness is basically concerned with the capability of a system to continue performing its function (without remedial interventions) after a part of the system has been affected by a disturbance (Immers et al 2004, 2009). Li (2008) defines robustness as the insusceptibility of a transport network to disturbing incidents, and thus maybe understood as the opposite of network vulnerability. A number of working definitions that have been collected by the Santa Fe Institute define robustness as the degree to which a system or component can function correctly in the presence of invalid or conflicting inputs (Santa Fe Institute 2000). Van Nes et al. (2007) define robustness as the capability of a system as a whole to compensate for external forces and failures in a safe and efficient manner. A transport system is said to be more *robust*, if it is capable of coping well with variations (sometimes unpredictable) in its operating environment with minimal damage, alteration, or loss of functionality. In other words, a more robust transport network is able to operate within the design specifications also for conditions that are outside the range of its design specifications and without applying remedial interventions at the operational level.

Literatures (e.g. Immers et al. 2004, 2009) use a couple of notions in relation with service reliability and network robustness as such:

- Vulnerability;
- Redundancy;
- Flexibility;
- Resilience.

Vulnerability of transport service networks is defined as the sensitivity of their services to variations of transport supply caused by external or internal distortions such as incidents that result in considerable reduction or even stop in transport system serviceability (Nicholson & Du 1994; Berdica 2002). This definition shows that there is an inverse relationship between vulnerability and robustness. In other words, decreasing vulnerability in transport networks results in an increase in network robustness. A network with 0% vulnerability yields 100% robustness. The degree of vulnerability of transport networks may be lessened/improved in both transport service networks as well as infrastructure networks.

In transport networks a higher robustness is achieved when they are designed in such a way that they tolerate certain variations or even failures in their components. Normally such networks are designed for through *redundancy* (Carlson & Dyle 2002). *Redundancy* (or spare capacity) is defined as the existence of more than one means to accomplish a given function (Immers et al 2004). In other words, it is the duplication of critical components of a system with the intention of increasing the reliability of the system, usually in the case of a backup. High network robustness is fundamentally achieved by designing for sufficient network redundancy. At the traffic level (infrastructure), the system is designed such that if an element fails, the remaining elements can take over the operations of the failed element enabling the system to continue to function (Makoriwa 2006). Sufficient redundancy in public transport networks can be achieved in both service network and infrastructure. Sufficient redundancy in service networks enables travellers to have multiple route alternatives between origin–destination pairs. In case of failure of some route, there might be still an alternative route available for trips for travellers. Sufficient redundancy in the infrastructure network enables the transit operator to divert service lines from their original paths and apply detours to pass the blocked segments. In this case, a service line still can be operated, albeit parts of its itinerary are blocked. We will elaborate more on these two types of redundancy in the upcoming section.

Flexibility in transportation is defined as the capability of transport systems to carry out more and other functions than it was originally designed for (Immers et al, 2004). Flexibility then is the property enabling a system to evolve with new requirements. One way to create higher flexibility in transport service networks is by providing extra facilities in the infrastructure network such as detours and short turns enabling flexible service operations. For instance, existence of U-turn facilities in the middle of line-operated rail tracks will enable operators to run partial services in case of blockades. In this case the service line terminates at the location of the U- turn facility. Creating high network flexibility thus will improve network robustness and connectivity reliability.

Resilience is the attribute of a system expressing how individuals, populations, or systems' components bounce back or respond to perturbations while still maintaining their original identities and functions (Holling 1973; Longstaff 2008). In transport systems resilience is defined as the capability of a transport system to repeatedly recover from a temporary overload or disturbance, preferably within a short time period by its response to dedicated remedial interventions (Immers et al, 2004). In fact resilience describes the system's sensitivity/elasticity to recover by taking remedial measures. Improving system resilience in public transportation, which is normally done at the operation level of planning, can accordingly lead to service reliability enhancement.
Figure 5-1 illustrates schematically the concept of resilience in transport networks. The service quality of a line in the regular condition is about 95% on average, albeit it suffers from minor variations between 90% and 100%. In case of disturbances caused by major discrete events, the service quality slumps down to 25%. If no adjustments are applied by the transit operator (indicated in black) the line's service quality will maintain low for long time; however, in case of operational adjustments service quality improves after half an hour and reaches to 75% of the desired level (indicated by the grey line). The quickness of operational reactions will shorten the transition phase and will lead to a sufficiently desirable resilient transport network.

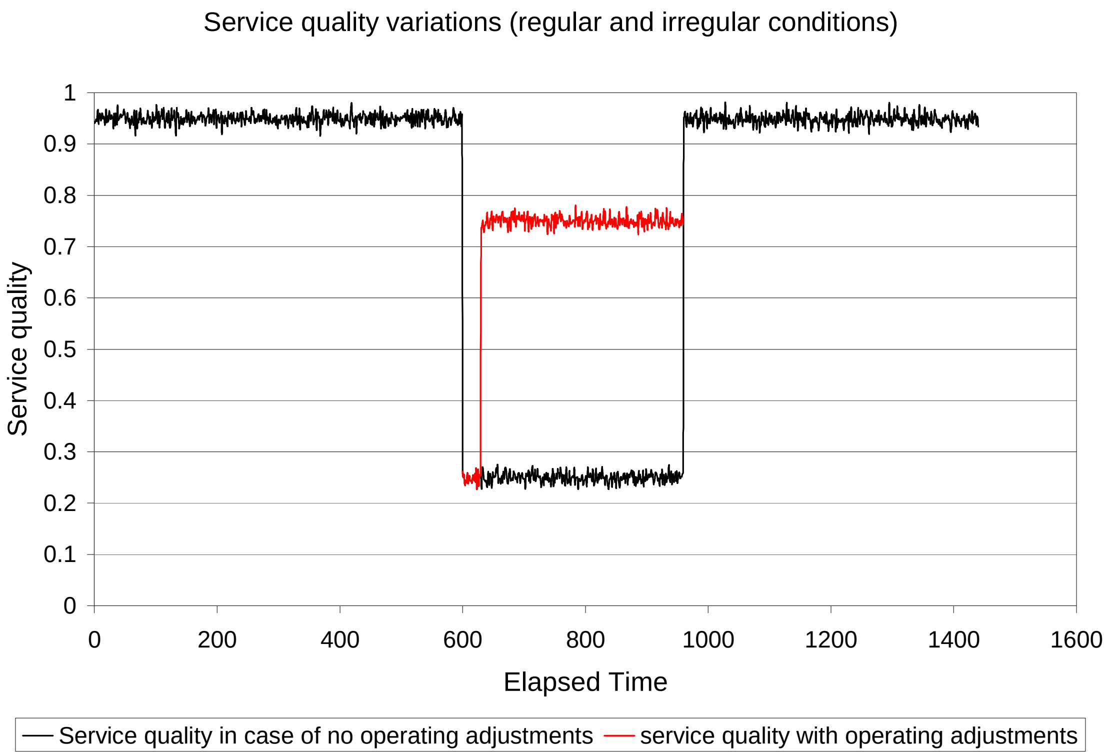

Figure 5-1: The transition phase expressing the network resilience property in case of disturbances

As stated before, impacts of minor quasi continuous ongoing events are mostly on travel time reliability, whilst major discrete events affect largely network connectivity reliability. Figure 5-2 (upper part) shows how connectivity reliability can be improved in public transport

networks. As indicated before connectivity reliability relates to network robustness and thus increasing network robustness will improve connectivity reliability in public transport networks. Also, increasing resilience, describing the system's sensitivity/elasticity to recover by taking remedial measures, can lead to higher network robustness.
However, network resilience and robustness are reversely impacted by network vulnerability. In other words, more robust and resilient networks are less vulnerable to disturbances.

Figure 5-2 (lower part) introduces measures that can be applied at the strategic level of network design to improve network robustness and consequently connectivity reliability. As indicated before, increasing service network redundancy and creating service network flexibility are two suitable methods to enhance network robustness and thus connectivity reliability. Figure 5-2 shows that increasing redundancy in the service network requires redundancy in infrastructure. This is especially the case for rail bound public transport which is operated only on the dedicated infrastructure.

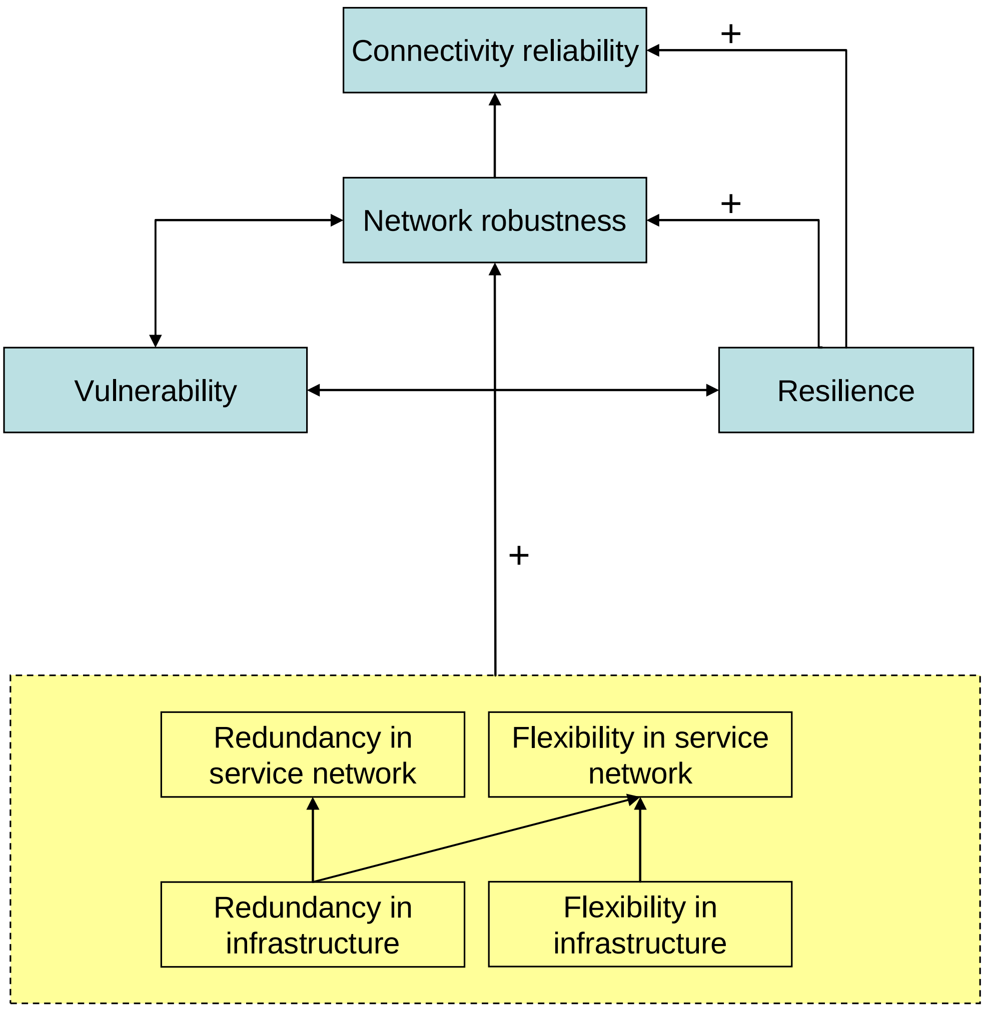

Figure 5-2: Reliability, robustness and related measures

Also, creating flexibility in the service network requires additional components in infrastructure (e.g. shortcuts, turning facilities) which make the infrastructure network flexible. For example, applying detours require that shortcuts and turning facilities in infrastructure already exist. Thus, creating flexibility in the service network requires higher redundancy and flexibility in infrastructure.

Given the aforementioned notions, reducing vulnerability, increasing redundancy and creating flexibility in the transport service network and infrastructure are relevant options at the strategic level of network design to improve network robustness and thus connectivity reliability. We will elaborate more on these options in the upcoming sections.

5-3 Reliability improvement in public transport systems

As discussed in chapter 4, public transport systems suffer from variations in service quality and performance. We also showed that these variations arise due to minor ongoing quasi-continuous events as well as major discrete events. Changes in service quality affect service reliability of a transit system accordingly.
As indicated in chapter 4, improving service reliability is an aim of the operator companies and can increase patronage as well. Approaches for improving service reliability in public transport networks can be categorised as:

- Prevention-oriented approaches;
- Coping-oriented approaches.

By applying prevention measures, the planner tries to increase robustness and to reduce vulnerability of both service network and infrastructure network. By applying coping measures, the transit operator tries to either eliminate or mitigate impacts of disturbance on services.
Implementing prevention-oriented approaches in many aspects facilitates applying operational measures. We will elaborate more on these issues in the upcoming subsections.

5-3-1 Prevention-oriented approaches

In the context of prevention, the planner tries to prevent variations and distortions caused by minor continuous events and major discrete events respectively. Corresponding actions are performed at the strategic management level, at the tactical level, at the strategic level of service network planning, and in the infrastructure network as well. Table 5-1 summarises the corresponding tactics at both levels of service network planning and infrastructure.

Strategic management:
Prevention approaches at the management level focus on strategic decisions aiming at reducing or eliminating sensitivity of services to variations and distortions. The decisions do not relate to network design; however, they might influence transit operations.

In the context of transit fleet utilisation using high quality vehicles and applying perfect maintenance are two suitable methods to ensure continuous operation and to prevent failures due to for example vehicle breakdowns. Of course applying such decisions in practice needs ample investments and thus requires strong motivation.

In a customer oriented perspective using low-floor vehicles is a suitable means for reducing dwell time variations. High-floor vehicles increase inconveniency and also the time required for boarding and alighting for elderly, disabled passengers, and also passengers carrying a push car. Hence, using low-floor vehicles is recommended to facilitate elderly/disabled

passengers and also to prevent dwell time variations and consequently service running time variations.
Regulating prepaid ticket systems is another method for reducing dwell time variations. It will prevent selling tickets inside the vehicle. Usually, purchasing tickets directly from drivers leads to extra dwell time and increase dwell time variations especially for long lines. By installing automated ticket machines at stops or inside vehicles, less variation in dwell time would be expected.
Finally, restricting transit drivers to the corresponding timetable prevents service irregularity and improves travel time reliability in services. This is especially more concerned for low frequency services. Missing a service due to early departure imposes a long additional travel time to travellers.

Table 5-1: Prevention tactics to preserve transit services from variations and distortions

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 signalling system for transit services
	Planning the service network with redundancy/ flexibility	

With respect to public transport network planning, at both tactical and strategic levels it is possible to improve service reliability using prevention-oriented approaches.

Tactical level of planning:
Prevention measures at the tactical stage normally focus on schedule and timetable modifications (Israeli 1996; Carey 1998). The measures that are used at this stage aim at increasing spare capacity in the timetable of public transport 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. We will elaborate more on this issue in section 5-4-1 discussing new public transport design dilemmas regarding reliability.
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, Rietveld et al. (2001) recommend increasing of train speed to have more transfer time in connection points to improve the travel time reliability of the Dutch train network.

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.

Strategic level of planning:
At the strategic level of public transport network planning, as indicated in section 5-2 reducing vulnerability, increasing redundancy, and creating flexibility in the public transport network layers are relevant approaches to improve service reliability.

There are few methods at the strategic level to improve service reliability in public transport networks as shown in table 5-1 (2^{nd} column).

Planning independent service lines
Vuchic & Musso (1991) compare the independent and the integrated operation of metro lines in terms of service reliability. Basically, the independent operation of lines in a public transport network is simple, but it might impose additional transfer to transit users. 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 that are run on sight, the dwell

time of the preceding vehicle affects running time of the following vehicles. It may influence prioritising systems in the network in such a way that the following vehicle can not benefit from prioritising signals.
With respect to the discussion above, Vuchic & Musso (1991) recommend using independent line operations with less vulnerability 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 they refer to the Paris and Tokyo metro systems that consist of independent lines only.

Shortening service lines
In addition to independent service line operations, reducing service line lengths is an appropriate way to reduce service line vulnerability and thus improve service reliability. We already discussed in chapter 4 that long lines suffer more from higher regular and irregular service variations generated by minor continuous ongoing events and major discrete events respectively, 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 travel time variations leads to improvement of travel time reliability, whereas a decreasing probability of line failure improves network robustness and connectivity reliability. Of course, replacing long service lines by short service lines has consequences for travellers. It will generally increase the required number of transfers and consequently increase the total travel time for transit travellers. Thus, reliability consideration will lead to a new network design dilemma. We will elaborate more on this issue in section 5.4.1.

Increasing stop spacing in the service network
With respect to service network space accessibility, a proper way to improve travel time reliability at the strategic level of network planning is reducing stop density in such a way that there are always few travellers at the stops (Van Oort & Van Nes 2006). This will prevent stop skipping by drivers and thus will decrease service running time variations. However, decreasing stop density will increase access and egress time accordingly.

Planning redundancy in fleet
Increasing redundancy in transit fleet is a proper way to improve service reliability (Table 5-1). Having redundancy in 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 contribute to maintaining service reliability in the long term.

Planning the service network with redundancy/ flexibility
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, 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.

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 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. We will elaborate further on this issue in the upcoming sections.

In the infrastructure network, other efforts are mainly oriented towards:

- Providing separated right of way for transit vehicles 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 service reliability high.

5-3-2 Coping-oriented approaches

In the context of coping-oriented approaches, the transport service network is modified temporarily during events to reduce impacts of disturbances. Coping-oriented approaches at the operation side focus on securing transit performance to reduce service variations and distortions caused by minor continuous ongoing events and major discrete events respectively. Measures at operational level benefit from or require measures at the tactical and the strategic level as well. For instance, applying operational adjustments in case of major discrete events requires the infrastructure network to be more flexible. Table 5-2 categorises coping-oriented approaches at the operational level as well as requirements recommended at the tactical and the strategic levels of design for both the service network and infrastructure.

As indicated in chapter 3, the actual operations in public transportation show deviations from their original plan in the stochastic perspective. Regular variations caused by minor continuous ongoing events result in differences between the actual operation and the original operation planning. Thus, the operator tries to adjust services during their operation. One way to close actual operations with its original planning is to adjust the services adaptively to disturbances as quickly as possible.

The applied tactics focus on *speeding up* and *slowing down* services (Gifford et al, 2001; Banks 2002; Chang et al, 2003). As an example Randstad Rail in The Netherlands use a systematic control and warning mechanism in case of disturbances in the network (Van Oort and Van Nes 2007). Adjusting the operations of Randstad Rail will be done by dispatchers in the central dispatch room. They have a full overview of all vehicles and their punctuality. Software tools are available to adjust operations and inform drivers as well as travellers.

In bus networks *leapfrogging* adjustment for a delayed bus is a common method (Banks 2002). In this method, the operator allows the following bus overtakes the delayed leader bus. In addition to leapfrogging technique, skipping stops for delayed and/or overloaded vehicles, and giving priority to delayed public transport services in the lines are other techniques applied to speed up late services (Gifford et al, 2001). To slow down early services, giving posteriority and increasing dwell time for services ahead of time could be used. Banks (2002) also suggests the *bobtail path* action for overloaded buses. In other words, turning back a vehicle that is preceding in the opposite direction to insert it in front of the overloaded vehicle.

Table 5-2: Tactics used in the coping-oriented approaches and the corresponding requirements for the prevention-oriented tactics

Service network			Infrastructure
Operational level	**Tactical level**	**Strategic level**	
Speeding up/ slowing down	*Allocating slack times in timetable*		
Deploying additional vehicles		*Opt for redundancy in fleet*	
Maintaining service frequency		*Opt for redundancy in fleet*	
Applying detours			*Redundancy in the infrastructure network*
Shortening service lines			*Flexibility in infrastructure network*
Rerouting travellers		*Planning the service network with redundancy*	

* The dotted arrows indicate the requirements at other design levels

Normally, the aforementioned tactics are achieved by the implementation of ITS (Intelligent Transportations Systems) and DTM (Dynamic Traffic Management). In other words, ITS and DTM enable the operational measures to be applied (Levinson 2005; Akiyama & Okushima, 2004; Chang et al, 2003; Gifford et al, 2001).
Applying the aforementioned tactics is eased in case of existence of slack time in the timetables. Hence, prevention-oriented approaches at the tactical level of planning will also assist the operator to apply adjustments for coping with impacts of disturbances.

In case of major discrete events, operational adjustments are directed towards the following tactics (table 5-2):

- Adding capacity to the affected services;
- Repairing affected service lines;
- Informing travellers about alternative routes.

Adding capacity to the affected services
Adding capacity to the affected services can be achieved by means of:

- Deploying vehicles with larger capacity in case of increase in public transport demand (e.g. due to bad weather);

- Establishing extra services in case of high increase in public transport demand (e.g. due to a public event);
- Deploying the reserved vehicles to maintain the planned service frequency in case of events such as vehicle breakdown.

Applying the indicated measures requires redundancy in the fleet and results in increasing network capacity. Thus, the transit operator uses available capacity in a flexible way to satisfy transit demand and thus to enhance service reliability on the long run.

Repairing affected service lines
The tactics for repairing an affected service mainly aim at maintaining service availability of affected lines. Depending on transit mode and availability of infrastructure different actions are applied as follows:

- Applying detours and diversion to avoid blocked paths and /or traffic jams in the affected service lines;
- Shortening service runs for the affected service lines.

These two measures are suitable for bus transit systems; however, for rail bound networks it requires dedicated infrastructure. As mentioned in subsection 5-3-1, in order to apply detours or short service runs for rail bound networks, flexibility in the service network by applying additional infrastructures (e.g. shortcuts, U-turn facilities) play a vital role. Thus, service line backup alternatives can be facilitated by additional infrastructures (table 5-2). Of course, these adjustments require quick and appropriate operational actions provided by the transit operator too.

Informing travellers about alternative routes
Guiding travellers for alternative routes in case of service line failures is a proper method to deal with disturbances in the network too. Planning for redundancy in the service network in the context of prevention-oriented approaches will enable the operator to offer alternative routes to travellers and to maintain connectivity reliability of the public transport network.
The network with a larger number of service lines allows the operator to offer the travellers alternative routes. In other words, if some routes fail due to stochastic events, there might be still some other routes available for them. For instance, various service line configurations such as combination of radial and ring lines will provide different route alternatives for travellers. In this case, if a radial line is out of use due to an incident, travellers can traverse via a ring line and transfer to another radial line and reach their destination.
In order to increase service line density, required infrastructure must be available. Adding a service line to the service network needs availability of suitable infrastructures. This is especially relevant for rail bound public transport networks which are operated only in a dedicated right of way. For instance, adding a ring service line to a rail bound radial service network requires dedicated infrastructure containing additional tracks, signals, and switches. Consequently, increasing redundancy in the transport service networks may lead to increasing redundancy in the infrastructure network (Figure 5-1).

5-3-3 Synthesis

Synthesizing the discussion above, there are several methods to improve service reliability at all planning levels. Furthermore, measures that are applied at the tactical and the strategic levels can ease and facilitate operational measures. At the strategic level of planning, opting for redundancy in fleet and planning for the service network redundancy are two measures enabling transit operators in case of disturbances to increase service capacity and to propose alternative routes to travellers respectively. In the infrastructure network, planning for redundancy and creating flexibility by means of additional infrastructures enable transit operators to repair service lines using detours and short runs and maintain service operation. Applying these measures improve service reliability in transit network especially for rail bound networks. Therefore, these measures should be included in public transport network design and lead to extensions of the public transport network design problem. This issue shall be described in the next section.

5-4 Including reliability in public transport network design

Incorporating service reliability considerations in the strategic network design stage requires extensions of the classical network design problem with respect to:

- Network design dilemmas;
- Network design objectives;
- Bi-level relation between traveller behaviour and network design.

As indicated in the previous section, incorporating service reliability considerations result in new design dilemmas. These dilemmas are originated from trade-offs between travel time and travel time reliability, operation costs and service reliability, and investment costs and service reliability. Understanding these dilemmas is essential to assess public transport networks in the stochastic perspective.

Improving service network flexibility and redundancy, and also applying operational measures to cope with disturbances will increase investment costs, operation costs, and travel costs, whilst decreasing reliability associated costs. Hence, in order to have a correct network design objective, the objective function should be modified accordingly to capture those costs alterations.

Considering stochastic events and related operational measures will lead to differences between the network originally designed by the transit planner and the actual network experienced by travellers. Moreover, major discrete events may influence transit demand leading to differences between expected demand and actual transit demand as well. In other words, the bi-level relationship between network design and travellers' behaviour needs to be extended to incorporate these impacts. In upcoming parts of this section, the aforementioned design issues are discussed extensively.

5-4-1 Reliability and new public transport network design dilemmas

Considering service reliability in network design yields additional design dilemmas compared to the traditional static design approach. These dilemmas are classified into two types:

- Design dilemmas due to minor continuous ongoing events;
- Design dilemmas due to major discrete events.

Table 5-3 summarises these new design dilemmas. In this table dilemma 1 to dilemma 4 belong to the first category, whereas dilemma 5 and dilemma 6 belong to the second category. Moreover, design dilemmas 1 to 3 are dealt with at the tactical level of planning, whereas design dilemmas 4 to 6 are addressed at the strategic level of network planning.

The *first design dilemma* regarding service reliability focuses on slack time in running time. An obvious trade-off with which one must deal with when timetables are constructed is that faster transport with shorter slack time will improve the scheduled travel times, but will have an adverse effect on service reliability (Powell & Sheffi 1983; Hall 1985; Bookbinder & Ahlin 1990; Carey 1994; Hallowell and Parker 1998). Services having less slack, either in run time or dwell time, offer faster stop to stop services, but severely limit to the measures for coping with variations in run times and dwell times and thus leading to more vulnerable services.

Table 5-3: New transit design dilemmas due to service reliability

Event Class	Dilemma Number	Corresponding Trade-off	Design dilemma	Planning stage
Minor quasi continuous ongoing events	Dilemma 1	Service running time vs. service reliability	Faster services with higher travel time variations versus slow services with higher reliability	Tactical
	Dilemma 2	Service frequency vs. service reliability	Timetables with short slack times and lower reliability versus timetables with sufficient slack time and higher reliability	
	Dilemma 3	Shorter access time vs. service reliability	Larger stop spacing with higher reliability versus shorter stop spacing with lower reliability	
	Dilemma 4	Fewer number of required transfers vs. service reliability	Longer service line with higher cumulated running time variations versus shorter service line with lower cumulated running time variations	Strategic
Major discrete events	Dilemma 5	Fewer number of required transfers vs. service reliability	Longer service lines with lower reliability versus shorter service lines with higher reliability	
	Dilemma 6	Network costs vs. service reliability costs	Lower investment costs and lower service reliability versus higher investments costs to increase network flexibility and thus service reliability	

The *second design dilemma* deals also with timetable design. Basically, a tight timetable has short headways between services and thus high capacity, but it eases the propagation of delays among service runs as well. This is due to short slack times between service runs that may not exceed delay time.

An approach dealing with this dilemma in train networks is presented by De Kort et al, (2003). They develop a methodology to compute the maximum number of train movements that can be executed on a particular infrastructure element to achieve a certain level of reliability in case of minor continuous variations. They apply their approach to a planned high-speed double-track line in the Netherlands which is slightly more than 100 km long. Results of their study demonstrate that decreasing service capacity measured by number of trains per hour per direction leads to increasing service reliability.

The *third design dilemma* regarding service reliability is related to stop density. The main idea of the stop density dilemma is that on the one hand a higher stop density will provide better accessibility for passengers which results in shorter access and egress times; but on the other hand it increases in-vehicle travel time because of larger number of stops (Egeter 1995). However, stop density may influence travel time reliability as well. Basically, one of the biggest sources of natural ongoing travel time deviations appears to be the dwell time (Van Oort & Van Nes 2006). Van Oort & Van NEs (2006) analyse the total dwell time of tram line 3 in city of The Hague during peak hours (7 AM till 9AM) for 42 days between month April and May 2005. The total number of service runs analysed is 555. Their results show a large deviation in the total dwell times of the line ranging from 4 minutes up to 17 minutes (figure 5-3). This might be due to the short stop spacing and indicates that higher stop density increases the accessibility of a service, but it reduces service reliability as well.
If there is no passenger to serve at stops, there is no need to halt the car and thus no dwell time for that particular stop. To improve travel time reliability, it's best to always have passengers at a stop, so the vehicle needs to be stopped every time. This method prevents large distributions of the dwell time to occur. In other words, stop consolidation might be a proper approach to achieve higher reliability and prevent dwell time vulnerability.

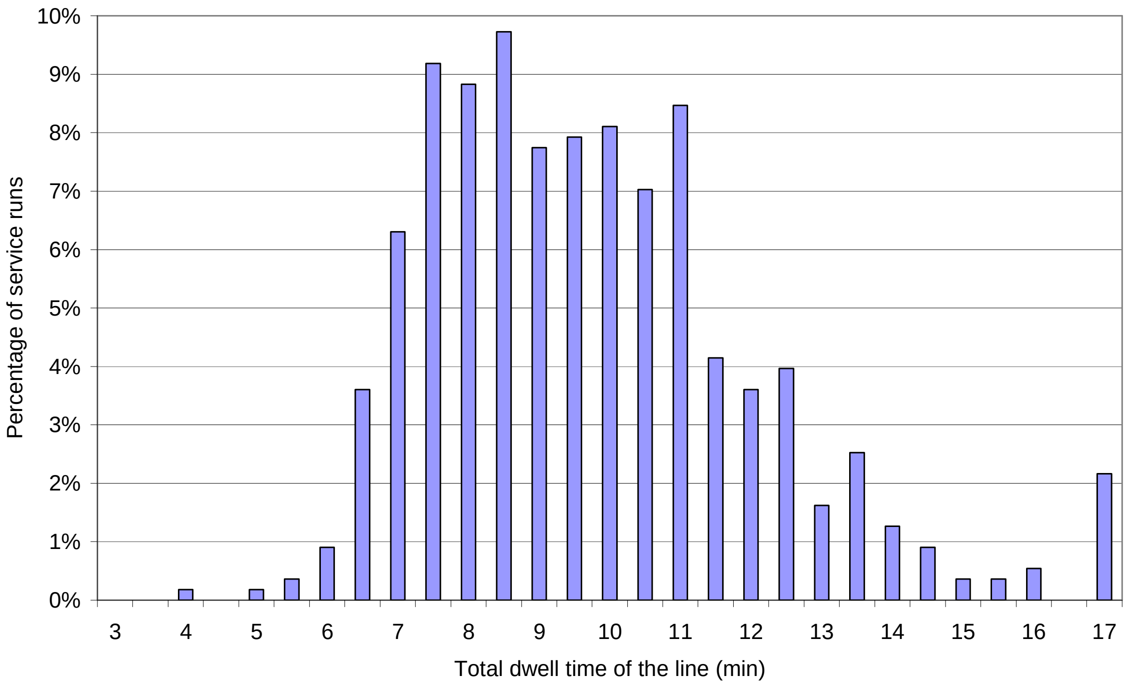

Figure 5-3: Distribution of the total dwell time of tram line 3 in The Hague (Source: Van Oort & Van Nes 2006)

Another approach, focusing on revising the stop spacing of bus networks, is applied in Portland in the United States (El Geneidy et al. 2005). The objective of the analysis is to test operating performance including travel time reliability in bus lines. Their outcomes support the aforementioned stop density dilemma for public transport network.

The *fourth design dilemma* focuses on service line length. The service line length is a source of design dilemma regarding the trade-off between service reliability and travel time. In general, longer lines offer more direct services between origins and destinations compared to shorter lines; however, they suffer from higher travel time variations due to minor continuous events. Figure 4-1 in section 4-2 already showed that running time variations increase along the line.

The *fifth dilemma* deals with vulnerability of service lines. As indicated in chapter 3 impacts of major discrete events on long service lines are higher than on short lines. This is due to higher probability of multiple affections at the same time. Applying adjustments to long lines (e.g. partial operation or detours) is more challenging than in short lines because of difficulty of operating the partial service, if different parts of a line have been affected by major events simultaneously.

Finally as the *sixth design dilemma*, the efforts to cope with major discrete events impacts yield a new trade-off between service reliability and the network costs. Investing in public transport infrastructure and facilitating it with backup infrastructures (e.g. shortcuts) will increase service network redundancy and flexibility and consequently service network robustness and service reliability; however, such investments are part of the total network costs as well. Thus, a design dilemma can be formulated between higher investments in the network and benefiting of higher reliability versus lower investments in and encountering unreliability.

As indicated before the first three dilemmas are primarily dealt with at the operational and tactical planning stages. However, the last three design dilemmas are mainly addressed at the strategic planning level. As indicated before, changing service network structure and planning for additional infrastructures are the main measures that are influenced by these three new design dilemmas. We will demonstrate these new dilemmas by a set of experimental studies in chapters 7, 8, and 9.

5-4-2 Including reliability in the public transport network design objective function

In the context of public transport network design modelling in order to incorporate reliability into the network design problem, the network design objective function should be extended accordingly to capture impacts of service reliability as well. There are few researchers dealing with this issue. In road networks for instance, Tung et al. (2001) have done an effort to modelling reliability improvement of road networks. They minimise the coefficient of variation (COV) of travel time as a travel time reliability indicator by changing the network links capacity under a budget constraint to improve travel time reliability. Their results are interesting and show that travel time reliability can improve by modifying network links capacity. In another study Yin & Ieda (2002) extend the road network design problem by incorporating reliability. They propose a continuous road network design model through which an optimal improvement scheme for existing links will be determined for the most reliable network. They use the standard deviation of travel time as a travel time reliability indicator. They assess which link has to be given priority to be improved in terms of capacity. The link improvement scheme is selected such that total travel disutility of travellers is minimised. Li et al, (2008, 2009) propose and establish a reliability-based dynamic road network design approach, where network reliability is incorporated in the design objective function while travellers' departure time and route choice behaviour under uncertainty are explicitly modelled with stochastic networks. They show that static network design approach may lead to poor designs compared to the dynamic road network design approach.

In public transport, the issue of reliability can be closely related to the network design objective as well. Jackson & Jocker (1981) specify a model where a traveller can make the trade-off between travel time and travel time reliability expressed by variance of travel time. They include both of these two elements in a cost function that travellers seek to minimise it. Carey (1998) applies a similar approach at the tactical level for constructing public transport timetables considering reliability.

As discussed in the previous section, service reliability in public transport networks may be enhanced by applying prevention-oriented and coping-oriented approaches. Operational measures, which are mainly coping-oriented, reduce service variations impacts; however, they still impose extra travel costs and operation costs to travellers and the operator respectively. As indicated in chapter 3, in case of detours, travellers are forced to travel via longer routes. In case of partial services, travellers may encounter extra transfers, probably forced to travel part of their trip on foot to other alternative routes. Even in some cases, they are forced to postpone or to cancel their journeys. In all cases, extra travel costs are imposed to travellers. Moreover, service adjustments that are applied by transit operators yield extra operational costs. For instance, deploying additional services to fulfil demand fluctuations, or applying detours that increase service running times.
Furthermore, increasing service network redundancy and flexibility by providing additional infrastructures increase network investments and maintenance costs. Hence, incorporating reliability at the strategic network design brings in consequences for the design objective.
We showed in chapter 2 (formula 2-8) that minimising the total network costs as a commonly used objective function can be formulated as follows:

$$Min\{C_n\} = Min\{\sum_j \sum_k P_{jk} C_{jk}(N) + C_o(N) + C_{im}(N)\} \qquad (2\text{-}8)$$

Where:
C_n= Total network costs
C_{jk}= Generalized door-to-door travel costs in the network between origin *j* and destination *k*
P_{jk}= Patronage between origin *j* and destination k
C_o= Total operational costs in the network
C_{im}= Total infrastructure and maintenance costs in the network

Accounting now for regular variations caused by minor quasi continuous ongoing events leads to different formulations of generalised travel time (costs), stated in chapter 2 by formulas (2-3) and (2-4), and thus total network costs. Now system properties such as travel times are stochastic variables, indicated by a hat. Corresponding parameters now are indicated by a prime.

$$\hat{T} = \beta'_a \hat{t}_a + \beta'_w \hat{t}_w + \beta'_{in} \sum_{y=1}^{n_t+1} \hat{t}_{in,y} + \beta'_{nt} n_t + \beta'_t \sum_{z=1}^{n_t} \hat{t}_{tz} + \beta'_e \hat{t}_e \qquad (5\text{-}1)$$

Where:
$\hat{T}$ = Generalised travel time in the stochastic perspective

$\hat{t}_a$ = Access time to the public transport service in the stochastic perspective
$\hat{t}_w$ = Waiting time for boarding in the stochastic perspective
$\hat{t}_{in}$ = In vehicle time in the public transport in the stochastic perspective
n_t= Number of required transfers between service lines
$\hat{t}_t$ = Transfer time in the stochastic perspective
$\hat{t}_e$ = Egress time from public transport to the destination in the stochastic perspective
β'_x = Corresponding weight for travel time components in the stochastic perspective

The generalised travel cost function, already stated by formula (2-4), is reformulated in the stochastic perspective accordingly:

$$\hat{C} = \hat{T}\cdot VOT + r_t + \alpha' = (\beta'_a\hat{t}_a + \beta'_w\hat{t}_w + \beta'_{in}\sum_{y=1}^{n_t+1}\hat{t}_{in,y} + \beta'_{nt}n_t + \beta'_t\sum_{z=1}^{n_t}\hat{t}_{tz} + \beta'_e\hat{t}_e)\cdot VOT + r_t + \alpha' \quad (5\text{-}2)$$

Where:
$\hat{C}$ = Generalised travel costs in the stochastic perspective
α' = PT mode preference constant in the stochastic perspective
(Once again for simplicity sake, we eliminated indices *j* and *k* expressing origin and destination respectively and *N* expressing network specifications in the formula above).

Including the stochastic generalised travel time (costs) stated by formula (5-1) and (5-2) in the network design objective function (2-8) results in a complicated formulation. To simplify those functions, route travel time variations, discussed in section 4-3 of chapter 4, can be explicitly included by using for example the standard deviation of travel time. Hence, we apply the classical mean-variance approach (see subsection 6-3-1 in chapter 6) in establishing our reliability-enhanced travel cost function. So instead of using stochastic variates, we adopt the expected values (indicated by an upper bar). The corresponding parameters are indicated with a double prime.
Thus, the stochastic generalised travel time function (T_s) in the stochastic perspective is formulated as follows:

$$T_s = \beta''_a\overline{t_a} + \beta''_w\overline{t_w} + \beta''_{in}\sum_{y=1}^{n_t+1}\overline{t_{in,y}} + \beta''_{nt}n_t + \beta''_t\sum_{z=1}^{n_t}\overline{t_{tz}} + \beta''_e\overline{t_e} + \beta_r t_r \quad (5\text{-}3)$$

Where:
T_s = Generalised travel time in the stochastic perspective
$\overline{t_a}$ = Mean access time to the public transport service in the stochastic perspective
$\overline{t_w}$ = Mean waiting time for boarding in the stochastic perspective
$\overline{t_{in}}$ = Mean in-vehicle time in the public transport in the stochastic perspective
n_t= Number of required transfers between service lines
$\overline{t_t}$ = Mean transfer time in the stochastic perspective
$\overline{t_e}$ = Mean egress time from public transport to the destination in the stochastic perspective

t_r= The travel time reliability indicator (e.g. STD of travel time)
β''_x = Corresponding weight for travel time components in the stochastic perspective

In the above formula, t_r expresses travel time variation caused by minor quasi continuous ongoing events in the traveller's route explicitly. We will elaborate more on this formulation more in chapter 6. A consequence of this however is that travel time components' weights that previously partly captured travel time reliability implicitly (β_x) might get changed values (β''_x) which usually are lower.

Formulas (5-2) and (5-3) are generic and therefore incorporate impacts of regular variations caused by minor continuous ongoing events on passengers' travel time (cost). However, they are incapable to capture impacts of major discrete events causing transit service distortions in the network properly. Thus, accounting for variations and consequent adjustments in case of major discrete events leads to including the following new components in the generalised cost function as well:

- Extra travel time converted to costs due to major discrete events;
- Trip cancellation penalties due to major discrete events;
- Extra operational costs for providing detours / and deploying extra vehicles due to major discrete events;
- Extra investment costs for required infrastructure to provide detour and U-turn facilities.

Formula (5-4) shows the extended design objective function considering impacts of minor quasi continuous ongoing events as well as major discrete events:

$$Min\left\{\hat{C}_n\right\} = Min\left\{\sum_j \sum_k (P_{jk}(\hat{C}_{jk}(N)) + \hat{C}_{te}^{jk} + \hat{C}_{tc}^{jk}) + C_o(N) + C_{im}(N) + \hat{C}_{oe} + C_{ime}\right\} \quad (5\text{-}4)$$

Where:

$\hat{C}_n$ = Total network costs in the stochastic perspective
$\hat{C}_{jk}$ = Generalised travel cost for travelling from origin j to destination k in the stochastic perspective;
$\hat{C}_{te}^{jk}$ = Extra travel costs between origin j and destination k due to major discrete events
$\hat{C}_{tc}^{jk}$ = Trip cancellation costs due to major discrete events
$\hat{C}_{oe}$ = Extra operation costs between origin j and destination k due to major discrete events
C_{ime}= Extra investment costs for building infrastructure shortcut possibilities to cope with major discrete events impacts

An alternative objective function is maximising social welfare. However, it's more complex to capture reliability related costs. The consumer surplus could be still a function of patronage *(P)* as follows:

$$\hat{CS}(\hat{C}_{jk}(N)) = \int_{\hat{C}_{jk}(N)}^{\infty} P(x)dx \quad (5\text{-}5)$$

Also, the producer surplus can be formulated as follows:

$$\overset{\wedge}{PS}(N) = \sum_j \sum_k R_{jk}(\hat{C}_{jk}(N)) - C_o(N) - C_{im}(N) - \hat{C}_{oe} - C_{ime} \qquad (5\text{-}6)$$

Furthermore, in case of major discrete events additional travel costs (C_{te}) and trip cancelation costs (C_{tc}) are imposed to public transport travellers. Modelling these two additional costs components does not fit in the consumer surplus function since they are considered in the short term only. Hence, by considering reliability the stochastic social welfare function is formulated as follows:

$$\begin{aligned} Max\{\overset{\wedge}{SW}\} = Max\{&\sum_j \sum_k (\overset{\wedge}{CS}(\hat{C}_{jk}(N)) - \hat{C}_{te}^{jk} - \hat{C}_{tc}^{jk}) + \\ &\sum_j \sum_k R_{jk}(\hat{C}_{jk}(N) - C_o(N) - C_{im}(N) - \hat{C}_{oe} - C_{ime})\} \end{aligned} \qquad (5\text{-}7)$$

Equation (5-7) shows that the social welfare considering reliability calculated in the stochastic perspective is lower than the social welfare calculated with the classical approach discarding reliability.

5-4-3 Conceptual comparisons between models and system properties in reality

In this we compare public transport systems performance calculated by the following models to the realistic properties:

- Classical modelling approach (stated in chapter 2);
- New stochastic modelling approach (stated in the previous subsection).

First, we distinguish two extreme cases of a public transport system, namely a fairly unreliable versus a highly reliable public transport system (Table 5-4, first column). It should be noted that the spatial pattern of demand and supply, and the pattern of events (both types) are equal in both networks, and only service reliability is different.

The second column expresses the corresponding system properties as the planner expects to be in reality. The qualifications high and low are relative to the other system. It can be expected that in an unreliable public transport system individual travel costs are higher, therefore patronage is lower and consequently production costs are higher relative to the reliable public transport system. We will demonstrate these issues by analysing a set of case studies in chapters 8, and 9. Results will show that reliability enhancing measures have a positive cost-benefit ratio for the production costs.

In the third column we have the estimated network properties obtained from the classical approach stated in chapter 2. In the classical model, as stated in chapter 2, unreliability is implicitly and only partly included by mode preference constant and a set of parameter values in the travel cost function. We compare these calculated properties with the expected properties in reality. Table 5-4 shows that the classical approach underestimates travel costs in unreliable public transport systems, because of undermining or ignoring probable variations and distortions which happen in reality in the system. For reliable public transport systems the classical approach results in a biased estimation of real properties but not as bad as for unreliable public transport systems.

Table 5-4: Conceptual comparisons between classical and stochastic models and PT system properties in reality

	System properties in reality	System properties calculated with the classical modelling approach	System properties calculated with the new stochastic modelling approach
Unreliable PT system	High travel costs. Low patronage; High production costs	Underestimation of travel costs; Overestimation of patronage relative to reality	Accurate estimation of real properties
Reliable PT system	Low travel costs. High patronage; Low production Costs	Biased estimation of real properties, but not as bad as in case of unreliable systems	Accurate estimation of real properties

Finally in the fourth column we compare public transport systems using the new stochastic reliability-based calculation model stated in the previous subsection. Obviously, we expect that applying this new model which considers impacts of minor quasi continuous ongoing events and major discrete events yields accurate estimation of real properties of public transport systems. In this model unreliability is explicitly included in various ways. Parameter values in travel cost function are adapted accordingly.

We already stated applying reliability enhancing measures, described in section 5-3, improves service reliability of public transport networks and reduces associated network costs considerably. Impacts of these measures as discussed in section 5-3 were observed in realistic case studies. However, positive impacts of reliability enhancing measures can be demonstrated by the new stochastic reliability-based calculation model too. Improving service reliability in public transport networks reduces extra travel costs ($\hat{C}_{te}$), and trip cancelation costs ($\hat{C}_{tc}$) for public transport travellers side, and also eases operational adjustments and consequently reduces extra operation costs ($\hat{C}_{oe}$) for public transport operators. Furthermore, increasing reliability, as stated in chapter 4, leads to higher patronage, and accordingly higher revenues and producer surplus (equation 5-6). Eventually, accounting for service reliability in the design problem can improve social welfare (equation 5-7).

Furthermore, another comparison can be made between the classical model approach and the stochastic model approach. The classical model approach neglects reliability related costs for public transport travellers and thus leads to an overestimation of the consumer surplus (CS) relative to the stochastic model approach.

Also, the classical model approach yields higher producer surplus (PS) relative to the stochastic model approach. This is because additional costs for operation in case of disturbances (C_{oe}) and investment and maintenance costs for providing additional infrastructure (C_{ime}) are accounted for in the stochastic model due to reliability considerations. Hence, by including these two additional cost components in the stochastic perspective the calculated total network costs are higher than those in the classical perspective approach.

Given lower producer surplus and additional cost components extra travel costs ($\hat{C}_{te}$), and trip cancelation costs ($\hat{C}_{tc}$) , as indicated in formula (5-7) the social welfare calculated in the stochastic perspective is lower than the social welfare calculated in the classical approach.

5-4-4 The stochastic public transport network design modelling framework

We showed in chapter 2 that the classical bi-level representation is a commonly used method to illustrate the public transport network design problem (figure 5-4: left side). The designer offers planned services to travellers and travellers react to them accordingly. The upper problem is the actual design objective in which the optimal network characteristics are determined given expected usage of the network by the travellers, while the lower problem describes travellers' behaviour given the services that are supplied.

Considering service variations in the transport network, due to minor quasi continuous ongoing events as well as major discrete events, will lead to differences between the planned services and the actual services offered to travellers. Therefore, the classical bi-level scheme neglects to account for impacts of these events and the corresponding operational measures as well. Figure 5-4 right side illustrates how the bi-level scheme may be improved by including random events. Stochastic events take place and affect the transport service network and / or infrastructure. Depending on the event type and its corresponding consequences on services, different operational measurements, mostly coping-oriented adjustments such as detours and partial services are applied by the operator. Thus, actual services will be based on event's impacts and corresponding operational measures.

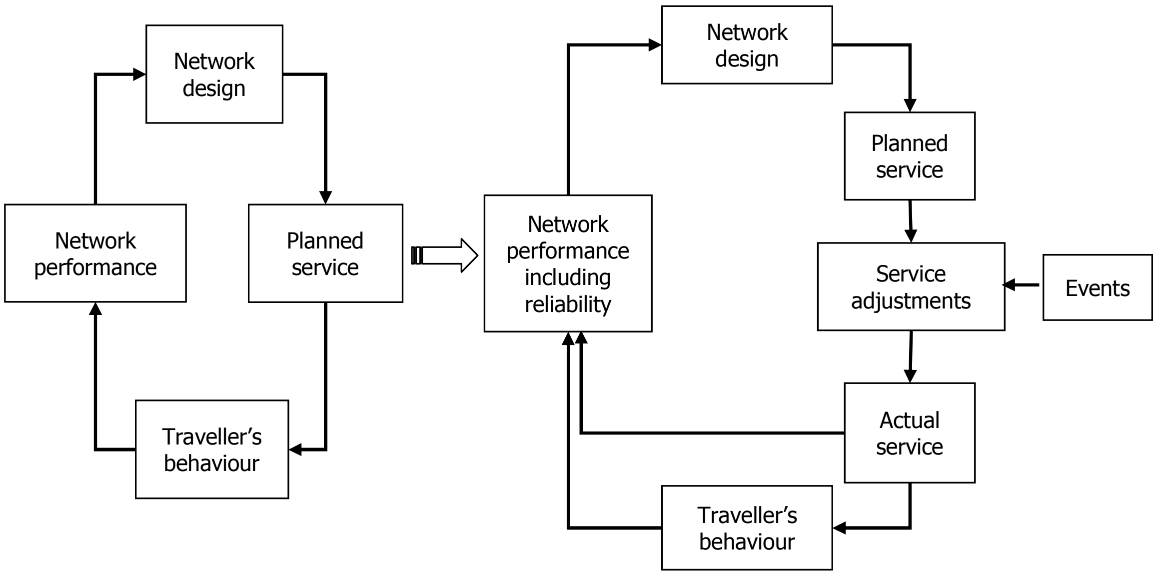

Figure 5-4: The bi-level network design framework in the stochastic conditions

Traveller's choice behaviour in the short term deals with route choice and departure time choice (Table 5-5). The table shows that traveller's route choice will be based on the actual situation in the network which may alter at very short term. For instance, in case of disturbances caused by major discrete events, he might face diverted services, partial services or even cancelled service lines. Hence, he might need to make decisions based on his information of the public transport network situation either pre-trip or en-route. In both cases, usually additional costs are imposed to travellers due to using irregular routes or trip cancelation.

Table 5-5 also shows that travellers make choices on frequently used routes in the mid-term scale based on their daily experiences and perceived service characteristics such as its timetable. Daily travel time variations during travellers' trip, and monthly/seasonally published service timetable offered to transit travellers are two influential factors affecting travellers' route choice in the mid-term time scope.

Table 5-5: Traveller's behaviour in different time windows

		Aggregate level (long time performance)	**Mid-term time scale**	**Short term scale**	
				Expected conditions-Regular variations	Unexpected conditions-irregular variations
Destination choice		√			
Mode choice		√			
Route choice			√		
Route choice	Pre-trip route choice			√	
	En- trip route choice				√
Departure time choice	Pre-trip route choice			√	

Departure time choice is also made in the short time window (table 5-4), when changed travel conditions are known prior to departure. Because mostly these conditions are unknown, departure time choice is at the strategic or tactical choice level where travellers consider average conditions and a reliability factor on these conditions perceived from past experiences (Li et al; 2008, 2009; Li 2009).

Departure time choice is relevant, when timetables are planned. In other words, it is primarily studied in the tactical planning context. Since the focus of our research is on strategic transit network design, we do not study departure time choice explicitly; however, we consider it implicitly by including travel time deviations of travellers between origin-destination pairs. Most travellers will depart earlier to allow for additional time, or add a travel time margin to the expected trip time, to avoid late arrivals. That is exactly strategic choice, not influenced by prevailing conditions. In other words, travellers allow for a longer travel time budget to hedge against travel time variability. The travel time budget can be formulated as follows (Lo et al, 2006)

Travel time budget = Expected travel time + Travel time margin (5-8)

The travel time margin can be a function of the standard deviation of travel time and a requirement degree for punctual arrivals:

$$T_m = \lambda \sigma_t \tag{5-9}$$

Where:

λ = A requirement degree for punctual arrivals

σ_t = The standard deviation of travel time

For trips with high penalty for lateness, travellers would allocate a relatively large travel time budget, or equivalently a high value of λ.

As another method Li et al (2009) model departure time choice behaviour using a travel cost function. Their model composes the mean travel time, the schedule delay based on the expectation of travel time, and the standard deviation of travel time.

Major discrete events can affect public transport demand and cause demand fluctuations in the short term. We discussed this issue in chapter 3 extensively. For instance transit demand rises for compulsory trips in case of bad weather, whilst it declines for other trip purposes. This leads to a difference between the expected transit demand and actual transit demand during bad weather periods. Figure 5-5 illustrates the impacts of events on public transport demand fluctuations. The lower box separated by the dashed lines refers to the short time scope.

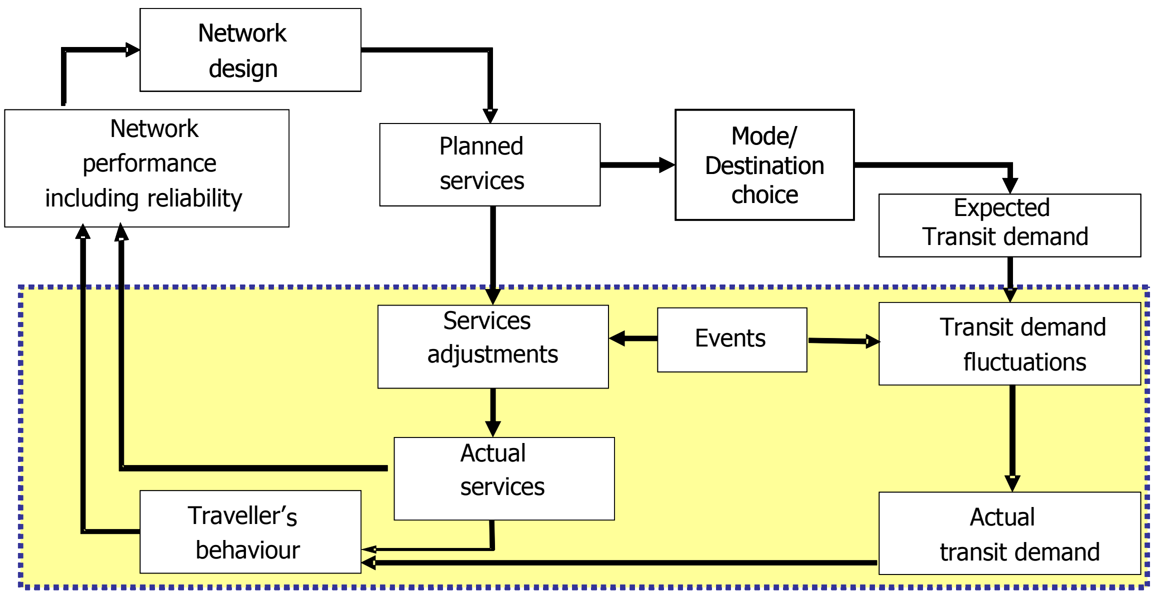

Figure 5-5: The extended public transport network design framework (The strategic level)

In the long term scope (upper right side of figure 5-5), the design framework is extended to capture impacts of service reliability on public transport demand. Service reliability, which is perceived by travellers based on the long term network performance, influence mode/ destination choice. In mode and destination choice, traveller's decisions depend on socio-economic factors and long term transport networks performance such as reliability. In other words, travellers usually do not change trip modes, their activities and corresponding destinations due to short time variations in transport networks especially for compulsory trips such as educational and commuting trips. However, their decisions will be based on a long term perception of the network performance which will among other matters include reliability. In other words, transit performance including service reliability will influence the demand pattern and trip volume via mode and destination choice.

To avoid more complexity in the aforementioned framework, influence of service reliability on public transport mode/destination choices is not shown directly. However, figure 5-5 indirectly illustrates that public transport network performance including reliability affect network design and accordingly planned services. The planned services influence mode/destination choices and consequently public transport demand.

Focusing on the lower level of the bi-level framework, proper travel behaviour modelling in mid / short term is essential for determining the cost components on the traveller's side. In other words, we should find out how travellers weigh components of the route's utility, include feasible routes in their choice set, and thus choose among them in case of disturbances in the network. In chapter 6 we will elaborate on the impacts of stochastic events and service reliability on travellers' route choice.

5-5 Summary and Conclusions

In this chapter, we addressed public transport network design in relation to service reliability. We indicated that increasing network robustness will yield higher connectivity reliability and thus improve service reliability in the public transport network. In order to increase service reliability, different methods might be applied. These methods have either preventing nature or coping nature.

In the context of prevention-oriented approaches, applying measures at the tactical and strategic level of network design are accounted for to increase network robustness and consequently service reliability. These measures facilitate operational measures applied in case of service disturbances.

In the context of coping-oriented approaches, tactics focus on adjusting transit services by operational measures based on the disturbance type. Operational measures are applied to reduce service variations caused by minor continuous ongoing events as well as major discrete events. In case of minor ongoing continuous events, operational measures are arranged for speeding up and slowing down services. In case of major discrete events, operational adjustments are directed towards repairing services by implementing detours or short runs, rerouting travellers and adding capacity to manage higher demand.
Coping-oriented approaches can be facilitated by applying prevention-oriented approaches at the tactical and the strategic level of network design. At the tactical level, adding slack time to timetables facilitates slowing down and speeding up tactics. At the strategic level providing service network redundancy as well as service network flexibility can enable applying detours, short service runs, and traveller re-routing.

In the context of prevention -oriented approaches at the strategic level reducing length of service lines and thus configuring short service lines in the network is an appropriate way to reduce service network vulnerability. Compared to long service lines they are less sensitive to variations and meanwhile applying operational adjustments on short service lines is easier. As another method, increasing redundancy in the service network can improve network robustness and thus connectivity reliability. Service network redundancy can be achieved by increasing service line density which provides multiple routes between travellers' origin and destination. In case of disturbances in the network, it also increases the probability of service restoration for the operator. To increase service network redundancy, required infrastructure

must be available. In case of rail bound public transport network, increasing service network redundancy requires increasing infrastructure network redundancy as well.
In addition to network redundancy, creating flexibility in the infrastructure network and consequently in the service network is another method for improving network robustness. Service network flexibility can be achieved through planning extra infrastructures which are used as backup facilities in case of disruptions in the network. Creating service network flexibility requires additional infrastructures and thus might lead to increase of infrastructure network redundancy as well.

Applying the aforementioned tactics results in extensions in the network design problem. Accounting for service reliability in network design yields trade-offs between travel time versus travel time reliability as well as service reliability versus network costs. These trade-offs result in new design dilemmas in relation with service reliability. Six new dilemmas are distinguished, however, only 2 of them are relevant with respect to major discrete events.

Including service reliability related costs and benefits into the network design objective functions adds additional cost components to the cost function, but it will reduce other costs components. These additional costs capture regular travel cost variations, extra travel costs, trip cancelation costs, extra operating costs, and extra investment costs for the additional infrastructure in case of major disturbances. The benefit is a more refined modelling which enables the transit planner to incorporate reliability in network design and thus to reduce reliability related costs by a better network design.

Accounting for operational measures, which are done in case of service disturbances in the network, includes new components and relations for the bi-level network design framework. The extended bi-level network design framework requires special attention on modelling travellers' behaviour. In the short time scope traveller's behaviour relates to route choice and departure time choice behaviour. Route choice behaviour is addressed in the context of the strategic network design, whilst departure time choice is dealt with at the tactical level. Hence, in chapter 6 we extensively elaborate on route choice modelling by considering impacts of reliability for public transport users.

In order to appraise consequences of incorporating reliability into network assessments and design at the strategic level, several analyses should be done for the approaches discussed in this chapter. These analyses will be done regarding the following topics:

- The new line length design dilemma : longer line with shorter travel time and higher vulnerability, vs. shorter line with longer travel time and lower vulnerability (dilemmas 4 and 5);
- Impact of increasing service network density on connectivity reliability;
- The new design dilemma between investment costs for building extra infrastructures and associated reliability benefits versus unreliability costs (dilemma 6).

We will pursue these analyses through a set of experiments: a hypothetical case study with typical network patterns in chapter 7 and 8 and a practical realistic case study in chapter 9 of this dissertation.

6 ROUTE CHOICE BEHAVIOUR AND RELIABILITY

6-1 Introduction

In the previous chapters 2 and 5 we showed how the public transport network design problem can be modelled by the bi-level framework. There is ample literature to solve the network design problem, whilst the lower level (traveller behaviour) is not discussed completely (Joksimovic 2007; Li et al, 2008 & 2009). In road network design, Li (2009) optimized network capacity (numbers of road lanes) considering reliability of departure time choice and route choice. In public transport networks there is scarce attention on the influence of traveller's behaviour on network design. Therefore, in this chapter we focus on traveller's choice behaviour considering impacts of service reliability. As stated in chapter 5, at the strategic level of network design the main focus is on the route choice behaviour.

In the past decade there were many efforts to model the impacts of regular travel time variations caused by minor continuous events on route choice behaviour of private car users as well as transit passengers (Jackson & Jucker 1981; Small 1982; Black & Towriss 1993; Senna 1994; Noland and Small 1995; Swanson et al, 1997; Ferreira 1999; Lam et al, 2003; Nuzzolo & Craisali 2004; Hollander 2005; Vincent & Hamilton 2008). In those researches, reliability is incorporated in the route choice models, but it is not dealt with perfectly in our opinion.
However, there are scarce studies that assess the impacts of all types of events, including major discrete events causing major disturbances in services, on travellers' route choice behaviour. Hence, in this chapter we intend to deal with route choice applications concerning impacts of all types of variations in public transport networks correctly.

As an overview of this chapter's contents, we first focus on fundamentals of the classical route choice problem in this chapter. It contains random utility maximisation models and explicit route set generation procedures. Finding out the mechanism of considering route alternatives by travellers will enable us to capture impacts of transit service variations on travellers' choice behaviour.

Then, we discuss the traditional methods incorporating service reliability in the route choice models. The focus of these methods is on including travel time variations caused by minor continuous ongoing events in the route's utility function.
Finally, we focus on incorporating impacts of major discrete events on route choice behaviour. As discussed in chapter 3, in case of major discrete events there might be large variations in transit operation and service adjustments such as detoured service lines, partial service lines, and cancelled service lines. Operational adjustments are applied accordingly by the transit operator to remedy impacts of disturbances. In such situations travellers have to change or vary their regular decisions. Thus, major discrete events lead to changes in travellers' route choice behaviour which can not be addressed by traditional methods proposed in the literature. Therefore, in this chapter we elaborate on impacts of major discrete events on travellers' route choice behaviour. Findings of this chapter will provide a relevant basis for modelling route choice of transit travellers in the stochastic perspective in upcoming chapters in which impacts of all kinds of events are accounted for.

6-2 Classical route choice problem

In this part we discuss briefly the classical route choice framework used in network travel demand analysis. Classical route choice models are building blocks for extending route choice models with the capability of incorporating service reliability. In modelling the decision making process of route choice in a transport network, two specific aspects might be clearly distinguished by the researcher:

- The model structure (the type of modelling approach for the choice of an alternative from the given choice set);
- The route choice set generation procedure.

Whereas in a traveller's mind those processes may be mixed up and may not be clearly distinguished, these two steps should be clearly separated in a modelling context (Bovy 2009). As a common route choice model structure, we opt for random utility maximization models, although there are competing approaches (Avineri & Bovy 2008, Van der Kaa, 2008). It provides the probabilistic route choice in which each considered route between an OD pair gets its own share from trip demand (Ben Akiva & Bierlaire 1999).
In order to determine a considered route set between each OD pair, an explicit route set generation procedure is applied. A proper explicit route set generation model provides full control in route set composition and gives full flexibility for implementing route choice behaviour models (e.g. non linear utility function, dealing with overlapping routes in the route set). Furthermore, it is advantageous in terms of computation time compared to implicit route set generation procedures. These issues will be shown in the upcoming subsections.

6-2-1 Random utility maximization model

The generic decision-maker in making a choice considers a limited number of alternatives that belong to his/her choice set. The decision-maker allocates a perceived utility to each alternative and chooses the alternative that maximises his/her utility. The utility allocated to each alternative will be determined based on influencing attributes that constitute the utility function of the alternative. Due to the lack of sufficient information about real choice conditions and also of the utility of each alternative, a certain degree of uncertainty in the model exists. This uncertainty can be expressed by a random error term in the utility function.

The main sources of uncertainty are unobserved individual preferences, unobserved alternative attributes, and measurement errors (Manski 1977).
In the route choice context the utility of route alternative k for decision-maker q (U_{kq}) is formulated as follows:

$$U_{kq} = V_{kq} + \varepsilon_{kq} \qquad \forall k \in CS_q \qquad (6\text{-}1)$$

Where:
U_{kq} = Random utility of route k for individual q
V_{kq}= Measureable utility part of route k for individual q
CS_q= Route consideration set of decision-maker q
ε_{kq} = Random utility term capturing the aforementioned uncertainties

It is usually not possible to predict definitely the route alternative that a decision-maker may choose. But, it is possible to express the probability of choosing specific alternatives. Therefore, the probability that route alternative k is chosen by individual q from his/her consideration set CS_q is:

$$P_{kq} = P[U_{kq} = \max U_{hq}] \qquad \forall h \in CS_q \qquad (6\text{-}2)$$

In addition to the deterministic part of the utility function, the properties of the model are determined by the unknown random part of the utility. If we reformulate equation 6-2 as such:

$$P_{kq} = P\left[V_{kq} + \varepsilon_{kq} \geq \max(V_{hq} + \varepsilon_{hq})\right] \qquad \forall h \in CS_q \qquad (6\text{-}3)$$

The specification of the random utility term determines the type of random utility discrete choice models. Different assumptions about the random term and the deterministic term will yield different models.
If the random error term (ε_{hq}) is assumed to follow the so called Gumbel distribution (Gumbel 1958), the well known multinomial logit results, whereas if a Normal distribution is assumed, a Probit structure results.
The main advantage of the Probit model is its ability to capture correlations among alternatives (e.g. in overlapping routes). However, due to the high complexity of its computation, very few applications have been developed. The logit model is much more popular because of its tractability, albeit it might be unrealistic in some contexts. Hence, the derivation of other models in the logit family is aimed at relaxing restrictions, while maintaining tractability.
A problem of logit models is their limitation to uncorrelated choice alternatives. For instance, in the context of route choice in networks overlapping routes yield a miscalculation of route choice probabilities.
There are three ways to deal with the overlapping problem in route choice models (Hoogendoorn_Lanser et al, 2005; Bovy et al 2008). Table 6-1 outlines these methods. In this table, C logit and Path size logit maintain the simple logit structure by including a correction term within the deterministic part of the utility function.

In the PT route choice context the deterministic part of the route utility function contains factors such as travel time involving access and egress time, waiting time at stop, waiting time for transfers, walking time for transfers, number of transfers, in-vehicle time, fare(s) are

accounted for normally. For an overview of the factors identified in literature, see Van der Waard (1988), Bovy & Stern (1990), Nielsen (2000), Axhausen et al (2001), Cascetta (2001), Nuzzolo (2003), and Hoogendoorn-Lanser (2005).
Meanwhile, personal factors corresponding to age, sex, occupation, income, and travel experience, and also trip factors should not be ignored. The personal factors determine the relative importance a traveller attaches to the various route attributes. For instance, people with high income weigh travel time more highly than low-income people. These personal factors are represented by the parameters in the utility function of routes. Trip factors correspond with trip purpose as well as trip distance. Trip purpose could be categorised into work, business, shopping, leisure, and so on.

Table 6-1: Classification of commonly used methods dealing with the overlap problem in the route choice context

Method	Modelling technique	References
Common links define a nesting structure	Cross nested logit; Generalised nested logit; Paired combinatorial logit	Mc Fadden 1978; Chu 1989; Vovsha 1997; Gliebe et al, 1998; Koppelman &Wen 2000
Common links determine a dedicated additional utility component	C logit, Path size logit	Cascetta et al, 1996; Bertini & Orrick 1998; Ben –Akiva & Bielaire 1999; Ramming 2002; Hoogendoorn-Lanser et al, 2005 Bovy et al (2008)
Common links specify a dedicated variance-covariance structure of the error terms	Multinomial Probit Model; Hybrid logit; Logit kernel	Bovy 1990 ; Ben-Akiva & Bolduc 1996; Walker 2002

Given the above discussion, a generic PT route utility function based on generalised travel cost can be formulated as follows:

$$U = T \cdot VOT + r_t + \alpha =$$

$$(\beta_a t_a + \beta_w t_w + \beta_{in} \sum_{y=1}^{n_t+1} t_{in,y} + \beta_{nt} n_t + \beta_t \sum_{z=1}^{n_t} t_{tz} + \beta_e t_e) \cdot VOT + r_t + \alpha + \varepsilon \qquad (6\text{-}4)$$

Where:

t_a = Access time to the public transport service

t_w = Waiting time for boarding at the first stop

$t_{in,j}$ = In- vehicle time (in leg *j)* in the public transport (scheduled)

n_t = Number of required transfers between service lines

t_t = Transfer time (scheduled*)*

t_e = Egress time from public transport to the destination

ß = Weight for travel time components

r_t = Fare paid by travellers

α = PT mode preference constant

ε = Random error term

In the formula above *ß* the corresponding weight depends on personal factors as well as trip factors.

6-2-2 Explicit route set generation

As indicated before, applying the explicit route set generation procedure provides full control of route set composition (Bliemer & Bovy 2008; Bovy 2009). By means of the explicit route set generation procedure, it is possible to determine which OD pairs are affected in case of blocked links during disturbances caused by major discrete events. So, this capability is a motivation for choosing the explicit route set generation model when impacts of major discrete events are to be considered in travellers' route choice.
Basically, route set generation consists in finding all feasible routes that a traveller might consider for travelling from his origin to his destination. The objective of the choice set generation phase is the maximisation of the coverage of the perceived routes. In a route choice context, the choice set composition is a critical aspect because many routes might be available, whereas only a limited subset of those are actually perceived while even less are actually considered by trip makers (Fiorenzo-Catalano 2007).

There is a systematic account of conditions that reasonable routes should satisfy from the traveller's perspective to become a member of a choice set (Hoogendoorn-Lanser et al. 2006; Fiorenzo-Catalano 2007; Bliemer & Bovy 2008; Bovy 2009). These conditions are general and could be applied in any network type either road networks or public transport networks. Of course, there are differences between road networks and public transport networks in terms of relevant factors, number of feasible route alternatives, and network levels (unimodal, multimodal); however, in general requirements for a reasonable route can be classified as given in table 6-2.
At the first step, properties of single routes are accounted for by specifying requirements. Afterwards, on that basis, the composition of reasonable sets of routes from an individual traveller's perspective is evaluated. Finally, the adequacy of route sets for groups of travellers, who are travelling from a same zone, are considered. Table 6-2 summarizes criteria used in both these steps.

Individual level:
The *Acyclic (Logical) criterion* concerns the topological form of routes in space and/or time. The term logical expresses that travellers don't undertake impossible and unnecessary actions such as travelling in cycles or loops, travelling backwards in time and so on.

Detour criterion: Generally, a reasonable route does not exhibit a detour in distance from the airline connection distance between an origin and destination pair larger than a maximum threshold. (e.g. twice of the airline distance)
According to Fiorenzo-Catalano (2007) if *F(l)* is the function that maps link *l* to its length, time, or generalised costs. And if the sequence of links of a route with $\Gamma r = \{ l_1, l_2, \ldots, l_z\}$ is denoted, *d(O,D)* is the shortest connection (in time, or generalized cost) between any nodes *O* and *D* and $\Theta_{det} \geq 1$ (detour criterion threshold), route *(r)* satisfies the detour criterion if the following holds:

$$\sum_{a\in\Gamma_r} F(l_a) \leq \theta_{\text{det}} \cdot d(O,D) \qquad (6\text{-}5)$$

Where:
θ_{det}= Detour criterion threshold

Table 6-2: Requirements for a reasonable route and an adequate choice set

	Individual (OD pair)	**Group level (OD zone level)**
Single route	Acyclic criterion Detour criterion Hierarchic quality Behavioural criteria Feasibility criteria	
Choice set	Overlap criterion Comparability Detour-max criterion Detour-min criterion Choice set size	Overlap criterion Comparability Detour-max criterion Detour-min criterion Choice set size Spatial variability Preferential variability

Hierarchic quality: A reasonable route is constituted by a systematic sequence of functional mode levels in the network such as heavy rail (train) to urban rail (Tram, Metro or Bus), avoiding route parts going from higher to lower level links and back, such as for example, repeated entrance to and exit from the same network levels. Please note that if transfers require, for example between trains stations, walking is considered as well.

Behavioural criteria refer to individual traveller preferences with respect to trip attributes involving transport modes, waiting times, walking times, costs, number of transfers (Fiorenzo-Catalano 2007; Hoogendoorn-Lanser et al, 2004). For instance, a transit route is suitable, if walking time and number of transfers are less than given thresholds in each trip component.

$$t_{wl} \leq \Delta_{wl} \tag{6-6}$$

$$n_t \leq \Delta_{nt} \tag{6-7}$$

Where:
t_{wl} = Walking time between stops, access and egress
Δ_{wl} & Δ_{nt} = Maximum limit of walking time and transfer number respectively
Typical value: Δ_{wl}= 20 min & Δ_{nt} = 2

Please note that for walking, the total walking time and walking time in each leg should not exceed than the limits. Obviously, the difference between the travellers' attitude leads to different thresholds.

Feasibility criteria regard the suitability of a route alternative in terms of time, space, vehicle availability, and physical (dis-)abilities. Feasibility in *time* can be accounted for by taking into account time constraints at origin and /or destination addresses. Feasibility in *space* refers to availability of transport modes not only at origin and destination, but also at transfer points that is especially relevant in multimodal trip making. *Physical disabilities* might restrict the use of public transportation. To account for physical disabilities, stations with lack of disable amenities or the routes with certain types of transfers can be omitted.

Overlap criterion: in general, route alternatives that largely overlap with others will not be identified as a distinct route by the traveller, and might be excluded from the choice set.
Any two routes of the generated choice set should have a mutual overlap (in terms of number of links, distance, or time) less than Δ percent with respect to the shorter one of the two routes (Fiorenzo – Catalano 2007).
Let *F(l)* be the function that maps link *l* to its length, time, or generalised costs. A route r satisfies the overlap criterion with respect to route p in terms of links, distance, or time, or in terms of the number of common links if the following unequal formula holds:

$$\sum_{l_a \in \Gamma_r \cap \Gamma_p} F(l_a) \le \Delta_{ovp} \cdot \min\left(\sum_{l_a \in \Gamma_r} F(l_a), \sum_{l_b \in \Gamma p} F(l_b)\right) \qquad (6\text{-}8)$$

Where:
$F(l_a), F(l_b)$: the function that maps link l_a and l_b to its length, time, or generalised costs respectively;
Δ_{ovp}= Overlap threshold
Γ_r = Link set of route *r*
Γ_p = Link set of route *p*

If this criterion is not satisfied, the longest (in terms of number of links, or distance, time or cost) route between route *r* and route *p* will be eliminated from the choice set. The amount of the overlap threshold is less than 1 and may vary between e.g. [0.5 0.8]. Whilst Fiorenzo-Catalano (2007) proposes 80% for unimodal networks, Schnabel and Lohse (1997) propose in the road network context that routes with overlap of more than 50% are not identified as separate routes.

The *comparability* requirement is based on the assumption that an individual traveller only considers alternatives below a certain threshold of maximum travel time, travel cost or disutility. Such a maximum might be for example one and half times the value of route with the lowest disutility (Fiorenzo-Catalano 2007).
Given the above definitions, a route *r* satisfies the comparability criterion with respect to route *p* in terms of distance, time or generalized cost if the following holds:

$$\max\left(\sum_{l_a \in \Gamma_r} F(l_a), \sum_{l_b \in \Gamma p} F(l_b)\right) \le (1+\theta_{cmp}) \cdot \min\left(\sum_{l_a \in \Gamma_r} F(l_a), \sum_{l_b \in \Gamma p} F(l_b)\right) \qquad (6\text{-}9)$$

Where:
θ_{cmp} = The comparability threshold.
The comparability threshold usually varies between 0 and 1.

The *detour-max criterion* is approximately the same as the detour criterion. The main difference is that in the detour criterion the whole route is accounted for, whilst in the detour –max criterion non –overlapping parts of two routes are taken into consideration.

The *detour-min criterion* is approximately similar to the overlap criterion. The main difference is that in the overlap criterion, the entire route is accounted for, whereas in the detour-min criterion only non overlapping parts of two routes are compared to determine the relative detour magnitude to the total length or time of the other route.
In transit route set composition, due to behavioural criteria and also the limited number of feasible routes, the detour-max and the detour-min criteria are normally not the case to apply.

Choice set size: the choice set is expected to have a limited number of route alternatives, even very few alternatives as is observed in reality (e.g. 6)

Group level
The *Spatial variability* criterion follows from the observation that choice sets of different travellers in a group may strongly differ in composition due to the fact that the group members have each their own knowledge, preferences and perceptions of the network. Even in a zone, different OD locations might exist, and thus different types of routes may be chosen with same perception and preferences. Hence, a broad variety of route alternatives should be available in the procedure of route set generation.

Preferential variability criterion: Variability in the choice set is another concern for researchers. The choice set should contain as many as possible routes representing the taste variation within the group of travellers. In public transportation network the route choice set should contain different routes served by different transport modes. For instance, for an OD pair the public transport choice set should include various route alternatives in combination of tram, bus, metro, and train.
Furthermore, preferential variability criterion could be imaginable even in a unimodal transport network. Different travellers weigh routes' utility based on their attitudes differently. Whilst, some people may prefer bus routes, others might opt for tram lines for example to avoid of car sick problem.

Based on the previous arguments, a set of routes is assumed reasonable, when its components meet separately all single route criteria, and also the entire route set meet the choice set criteria as well as the group level criteria. In unimodal urban public transportation, the hierarchic quality criterion is not considered. At the zonal level, when centroids are representative of nodes, the group level criteria are considered for route set composition.

6-3 Incorporating service reliability in route choice applications

In this part, we intend to find out how service reliability can be included in route choice models. To do so, impacts of transit service variations on travellers' route choice behaviour are considered. As indicated in chapters 3, 4 and 5, there are two types of events causing variations:

- Minor quasi continuous ongoing events;
- Major discrete events.

In case of minor continuous ongoing events a commonly used approach proposed in literature is to include an indicator for the variations (e.g. the standard deviation) into the utility function (see 6-3-1). This method is suitable when service quality variations are limited to service running time variability and if there are not any major changes in transit services offered to travellers. Therefore, traditional methods are incapable to consider impacts of major discrete events.

In case of major discrete events causing disturbances in transit services, including a travel time reliability indicator in a route's utility function seems not to be sufficient. Due to events' impacts, there might be major changes in services offered to travellers. For instance, service might be run partially, or be cancelled temporarily. Consequently, passengers might need to change their behaviour. For instance, they may be obliged to opt for other routes in case of disturbances of their frequently used lines. Availability and adequacy of passenger's information about network situations play an important role. Pre-trip or en-route choice behaviour can be followed by passengers depending on their information level and type of encountered event. If passengers are informed about disturbances in the transit network beforehand, they can make a pre-trip decision; however, if they do not have information in advance, they might encounter disturbances somewhere during their trip. In this case, they should make a decision en-route during travel. We will elaborate more on this issue in section 6-3-2.

Given the discussion above, we discuss two distinct methods for incorporating impacts of disturbances on passenger's route choice behaviour. In case of minor ongoing continuous events the route utility function is extended to include travel time reliability; whilst in case of major discrete events in addition to extending the route's utility function, the route set generation procedure is modified and en-route travellers' choice behaviour is implemented as well.
The outcomes of this section will provide an appropriate base for capturing the impacts of all types of stochastic variations on public transport service performance and thus for modelling the lower level of extend bi-level framework discussed in chapter 5.

6-3-1 Extending route's utility function to include travel time reliability

As indicated in chapter 4, in addition to other factors such as travel time, travel time reliability of a route plays an important role in passenger's route choice behaviour. In several studies reliability-related attributes have been found among the most important service attributes in a variety of situations (Jackson and Jucker 1981; Black and Towriss 1991; Schmöcker & Bell 2002; Senna 1994; Vincent & Hamilton 2008). In an empirical study by Abdel-Aty et al. (1994) travel time reliability was found as one of the most important factors for route choice, with about 54 percent of respondents in a route choice survey indicating that travel time reliability is either the most important or second most important reason for choosing their primary commute routes. A British study explores that if delays are often experienced, travellers will re-consider their preferred routes (Schmöcker & Bell 2002). Black and Towriss (1991) indicated that travellers are likely to suffer disutility because of uncertainty or unreliability in travel times. For further discussion, refer to chapter 4.
As indicated in the previous section, travel time reliability can be included as a component in the route's utility. There are two methods to include travel time reliability in a route utility function (Jackson & Jucker 1981; Small 1982; Black & Towriss 1993; Noland and Small 1995; Li et al 2008, 2009; Li 2009; van Amelsfort 2009):

- Implicit inclusion;
- Explicit inclusion.

In traditional models (as discussed earlier), travel time reliability is implicitly expressed by parameter values of other involving components (e.g. mode-specific constant, transfer time,

waiting time). In other words, it was not included as a separate attribute into the route's utility function. However, it is in fact included implicitly in the weights of for example waiting time. In other words, travellers perceive waiting time with higher disutility compared to in-vehicle time.
If travel time reliability is explicitly included by using for example the standard deviation of travel time, it leads to a more accurate insight into the importance of trip attributes and especially of reliability. A consequence of this however is that weights that previously partly captured travel time reliability implicitly need to get adapted values.
For explicit inclusion of the travel time reliability there are two approaches proposed in the literature as follows (Jackson & Jucker 1981; Small 1982; Black & Towriss 1993; Senna 1994; Noland and Small 1995; Hollander 2005; Li et al 2008, 2009; Li 2009; van Amelsfort 2009):

- Scheduling approach;
- Mean-variance approach.

The scheduling approach focuses on the actual consequences of uncertain travel times, namely departing or arriving early or late. The scheduling approach combines route choice with departure time choice. Therefore, it is suitable for departure time choice when the timetable is considered. This is in the context of tactical level of PT network design. Since travellers may value early and late arrivals differently due to their different consequences, they are assumed to separate these into possibly four terms namely:

- Arrival or departure schedule delay early;
- Arrival or departure schedule delay late.

Thus, the utility function may not only include travel time but also include the scheduling delays (early and late) as well.

The second approach, the mean-variance method, does not focus on schedules. The main advantage of this approach is its flexibility and freedom to apply (Jackson & Jucker 1981; Small 1982; Black & Towriss 1993; Noland and Small 1995). In this approach different travel time reliability indicators could be used. The standard deviation of travel time is the most used indicator. Another indicator, could be used, is the coefficient of variation of travel time (COV) (Vincent & Hamilton 2008). The mean-variance approach is commonly applied, perhaps because it is relatively easy to implement and it produces reliability ratios reasonably.
We refer to recent work of Li (2009) who has shown the principal equivalency between both methods and developed a generalisation of the two methods into a single modelling approach. For simplicity sake and because departure time choice is not at stake here, we however will apply the mean-variance model.
Given formula (6-4) expressing a common transit route utility function, in the mean-variance approach a route utility function is extended as follows:

$$U' = T_s \cdot VOT + r_t + \alpha' = (\beta''_a \overline{t_a} + \beta''_w \overline{t_w} + \beta''_{in} \sum_{y=1}^{n_t+1} \overline{t}_{in,y} + \beta''_{nt} n_t + \beta''_t \sum_{z=1}^{n_t} \overline{t}_{tz} + \beta''_e \overline{t_e} + \beta_r t_r) \cdot VOT \qquad (6\text{-}10)$$
$$+ r_t + \alpha' + \varepsilon$$

$T_s =$ Simplified generalised travel time in the stochastic perspective
$\overline{t_a} =$ Mean access time to the public transport service in the stochastic perspective
$\overline{t_w} =$ Mean waiting time for boarding in the stochastic perspective

$\overline{t}_{in}$ = Mean in-vehicle time in the public transport in the stochastic perspective
n_t= Number of required transfers between service lines
$\overline{t}_t$ = Mean transfer time in the stochastic perspective
$\overline{t}_e$ = Mean egress time from public transport to the destination in the stochastic perspective
t_r= Travel time reliability indicator (e.g. STD of travel time)
β''_x = Corresponding weight for travel time components in the stochastic perspective
r_t = Fare paid by travellers
α' = PT mode preference constant
ε = Random error term

In the formulation above, t_r is a travel time reliability indicator that can be quantified in a route by an indicator such as the standard deviation of travel time or any other variable expressing the day-to day variability of travel times.
The weight of travel time reliability represents the degree of risk aversion of travellers (Tatineni et al, 1997; Recker et al, 2005; Tseng et al 2005). For instance, a risk averse traveller will trade-off a reduction in travel time variability with some increases in expected travel time, whereas a risk prone traveller may choose a route with a greater variability so as to increase the possibility of a smaller travel time. A risk neutral traveller would choose a route based on only expected travel time without consideration of its variability. Please note that the weight of the travel time reliability indicator may be negative for risk prone people (Senna 1994).
As stated in section 4-2 in chapter 4, variable t_r depends on the route length and the line type. By increasing the route length, t_r increases accordingly. Also, as empirical studies demonstrate t_r is normally higher for routes served by bus compared to routes served by tram.

In addition to traveller's attitude, trip purpose is the other factor influencing travel time reliability perception. Bates et al (1997) found that for commuters the ratio of the travel time reliability weight to travel time weight ranged from 1.04 to 1.22. However, for leisure travellers, this ratio seems to be only 0.66. The former is similar in magnitude to the results of Noland et al (1998) and Levinson & Tilahun (2006), while the latter is similar to the result of Black and Towriss (1993).
In a recent research performed by RAND Europe and AVV Nederland (2005) a monetary value for improved reliability of travel times has been estimated for car traffic, public transport and freight transport. This measure yields a generic value of travel time reliability perception regardless of trip purpose. The value of reliability (VOR) is expressed as the value of a minute change of the standard deviation of travel time. Combined with the differences in value of time (VOT) for different trip purposes such as commuting, business, education, shopping, and leisure, the value of reliability appears to be the same for all trip purposes. For car users, the value of reliability then is about 0.8, whereas for public transport passengers it is 1.4. This higher value of reliability for public transport may be understood because in transit trips with connections a small delay can result in missing a next connection and so in arriving much later at the destination than planned.
Given the discussion above, we can conclude that including a travel time reliability indicator into route utility functions is a suitable method for capturing the impacts of minor continuous ongoing events on travellers' choice behaviour adequately.

6-3-2 Incorporating impacts of major discrete events into route choice models

We stated in chapter 3 that major discrete events cause major disturbances in the network. These major disturbances impact travellers in such a way that it does not fit in the context of regular travel time variations. Due to major discrete events, transit service quality may alter significantly. Transit operators apply remedial solutions to mitigate the adverse impacts of events. As mentioned in chapter 3 applying detours, and partial service runs are two typical remedial solutions applied by transit operators if major discrete events occur. Accordingly, passengers may encounter service variations and may not travel via their regular routes. In this case, passengers may experience longer routes which strong increases of their travel time. Thus, in case of major discrete events, not only travellers may suffer from substantial travel time variations causing jumps at the right tail of travel time distribution (appendix 2), but also they might encounter different route alternatives to choose from.

In case of major disturbances caused by major discrete events, travellers' route choice behaviour depends on availability and adequacy of information. Thus, pre-trip and en-route choice behaviour are considered. Figure 6-1 illustrates how travellers' route choice behaviour maybe different depending on the availability of information provided for them. Due to events' impacts on transit networks, affected transit services are adapted by transit operators (e.g. applying detours, partial services) and thus there is a distinction between the planned service network and the adapted service network. If passengers do not suffer from adverse consequences of service changes, they choose their routes as they normally do, and thus there may be no consequence for them. However, for affected travellers depending on their information about the network situation beforehand, two kinds of choice behaviours are considered:

- Pre-trip route choice behaviour;
- En-route choice behaviour.

If they are adequately informed before starting their trip (e.g. in case of public events), they will make up their mind on choosing their route pre-trip (Swanson et al, 1997; Ferreira 1999; Lam et al, 2003; Nuzzolo & Craisali 2004). This depends on the events' nature. For predictable events such as major road work, and public events, transit operators inform travellers in advance.

In order to avoid trip cancelation, affected travellers might accept routes with higher disutility, for example routes with longer in-vehicle time, extra transfer(s), and longer waiting times. They might even opt for public transport routes including long walking legs. Such routes may not be considered in travellers' route set under normal conditions. Thus, constraints for preferred routes under regular conditions are no longer available. In other words, affected travellers inherently accept routes with higher disutility by relaxing the route set constraint to get rid of trip cancelation or switching to another transport mode. Whilst due to major discrete events some routes are eliminated from the route set of affected passengers, a kind of relaxation behaviour of route set constraints enables affected passengers to see new route options in their route set in case of necessity, and accordingly an adapted route set is considered by them. Given the new route set they make a decision among these new routes as usual.

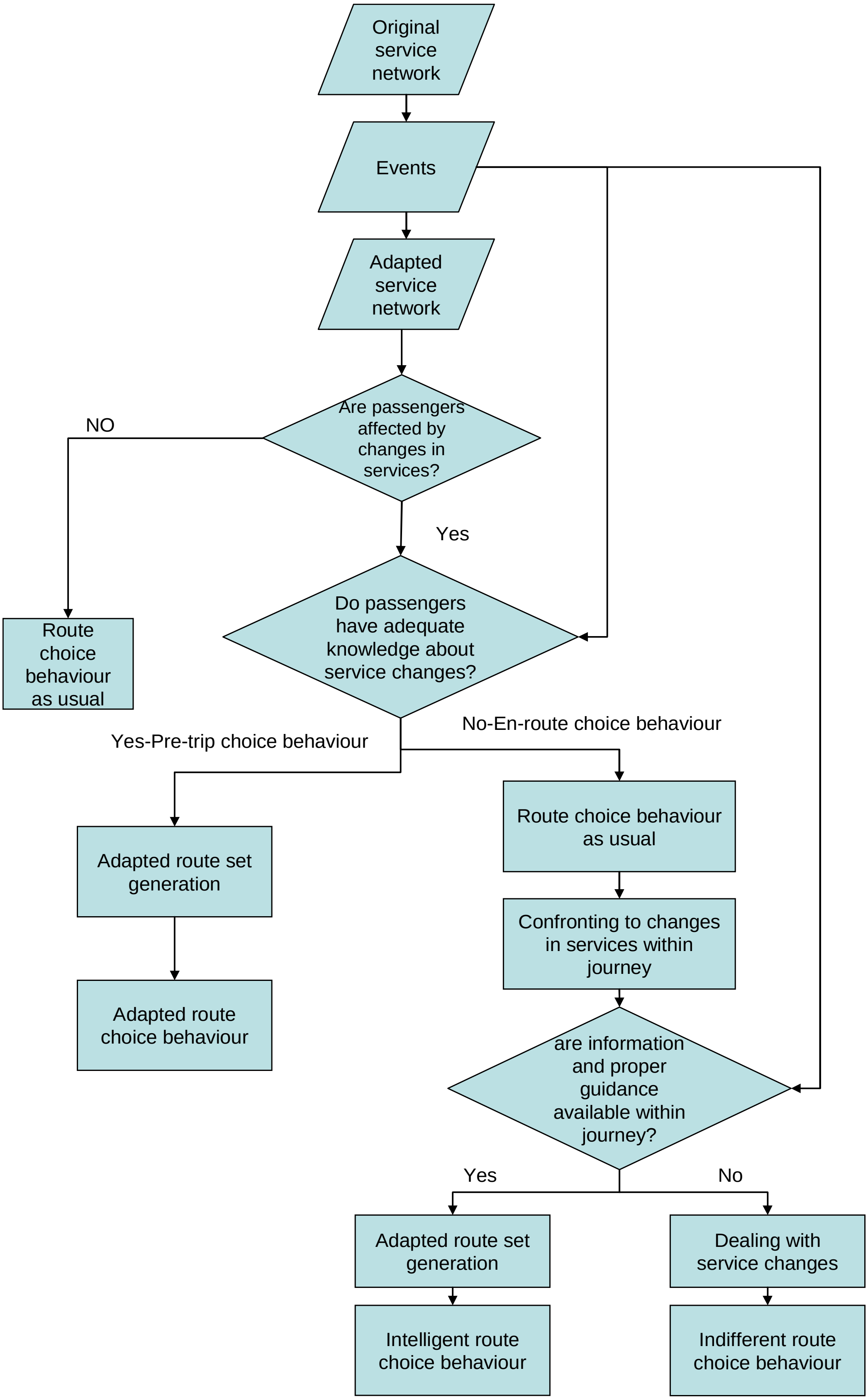

Figure 6-1: Passenger's route choice behaviour due to disturbances in a transit network

If travellers are not aware of events and their impacts on public transport services in advance (e.g. in case of incidents), they might make decisions as they normally do. Thus, they follow their frequent routes until they are informed of service disturbances. For instance, they might board on a service and confront within their trip an uneven path (e.g. a diverted path). In this case depending on the availability of information, the affected travellers may either look for new alternative(s) for the rest of their trip or comply with irregularities in services. If adequate information and guidance are provided for travellers, for example by driver or at the stations, travellers can look for an alternative route in the middle of their trip thoughtfully. Otherwise, they have to comply with irregular services and find the least cost alternative to reach their destination. In the case of complying with irregular paths, travellers might suffer from additional travel time, for example, when they involve in a diverted service path and have to walk longer.

In both cases (pre-trip choice and en-route choice) changes in the ordinary route choice behaviour are to be expected (Hickman & Bernstein 1997; Nguyen & Pallottino 1998). Thus, impacts of major discrete events should not only be considered in the routes' travel times, but also in travellers' changed route usage.

The discussion above demonstrates that traditional methods capturing service quality variations by a travel time reliability indicator added to the routes' utility function are incapable of dealing with impacts of major discrete events on route choice behaviour.

Therefore, in risk-related travel demand analyses route choice modelling has to be extended with respect to the route utility function, the route set generation procedure, and route choice behaviour in order to capture the impacts of major discrete events adequately.

6-4 Summary and Conclusions

In this chapter we elaborated on modelling PT route choice behaviour influenced by service reliability. We extended classical PT route choice models as building blocks in order to incorporate the influence of service reliability. This is especially of concern when public transport networks suffer from disturbances caused by all types of events including major discrete events. These events may cause severe service quality variations.

In this chapter we reviewed briefly the fundamentals of classical route choice modelling to provide an appropriate basis for dealing with impacts of stochastic events and service reliability on PT route choice behaviour.

Depending on the nature of service disturbances, different methods maybe applied to incorporate service reliability on route choice decisions. In case of minor continuous ongoing events, traditional methods address impacts of service variations on choice behaviour by including a travel time reliability indicator into the routes' utility function. The standard deviation of travel time is a commonly used travel time reliability indicator.

In case of major discrete events occurring, consequent disturbances are large enough to impact travellers' behaviour as well. Due to major discrete events, transit services are not operated as usual. Detoured lines, partial lines, and temporarily cancelled services are typical consequences seen in service quality. Due to these changes in transit service quality offered to passengers, passengers are assumed to exhibit different route choice behaviours depending on the availability and adequacy of information about the transit network situation. If passengers are informed sufficiently beforehand about transit service changes, they make a decision pre-trip. However, if passengers are not aware of disturbances in transit services in advance, they make choices as they normally do and during their trip, they might be obliged to make a route choice again en-route. In this condition, they may suffer from additional travel time, or involve in a diverted service path and walk longer.

Consequently, incorporating service reliability in route choice behaviour enforces modellers to apply a series of extensions in route choice modelling. The findings of this chapter demonstrate that impacts of stochastic events on route choice behaviour maybe different. In case of minor continuous ongoing events, dealing with service reliability is limited to the extension of the route's utility function by including a travel time reliability indicator; whereas in case of major discrete events the route set generation procedure and route choice behaviour are also extended by relaxing route set generation constraints, and considering pre-trip and en-route choice behaviour respectively. In the next chapter we will implement these extensions in a simulation model aimed at estimating the effects of disturbances on the PT travel patterns.

7 IMPACTS OF RELIABILITY ON PUBLIC TRANSPORT NETWORKS ASSESSMENT

7-1 Introduction

In chapter 5 we discussed that service reliability in public transport networks can be improved by applying strategic, tactical, and operational measures. In the context of strategic network planning we indicated that effective measures are reducing service network vulnerability, increasing service network redundancy and creating service network flexibility. Applying these strategic measures also facilitates operational adjustments, which are applied to mitigate service disturbances and to maintain service reliability high.

We discussed in chapter 5 that both strategic and operational measures have consequences on overall network performance which are related to a number of questions being raised as follows:

- To what extent do strategic and operational measures affect public transport network assessments and design?
- Which impacts do reliability improving measures have on overall network performance?
- Are the impacts of reliability improving measures large enough to change classical public transport service network design approach?
- What are the net results of network design dilemmas (dilemma 4, 5 and 6) stated in chapter 5 for typical urban public transport networks?

In this chapter we intend to address the aforementioned questions through a set of experiments. We focus on the following measures:

- Reducing service network vulnerability (e.g. by shortening existing service lines);
- Increasing service network redundancy (e.g. by including ring lines to a radial network);

- Creating service network flexibility to facilitate operational adjustments (e.g. by including additional infrastructures such as shortcuts to the transit infrastructure network).

The first two measures, focusing on the transport service network, are the subject of this chapter, whereas the third one dealing with infrastructure will follow in chapter 8.

The above measures are analysed with an assessment model developed on the bases of the frameworks proposed in chapter 5 (network design) and 6 (traveller's behaviour modelling). The model simulates stochastic conditions in the network by generating major discrete events. Also, impacts of minor quasi continuous ongoing events are captured by measuring regular travel time variations for transit travellers.

The model produces several outputs focusing on travel costs, operation costs, and also service reliability related costs consisting of travel time reliability costs and connectivity reliability costs at the disaggregate level (OD pairs) as well as the aggregate level. In order to evaluate network performance, the model produces aggregate output of total network costs expressing the overall network performance.

Given the discussion in chapter 3 stated by table 3-6, we adopt a tram network for demonstration purposes. It is vulnerable in case of disturbances caused by major discrete events, and operated only on dedicated infrastructure network. Therefore, facilitating operational measures depends on infrastructure availability in tram networks.
We perform experiments for a hypothetical tram network with a radial pattern. As indicated in chapter 2, this is the dominant pattern for urban public transportation in European cities. The service network configurations consist of radial lines and ring lines varying with respect to the availability and the location of the ring infrastructure and the corresponding ring line. Accordingly, they configure different levels of line density and thus service network redundancy. Also, we will replace radial lines by transversal lines to have a transit network with higher vulnerability. We indicated in chapter 5 that lengthening service lines would aggravate service network vulnerability. Thus, different experiments having different levels of redundancy and vulnerability will be set up and their overall performance including reliability will be assessed.

In general, the outcomes of the analyses in this chapter will validate whether or not considering reliability in the network assessment leads to different assessment results and thus changes in public transport network design.

7-2 Modelling framework

Based on the previous discussion of the extension of the public transport network design problem regarding service reliability (chapter 5 and 6), a simulation tool has been developed for assessing public transport network performance including service reliability. In this section, the main components of this simulation tool will be described. More details can be found in appendix 3.

7-2-1 General setup

Figure 7-1 shows the algorithm of the simulation model. The public transport network consisting of both infrastructure and the transport service network as well as transit demand are main inputs of the model. The model assumes a predefined infrastructure network as well as a predefined transport service network. The public transport service network is defined as a set of lines using the infrastructure network and a budget for operating the services under regular conditions. Furthermore, the model assumes a public transport demand pattern between zones according to land use.

We consider two phases in the model:

- The deterministic phase in which impacts of major discrete events are not accounted for;
- The stochastic phase in which impacts of major discrete events are accounted for.

As described in section 5-4 we use different travel cost functions in these two analyses
For both phases an output presenting total travel costs is computed. For the stochastic phase total travel costs include extra travel costs as well as trip cancelation costs and total operation costs including extra operation costs are computed given adapted parameters value in the cost function. Thus, an output containing the following cost components are generated:

- Travel time (converted to costs) for each OD pair;
- Extra travel time (converted to costs) for each OD pair due to major discrete events;
- Trip cancelation number (converted to costs) for each OD pair;
- Operating costs;
- Extra operating costs in case of disturbances in the network.

In valuing extra travel time, we expect that the value of time for the additional travel time is higher due to the related uncertainty. A penalty for cancelled trips is included in the travel costs as well a cancellation penalty based on origin-destination distance, thus accounting for the costs of using alternative modes.

For the overall network performance assessment, the aforementioned indicators are aggregated for the entire network to provide a relevant assessment of transit service performance.
For further details about the model and parameter values, please see appendix 3.

7-2-2 Phase I: deterministic perspective

In *the 1st phase* the model assigns public transport demand to service lines by a route choice mechanism. We apply an explicit route set generation procedure. For each OD pair potential routes are generated using a systematic enumeration procedure and then appropriate routes that meet given route set criteria are included in the route set. Various route set generation criteria proposed in chapter 6 are applied to generate proper route sets between OD pairs. In addition to obvious criteria such as logical criteria and feasibility criteria, we apply the directional constraint to limit maximum detour length for public transport travellers. This criterion will prevent traversing via longer routes that are not usually acceptable for public transport travellers. Furthermore, we limit the route set size by including attractive routes having a high probability of being chosen. This will prevent inclusion of routes that may rarely be chosen by a traveller.

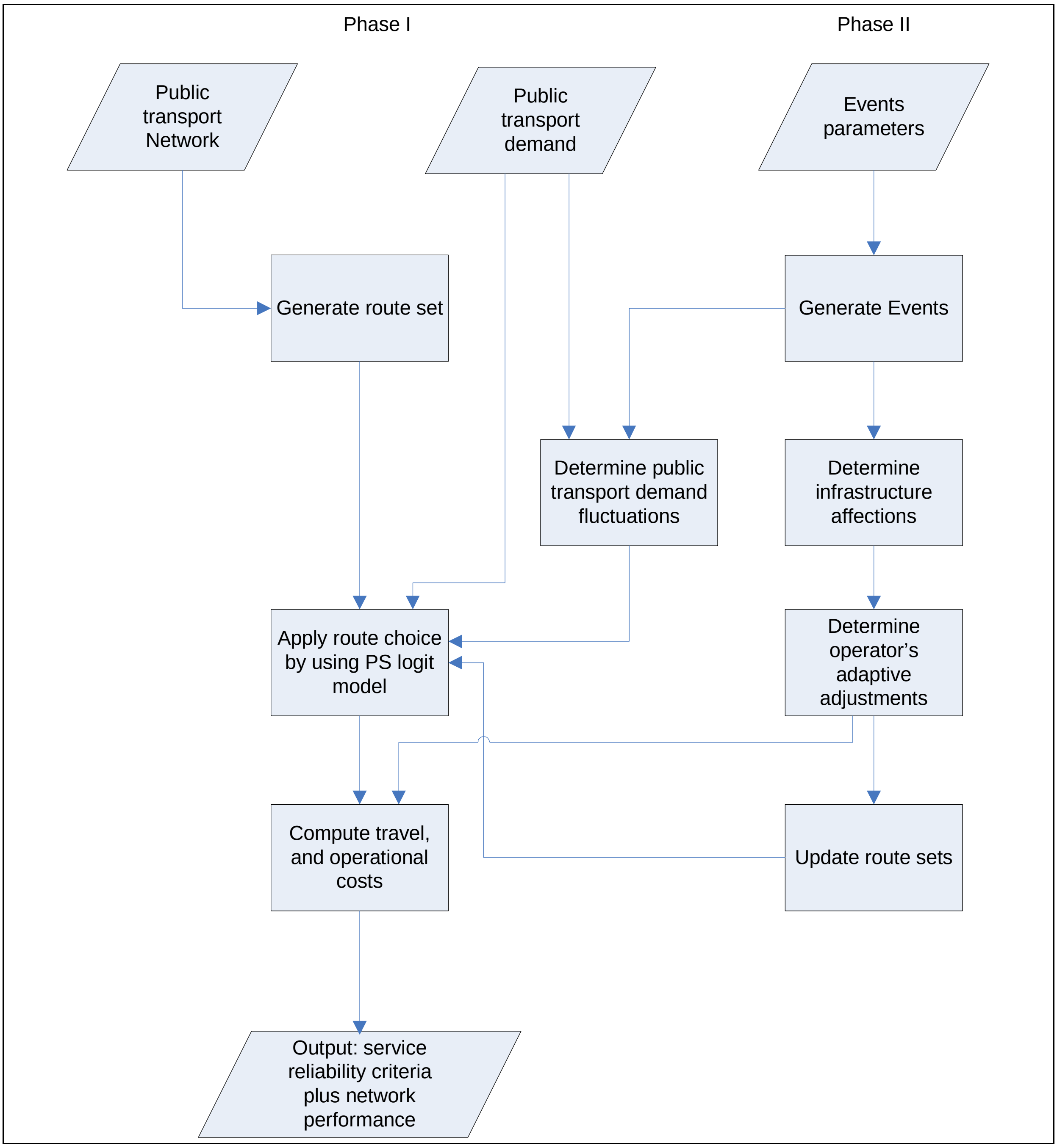

Figure 7-1: Algorithm of the network assessment model

We apply the extended route utility function (Equation 6-10, chapter 6) to incorporate explicitly impacts of travel time variations caused by minor quasi continuous ongoing events. Thus, travel time reliability is a component of the route utility function using the mean-variance approach. For modelling route choice, we use the path size logit model. This structure is an advanced logit model which deals with the overlap problem (Ben Akiva & Bierlaire 1999; Hoogendoorn-Lanser, et al, 2005; Bovy et al, 2008). The used route utility function contains waiting time, in-vehicle time, number of transfers, waiting time at transfer points, and travel time reliability. We define centroids representing a number of nearby stops and thus exclude access and egress time.

Regarding relative high service frequency, the model computes average waiting times assuming that passengers arrive at the departure point randomly with a probability distribution for example uniform, or Poisson distribution (Tisato 1998). The weight of utility function components are set based on realistic surveys' outcomes. All corresponding parameters' values have been stated in appendix 3.

As stated before, to include travel time reliability in regular conditions, we consider regular travel time variations arising due to minor ongoing continuous events. We use the standard deviation of travel time as the travel time variation indicator. This indicator is included in the routes utility function as formulated in chapter 6 mathematically.
To generate cost related outputs, all travel time components are converted to the costs by a relevant value of time. As the main output deterministic travel costs as well as operational costs are computed.

7-2-3 Phase II: Stochastic perspective

The *2nd phase,* dealing with network performance evaluation in the stochastic situation, consists of *6 stages*. In this phase we assess the network performance including service reliability in stochastic conditions focusing on disturbances caused by major discrete events (Figure 7-1 right side). In *the first stage* we use Monte Carlo simulation techniques to create events for a certain period of time, e.g. a year. Thus, different kinds of major discrete events with their specific time intervals and durations are generated. For determining the interval between events an exponential distribution is used (Tsakiris & Agrafiotis 1988), whilst for the duration of the events a lognormal distribution is applied. (Golob et al, 1987; Giuliano 1989). Examples of major discrete events are bad weather including storm, black ice, heavy snow, as well as public events, road works, incidents, and vehicle breakdown. The parameters for frequency and duration of each event type are determined based on realistic estimates. Seasonal events such as black ice and snow can only occur during 25% of the modelling period (i.e. 90 days). For more details refer to appendix 3.
The events are sorted along the time axis, so that for each moment in time it is known whether there is a disturbance and if so, which type(s). Please note that multiple events might take place at the same time. Also, as indicated in chapter 3 correlations between events and their impacts on public transport demand fluctuations are considered.
The second stage of phase 2 determines which link(s) of the infrastructure network are affected by major discrete events. A Monte-Carlo approach is used to select failing links. Probability of link affections depends on the link length and the other factor of link sensitivity to failures. Furthermore, as stated in chapter 3 the correlation between bad weather and incidents are considered meaning that during bad weather conditions the probability of incidents rises.
Please note that in case of service network failure such as a vehicle breakdown, the infrastructure network is affected accordingly. This is especially the case for rail networks.
In case of public events, we assume fixed time and locations for events. Thus, corresponding segments that are affected can be identified beforehand. For events with extensive geographical impacts such as snow and storm a part of the network involving a number of links are affected simultaneously, whereas for other types of events such as incidents only a single link is blocked at the time of the incident.

In *the third stage* impacts of the generated events on public transport demand are determined. The relevant events are bad weather and public events. As indicated in chapter 3 these events can increase public transport demand substantially.

The *fourth stage* considers operator adjustments and remedial solutions applied to mitigate disturbances. Remedial solutions are applied according to a priority order. The priority list is used to determine which measure is applied. The priority order is ranked by applying detours, and other remedial solutions consisting of splitting services, and applying partial services.
The first priority is applying detours. The main requirement for applying detours is availability of infrastructure. In addition to the required infrastructure, the operator might consider other factors consisting of extra running time, operation costs, and number of skipped stops as well. If applying detours increases operation costs largely, or if a large number of stops are skipped, the operator may choose other options.
If applying detours is not possible, the operator will try to split service lines into independent lines or to apply short runs. Depending on the location of event(s), the service line could be split into two parts. It is also possible that there is a gap between the split parts. In this case public transport passengers are forced to travel this gap on foot. Please note that the availability of short turn facilities is an important requirement for applying partial services for rail bound networks.
To deal with higher transit demand in case of events such as bad weather, transit operators can follow the increasing capacity strategy described in chapter 5. It is usually achieved by increasing service frequency using their reserved vehicles. Please note that increasing service frequencies might not be feasible for heavy rail modes with high service frequencies (e.g. metro), since a minimum headway must be maintain between successive services for safety purposes.
And finally, if a transit line is affected at different locations simultaneously or there is no possibility for detour or line splitting, the service line will be cancelled temporarily during the event's occurrence.
Given the aforementioned measures, the adapted network including adjusted transit lines at the time of disruption(s) is determined. Please note that in this stage as indicated in chapter 5, the transition phases for commencement of adjustments aren't considered and the transit network situation in the steady state is accounted for only.

Given the adapted service network, in the *fifth* stage public transport travellers will choose their routes accordingly. In this situation a different route search procedure with relaxed constraints as discussed in chapter 6 is applied for public transport travellers suffering from disturbances. Please note that we assess public transport traveller's behaviour for a tram network while intermodal behaviour is not accounted for. Constraint relaxation is done by the following adjustments:

- Allow larger number of transfers;
- Allow walking to change between lines;
- Allow higher detour thresholds.

The *sixth stage* focuses on public transport traveller's route choice behaviour in irregular conditions. Pre-trip decision making is considered for expected events such as road works, or public events. The assumption here is that the public transport travellers are already aware of adjusted services due to these events. En- route decision making is taken into account in case of unexpected events such as incidents, and vehicle breakdown. In this condition, passengers may be obliged to travel via longer routes or even walk a part of the route. In the worst condition, they might need to postpone their trip until an alternative route is available. For further details, we refer the reader to part 6-3-2 of chapter 6.

7-3 Selection and setup of experiments

In this section the setup of experiments is described. Based on the discussion in chapter 2, we focus on public transport network fundamental characteristics consisting of the transport network type and the service line type. These are main topological characteristics that are dealt with at the strategic network planning stage.

7-3-1 Service supply pattern and properties

For the experiments as indicated before, a symmetric network with radial pattern is chosen. The symmetry of the network will avoid that the outcomes completely depend on network topology especially for the analysis of the new design dilemma regarding line length. Choosing a radial network is motivated by its dominance in European cities. Consequently, the hypothetical network has a predefined radial infrastructure (Figure 7-2). The chosen length of radial infrastructure is 9.5 km. This is similar to transit network pattern in large cities (e.g. Oslo, Frankfurt).

The city is served by a tram network with a separated right of way. The tram speed on lines is assumed to be equal and is set to 20 km/h including dwell times at stops. This is according to the average speed of tram networks in several European cities such as The Hague, Brussels, Gothenburg, and Oslo (HTM 2004; Urban Rail.net 2009). The public transport service network is defined as a set of lines using the infrastructure network and is limited by a budget for operating the services in regular conditions. Thus, headways between services depend on the operator's budget. The operator's budget has been set in such a way that there are tram lines with high service frequency (e.g. 6 veh/hr) in the system. The operation costs are assumed to be estimated only based on vehicle-kilometres. The service operation time per line is set at 18 hours per day. For more details on network characteristics, please refer to appendix 3.

For the experiments, we define different network types according to their service line configurations. Different network types, i.e. combinations of infrastructure networks and service networks, are considered, varying with respect to the availability and the location of the ring infrastructure and the corresponding ring line. The following combinations are studied (For schematic illustration, refer to figure 7-2):

1. Eight radial lines only;
2. Eight radial lines and a centre ring infrastructure and centre ring line;
3. Eight radial lines and a medium ring infrastructure and medium ring line;
4. Eight radial lines and a large ring infrastructure and large ring line;
5. Eight radial lines and an outer ring infrastructure and outer ring line;
6. Four transversal lines only;
7. Four transversal lines and a centre ring infrastructure and centre ring line;
8. Four transversal lines and a medium ring infrastructure and medium ring line;
9. Four transversal lines and a large ring infrastructure and large ring line;
10. Four transversal lines and an outer ring infrastructure and outer ring line.

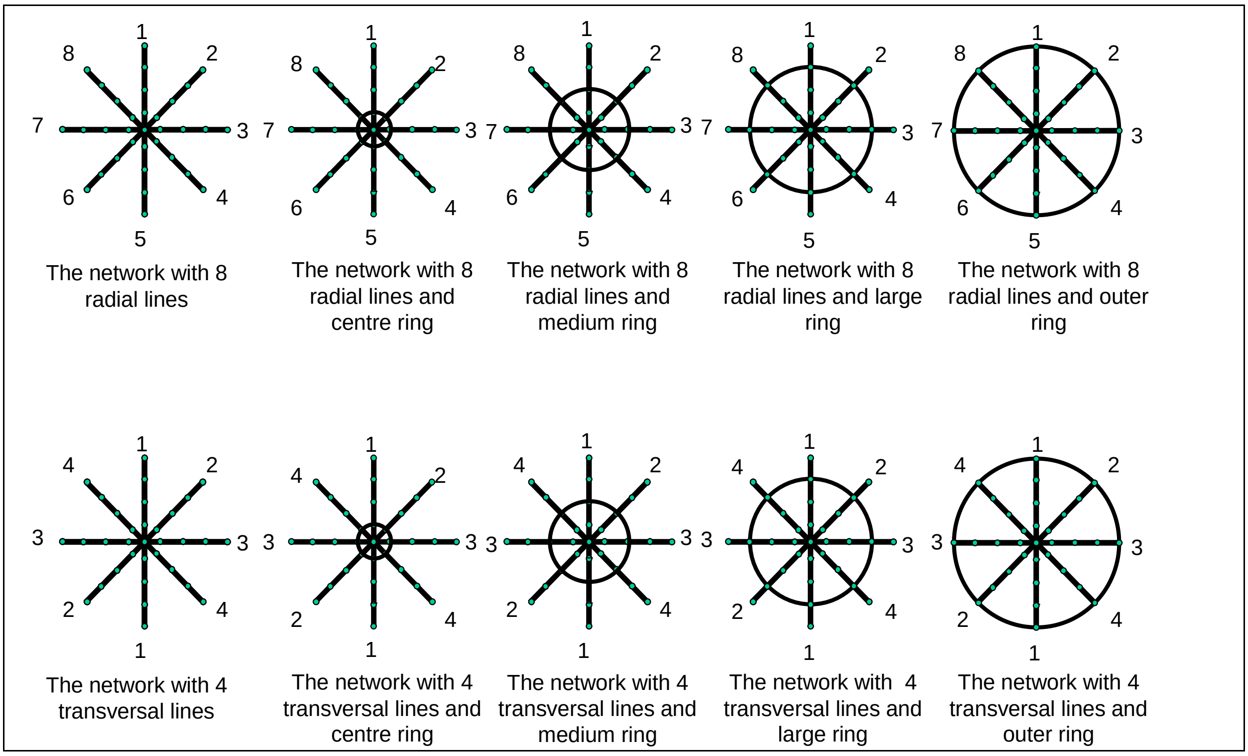

Figure 7-2: Schematic illustration of the infrastructure alternatives in the experiments

These combinations are arranged based on the aforementioned discussed on redundancy and vulnerability notions. Therefore, variants 1 to 5 and variants 6 to 10 are distinguished according to the vulnerability notion: as discussed in chapter 5, vulnerability of a transport service network depends on the line length. Therefore, by replacing radial lines by transversal lines (variants 6-10), an increase in service network vulnerability may be expected.
Furthermore, as indicated in chapter 5, service network redundancy could be achieved by increasing line density. Hence, in variants 2-5 and 7-10 we combine a ring service line with either radial or transversal lines. Regarding location of the ring line, different levels of network redundancy are generated. By increasing the radius of ring line, line density increases. Increasing line density will offer multiple routes to larger number of origins-destinations and thus leads to higher service network redundancy. In order to have an overview of infrastructure investment and maintenance costs, operation costs, and travel costs, see appendix 3.

Figure 7-3 illustrates the infrastructure network for variant 3 (radial lines combined by a medium ring). Obviously, merging a number of radial lines at the city centre deserves special attention on the required infrastructure. We discuss this issue in appendix 3. The dashed lines indicate the location of the rings for the other variants. Please note that in each case only the infrastructure used by the service network is available.
As a result it can be expected that variants (1 and 6) will be quite sensitive for failures in infrastructure availability as there are no possibilities for detours. Depending on the location of the ring line, the other variants could be more robust. For instance, a detour for a radial line uses a part of the ring to switch to a neighbouring radial line. In the case of ring lines only detours via the city centre are possible. The operational budget is assumed to be identical for all alternatives. Consequently, the associated frequencies are the highest for variant 1 and 6 and the lowest for variant 5 and 10.

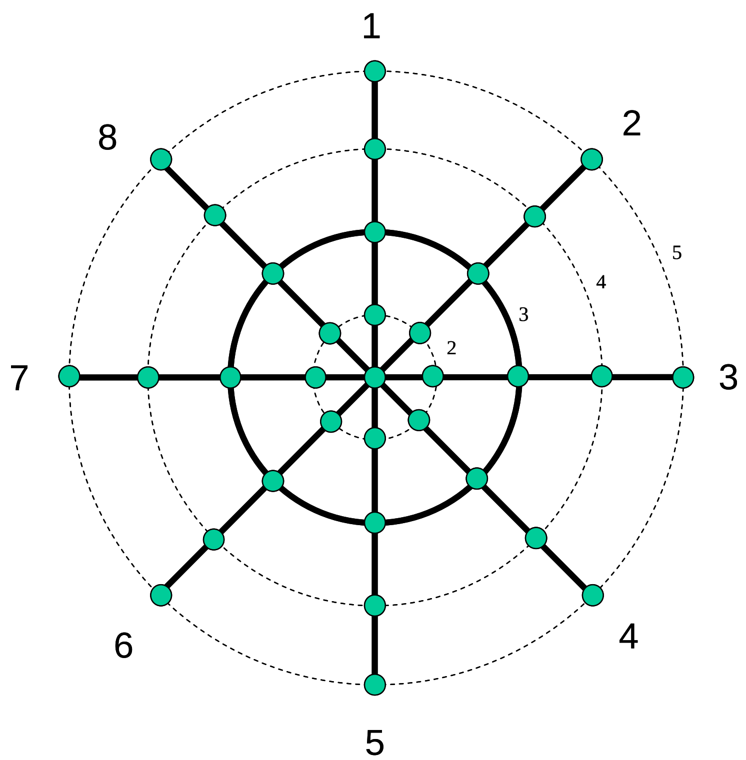

Figure 7-3: Lay-out of the service network and the infrastructure network for variant 3: radials and medium ring (dashed lines indicate the infrastructure for the other variants)

7-3-2 Transit demand pattern and behavioural parameters

Following the findings in chapter 3, the public transport demand pattern is predefined and classified periodically (peak, off-peak), seasonally, based on four user classes:

- Commuters;
- Students;
- Shoppers;
- Other travellers.

As indicated in section 7-2, the level of demand is assumed to be independent of the quality of the services offered. It is about 32.1 million trips in a year for the public transport network. Public transport demand is assumed primarily centre oriented, while four sub centres also attract their share of the demand (Figure 7-4). The transit demand is distributed over 33 centroids. The demand matrix is assumed to be symmetric. We assume that the city centre zone attracts 25% of the whole transit demand while this rate is 12.5% for each sub centre.

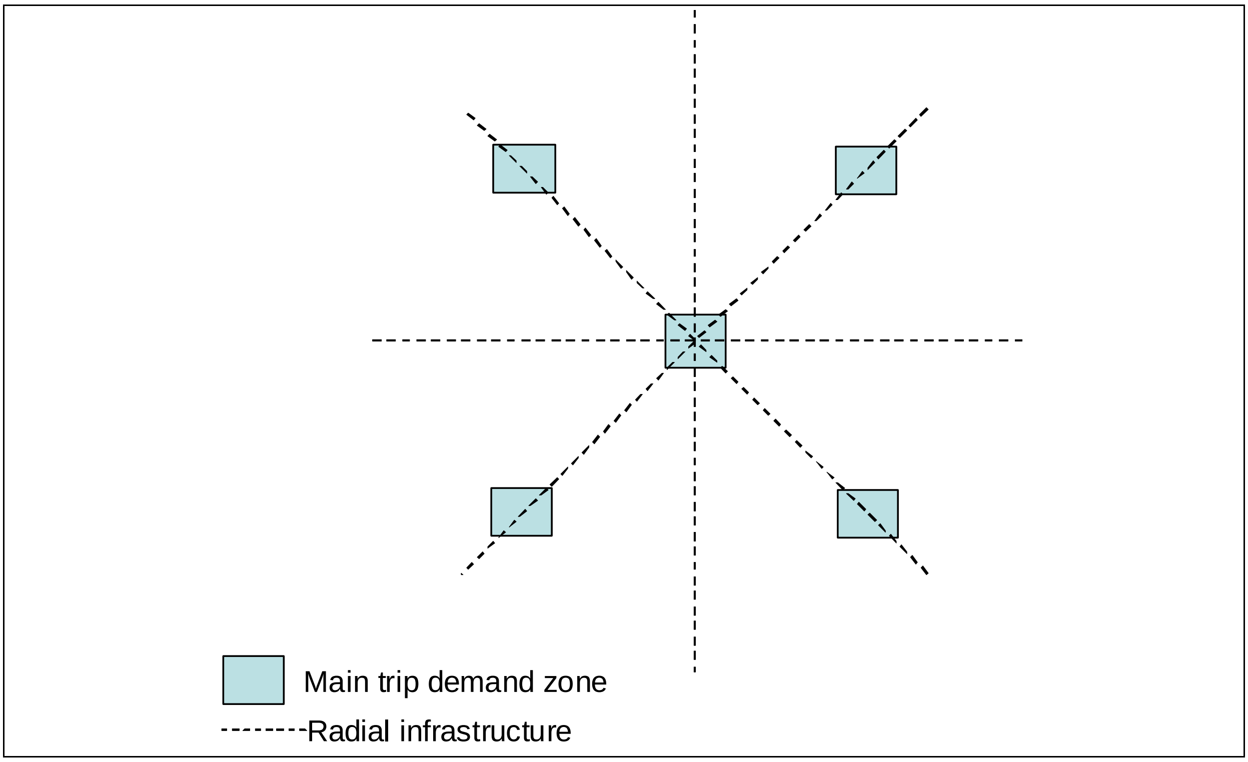

Figure 7-4: A city layout with predefined radial infrastructure and transit demand

Since we define centroids as representatives of the corresponding zones containing stops, we skip access and egress times consequently. Based on travel time components' weights found by Van der Waard (1989), and Wardman (2004), and travel time reliability perception found by Tseng et al (2004), the implied route utility function is formulated as follows:

$$U = 10(1.5t_w + 1\sum_{j=1}^{n_t+1} t_{in,j} + 8.2n_t + 1.2\sum_{i=1}^{n_t} t_{ti} + 1.7t_r) + r_t + \varepsilon \qquad (7\text{-}1)$$

The value of time in regular condition as stated is set to 10 €/hr for passengers. This value is an average value of time for car, train and tram/bus users according to the cost benefit analysis performed by Dutch Ministry of Verkeer and Waterstaat in 2000. The value of time increases to 20 €/hr in case of disturbances in the network.

7-3-3 Network performance

Table 7-1 provides an overview of public transport supply and trip attributes data adopted in the experiments. As indicated in the previous section we set the mean waiting time to be one-half of the service headway. For instance, we set 5 minutes as the mean waiting time for the network with service frequency of 6 veh/hour. Given the demand pattern, the average trip length is 9.2 km, and the average unweigthed travel time for the network with transversal lines is about 38 minutes (table 7-1). Obviously, the average travel time for the network with radial lines is longer, because a larger number of transit trips are made via transfers.

Table 7-1: An overview of network main supply and trip attribute for the experiments

	attribute	Corresponding value
Public transport supply	Hourly service frequency per line	8
	Service operation time per line (hour)	18
	No. of vehicles per line	8 (R), 16(T)*
	Vehicle speed considering dwell times(km/h)	20
Transit trip	Average trip length (km)	9.2
	Average unweighted travel time including waiting times (min)**	38
	Average waiting time (min) excluding transfer time	5
	Percentage of total trips using a transfer**	60%

*8 vehicles for radial lines and 16 vehicles for transversal lines
** The network with transversal lines

7-4 Assumed characteristics of simulated events

In this part the characteristics of the major discrete events simulation will be discussed. Event characteristics such as average number of generated events per year, and their duration are presented. Characteristics of events are found out after simulating for a number of runs representing years (e.g. 20 years). This will provide an overview of the network situation due to stochastic events for a long time period. Furthermore, we will present assumed statistical characteristics of events such as the coefficient of variation and the probability distribution for each type of event. We address how each event type affects transit network performance. Dealing with this issue will enable us to make a comparison between events' effects on the network performance. Results will lead to finding out how much generating network disturbances depend on the number of simulation runs. In other words, how many simulation runs we need in order to be able to analyse the networks in an average irregular situation.

On average after 20 simulation runs, an arbitrary link is affected 8 times per year by events and the average duration of disturbances per link is about 2 days per year (Table 7-2). The coefficients of variation of number of generated events and events duration are expressed in the last two columns. Note that, since many public events have predefined patterns, they may repeat every year with the same number and duration (e.g. annual exhibitions, ceremonies) and thus its coefficient of variation will be zero.

In order to find out whether the impacts of frequent and non frequent major discrete events on transit networks are different, we quantify the probabilities of occurrence for different number of generated events. Given the simulation results stated in table 7-2 (the 1st column), we choose bad weather and work zones as non frequent events, and vehicle breakdown as a frequent event. The coefficient of variations (COV) of number of generated events differ between impacts of major discrete events with larger number of occurrence (frequent events) and major discrete events with smaller number of occurrence (non frequent events). Frequent major discrete events such as vehicle breakdown take place more or less with the same frequency in the network (COV = 0.18) and therefore, they have the same impacts on the network in terms of disturbances within several years. However, the impacts of non frequent events such as bad weather vary substantially within years (e.g. COV=1.59) and thus fully depend on occurrence pattern.

Table7-2: Characteristics of the generated events affecting the network per year

Event type	Average number of events in the network	Average number of events per link	Average duration of events in the network [days]	COV of number of events in the network	COV of duration of events in the network
Incidents	447.9	7.00	0.55	0.05	0.11
Storm	2.6	0.04	0.11	0.68	0.63
Ice	0.5	0.01	0.01	0.97	0.99
Snow	0.5	0.01	0.05	1.59	1.50
Thunderstorm	3.4	0.05	0.02	0.42	0.37
Work zone	4.2	0.07	1.06	0.42	0.42
Public events	5.1	0.08	0.09	0.00	0.00
Vehicle breakdown	50.5	0.79	0.09	0.18	0.17
Total	515.1	8.05	1.99	-	-

Figure 7-5 illustrates the distribution of the number of events for bad weather as a non-frequent event by a trend line. As the figure shows, the large variation in probability of occurrence is observed for diverse number of generated events.

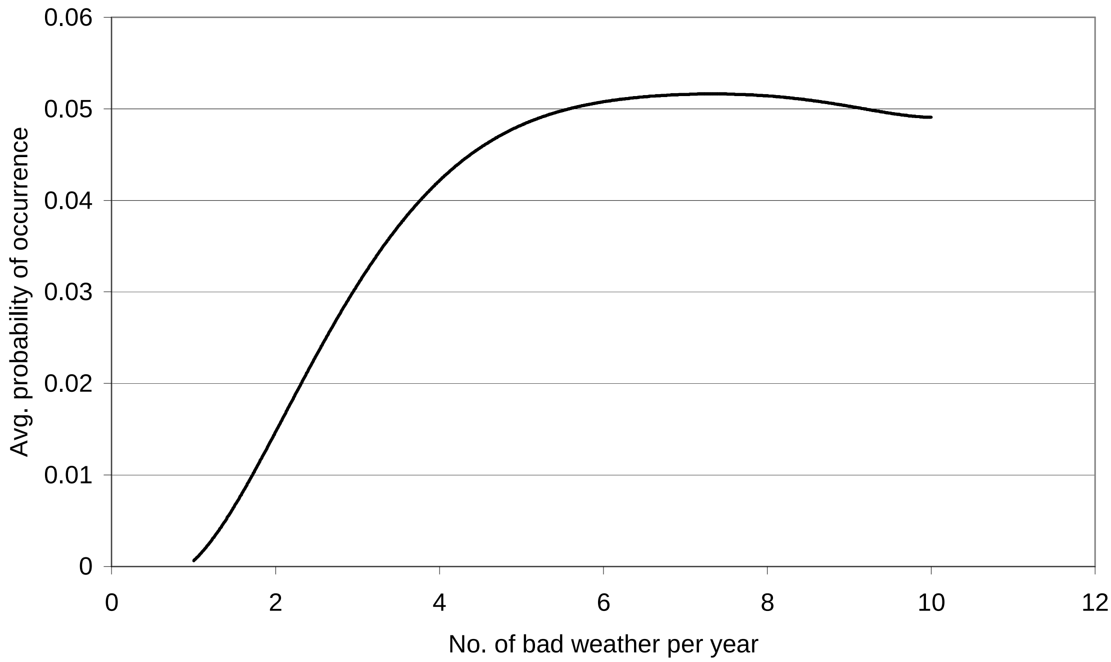

Figure 7-5: Diversity distribution of No. of bad weather occurrence

Given these analyses and in order to assess the network performance accurately in the stochastic perspective, a question is raised: how many simulation runs (years) do we require having an acceptable sample for determining uniformly and adequately the impacts of non frequent events on the service network? In other words, how many simulation runs result in equal affections in the symmetric service network?

In order to address this question and to find out the required sample size, we assess the results of non frequent events simulation with various sample sizes differentiated by a 5 years range (e.g. 5 years (1800 days), 10 years (3600 days), 15 years (5400 days), 20 years (7200 days), 25 years (9000 days) and 30 years (10800 days)). Based on the previous discussions and table 7-2 results, we choose work zone and bad weather as non frequent events.
To determine the minimum sample size *(n)*, we use a statistical rule of thumb formula as follows (Van Belle 2002):

$$n = \frac{8COV^2}{PC^2} \cdot \left[1 + (1 - PC)^2\right] \qquad (7\text{-}2)$$

Where:

PC is the proportional change in means. (The amount of *PC* is suggested to set as 20% (Van Belle 2002);

Below, we show the results of analyses for the minimum acceptable sample size *(n)* only. Table 7-3 shows, the average number of affections per line for a simulation period of 20 years:

Table 7-3: Average number of affections due to work zones per line (simulation period is 20 years)

	line1	line2	line3	line4	line5	line6	line7	line8
The average number of affections	0.25	0.35	0.30	0.25	0.25	0.20	0.25	0.15

For these eight radial lines the overall *COV* is equal to 0.239 assuming *PC* 20 %. Thus, the minimum size for this sample based on formula 7-1 will be 6732 days which is less than 7200 days.
We repeat this analysis for bad weather as well. The outcomes lead to smaller number of runs. Thus, these calculations demonstrate that 7200 days (20 years) are sufficient for correctly determining the impacts of non recurrent events on the network.

7-5 Network performance assessment

In this part, we will assess the network performance for different network types following from model calculations:

- Networks with eight radial lines and a ring line (variants 1,2,3,4,5);
- Networks with four transversal lines and a ring line (variants 6,7,8,9,10).

7-5-1 Cases

To assess the network performance for the aforementioned network types, four cases are defined accordingly:

- *Case 7-1:* assessing the networks with radial lines in the deterministic perspective;
- *Case 7-2:* assessing the networks with radial lines in the stochastic perspective;
- *Case7-3:* assessing the networks with transversal lines in the deterministic perspective;
- *Case 7-4:* assessing the networks with transversal lines in the stochastic perspective.

In the *first case* we assess the overall network performance in the networks with radial lines combined by a ring line in the deterministic perspective. We intend to determine the impact of increasing line density, which is provided by the ring line, on the overall network performance.

In *the second case* we determine how increasing service network redundancy may result in an improvement in service reliability. Thus, we re-assess the overall network performance including service reliability in the network with radial lines and combined with a ring service line in the stochastic perspective.

In *the third case* we assess impacts of lengthening service lines on the network overall performance. Therefore, we replace the eight radial lines by four transversal lines and re-assess its impact on the overall network performance in the deterministic perspective. According to discussion addressing service line length design dilemma in chapter 5, we find out whether this replacement leads to a better design option in the deterministic situation.

In *the fourth case* we evaluate impacts of service line length on network vulnerability and consequently service reliability. We re-assess the overall network performance as well as service reliability in the network with transversal lines in the stochastic perspective. We expect that by considering reliability measures in this phase we can find out whether larger vulnerability of transversal lines reduces their benefits in terms of travel costs.

Case 7-1: In this case, we compare networks in a deterministic perspective in terms of overall network performance. Obviously impacts of major discrete events expressed will not be taken into consideration. This is in fact a traditional network assessment since impacts of major service distortions are not accounted for. Figure 7-6 illustrates the relative total network costs as an overall network performance criterion for five variants. Variant 1 (radial only) is set as the reference case. For this variant the calculated total network costs per year consist of 65% of travel costs, 23% of operational costs, and 12% of infrastructure costs. It should be noted that these percentages depend on the selected value of time too. For different values of time, different cost shares are expected. The total network cost for this variant is approximately 397 M€ /year.

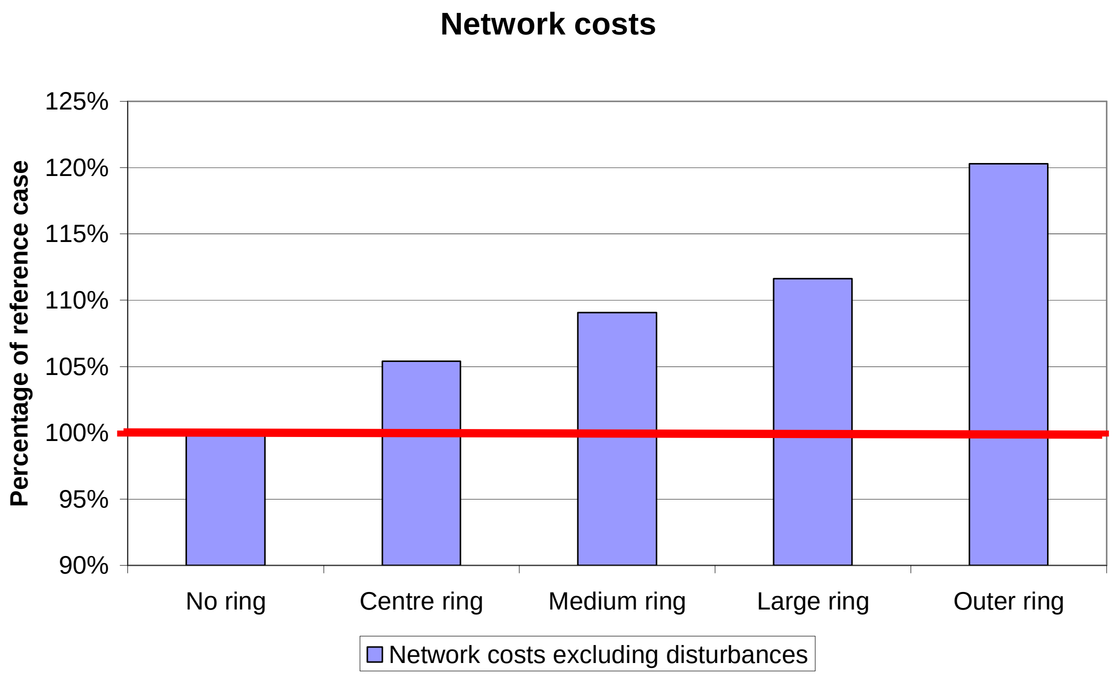

Figure 7-6: Relative total network costs for radial network variants in the deterministic perspective

As Figure 7-6 clearly illustrates, the total network cost is increasing with ring line radius increase. This is according to the traditional line density design dilemma which shows that increasing line density will increase travel costs given a fixed budget. This is due to a reduction of service frequency in the network. Obviously the result is strongly determined by considering of fixed operational budget. The alternative case of a fixed frequency in all variants, however, yields similar results due to the substantial increase of operating costs.

Case 7-2: In the second case we compare the variants in stochastic perspective in terms of overall network performance including service reliability. We intend to find out the role of service network redundancy on service reliability as well as the overall network performance. Hence, not only are total network costs taken into account, but also connectivity reliability and travel time reliability costs. Obviously, the calculated total network costs will be higher in the stochastic perspective. This is due to the introduction of additional components being included in the total network costs such as:

- Extra travel costs in irregular conditions caused by major discrete events;
- The trip cancellation cost in irregular conditions caused by major discrete events;
- Extra operation costs in irregular conditions caused by major discrete events.

Figure 7-7 compares the variants in terms of the connectivity reliability cost and travel time reliability costs in the stochastic perspective. This cost has three components. The first component consists of the regular travel time variations due to minor continuous ongoing events. They constitute approximately 4.5 % of regular travel costs. .
Trip cancelation costs due to major discrete events are the second component. The number of trip cancelations has been converted to costs by trip cancelation penalties which depend on the origin-destination distance. As it can be observed, the amount of trip cancelation costs reduces from left to right by an increasing redundancy level.

The third component consists of extra travel time variation costs due to major discrete events. The extra travel costs indicate longer travel times imposed to passengers. These longer travel times arise due to abnormal routes after disturbances in the network. For the option without ring service line, extra travel time is only due to walking in case of partial services, whereas for the other variants extra travel times due to detours and partial services are considered as well.

The results demonstrate that by increasing the radius of the ring line, the connectivity reliability cost expressed by the number of trip cancelation decreases. However, the alternatives provided (detour, partial lines, walking) yield extra travel time too. Reductions of cancelled trips thus increase extra travel time. The net effect is clearly positive.

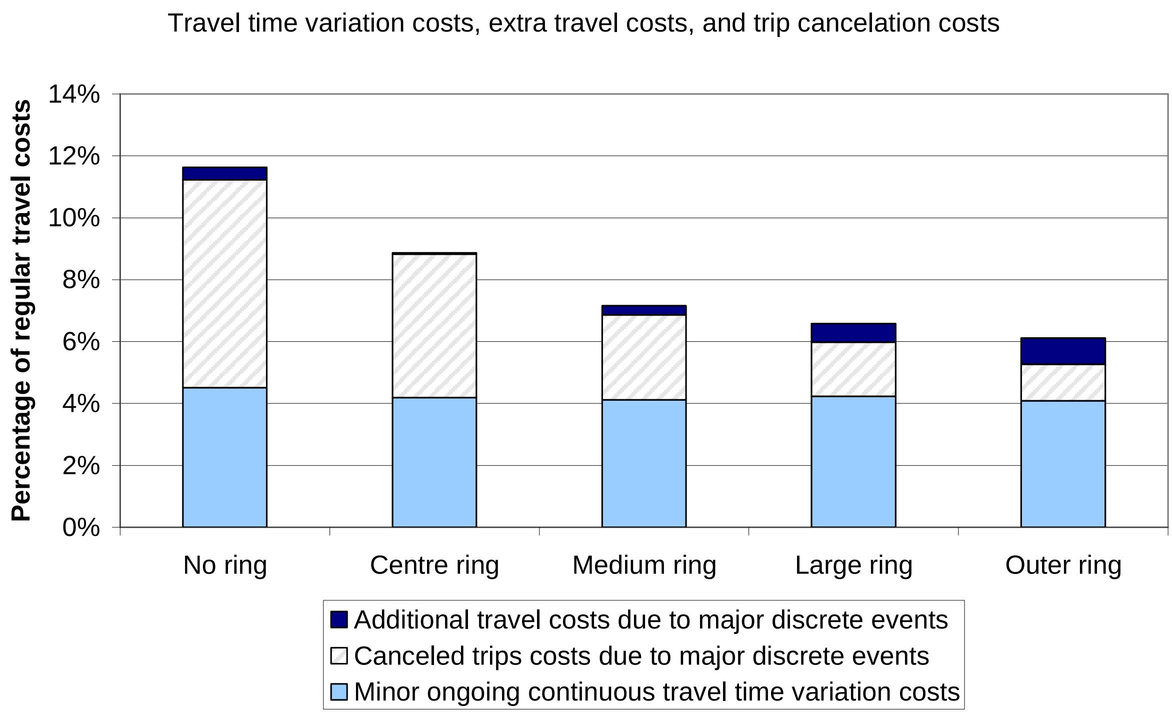

Figure 7-7: Reliability related costs for the networks with radial lines

The result illustrates that additional travel costs are substantial, especially for larger ring lines. The benefits of implementing the outer ring line in terms of reliability related costs are approximately the same as benefits of large ring line due to the demand pattern as well as the detour constraint. The outer ring line provides long detours that in many cases are not acceptable for transit passengers. Furthermore, these long detours cause long trips that impose higher extra travel costs to passengers. Hence, the positive effects of including ring service lines decrease for variant 5 having the outer ring. Given the aforementioned analysis, two results are noteworthy:

- Network redundancy reduces unreliability costs. From left to right by increasing the radius of ring line and therefore increasing network redundancy, trip cancellation reduces (Figure 7-7);
- In the deterministic perspective, travel costs are underestimated by approximately 10% because of ignoring probable disturbances in transit networks.

Figure 7-8 illustrates the relative total network costs for five studied variants. As before, variant 1 (radial only) in the deterministic perspective is set as the reference case. Thus, we can also compare the total network costs in the stochastic perspective to the total network costs in the deterministic perspective. Obviously total network costs in the stochastic perspective are higher due to unreliability related costs (e.g. cancelation costs).

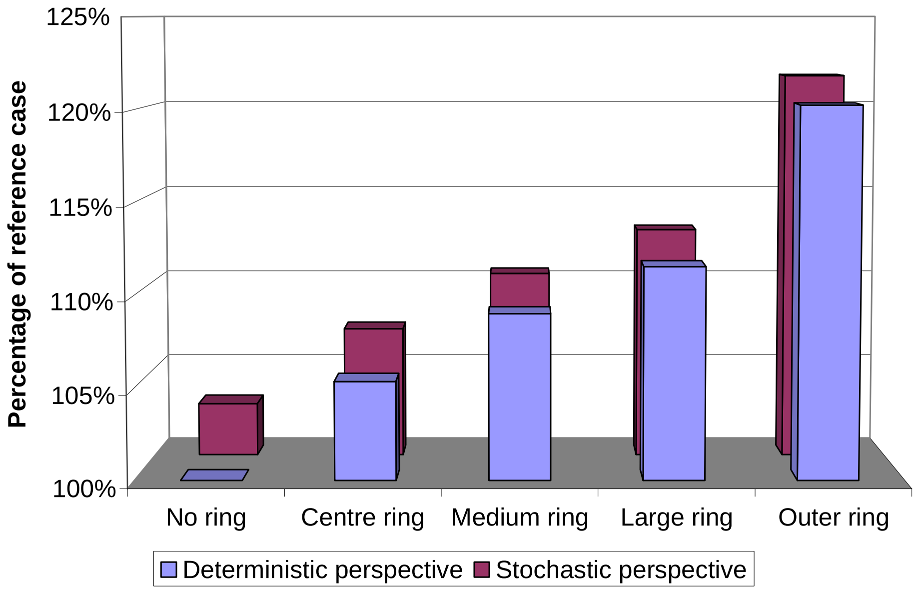

Figure 7-8: Relative total network costs for variants of the radial line network: the determinist perspective vs. the stochastic perspective

As figure 7-8 shows, the previous pattern illustrated in figure 7-6 has not changed. In other words, introducing an outer ring service line won't be beneficial in the stochastic perspective too.

In general the results of case 7-2 demonstrate that increasing network redundancy by including ring lines improves the service reliability, but does not lead to better overall network performance (Figure 7-8). In other words, the influence of service reliability as operationalised in our study on network design seems not large enough to change the trade-off of traditional line density dilemma. This implies that the traditional network design problem seems still dominant.

Case 7-3: in this case we assess the overall network performance for the network with transversal lines in the deterministic perspective. We intend to see whether replacing radial lines by transversal lines leads to better overall network performance in the deterministic condition. Figure 7-9 illustrates the network including 4 transversal lines for variant 3.

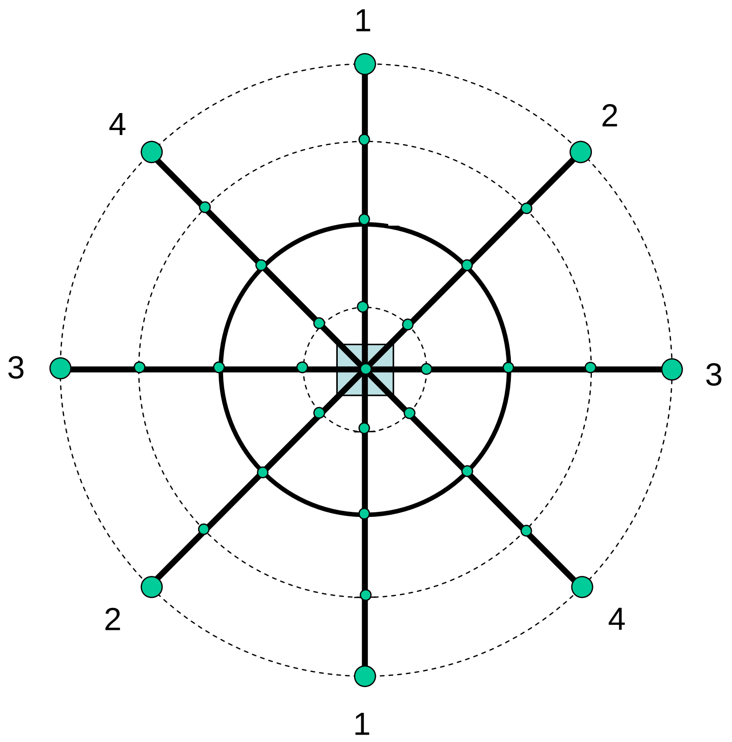

Figure 7-9: Lay-out of the infrastructure network for variant 3: transversal line and medium ring (Line number indicated; dashed lines indicate the infrastructure for the other variants)

Figure 7-10 compares the overall network performance variant by variant between the networks with radial lines and the networks with transversal lines in the deterministic perspective. Again, the radial network without ring service lines is set as the reference case.
A comparison between the networks with radial lines and the networks with transversal lines shows that the total network costs in the latter network is lower and thus the network with transversal lines is to be preferred. This is because transversal lines offer more direct services which lead to lower travel costs in the network, while other cost components such as operation costs are roughly the same for both network types. This reduction is around 5%. Thus, the design dilemma number *5* in chapter 5 stating that longer lines provide shorter travel time is corroborated in this case study.

Looking at the impacts of line density on the overall network performance (figure 7-10), the results demonstrate that the total network costs in the networks with transversal lines rise by increasing the radius of ring line similarly as the networks with radial lines and thus the network with minimum line density is again the optimum option. Therefore, for both service networks having radial lines and transversal lines, the optimum is the option without a ring line.

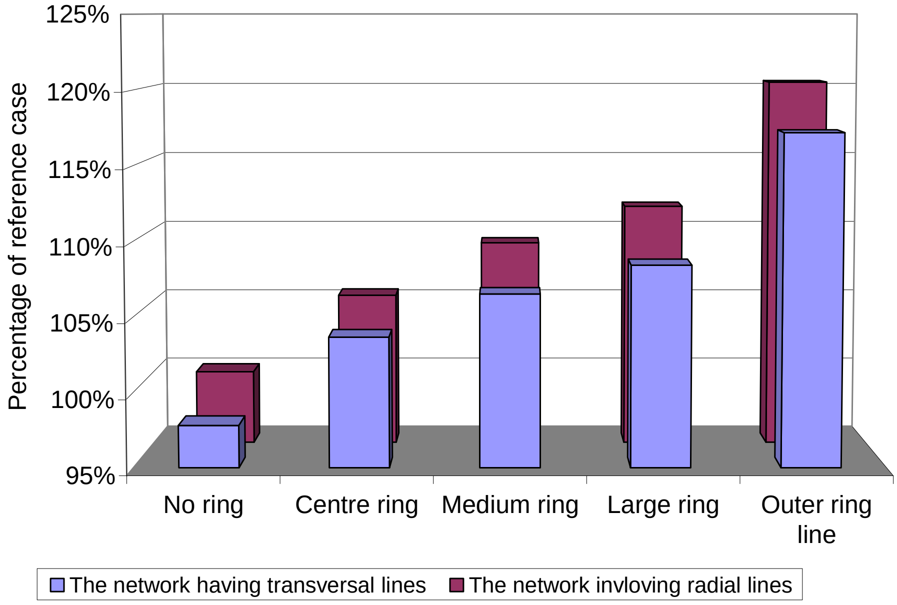

Figure 7-10: Relative total network costs for variants in the deterministic perspective in the network with radial lines and the network with transversal lines

Case 7-4: In this case we assess service reliability and the overall network performance of the network with transversal lines in the stochastic perspective. This case is similar to case 7-2; however, we replace radial lines by transversal lines. The results will verify network design dilemmas *4* and *5* in chapter 5 stating lengthening service line will raise unreliability costs.

Figure 7-11 compares unreliability related costs for variants of the network with transversal lines to the network with radial lines (1^{st} and 2^{nd} bars from left). The results demonstrate that unreliability related costs for the network having transversal lines are higher than the network having radial lines (27% vs. 11 %).
Firstly we focus on minor quasi continuous ongoing travel time variations costs indicated by C_{tv} in formula 5-2 in chapter 5. We discussed in section 5-4-1 that longer service lines suffer from larger travel time variations compared to shorter service lines. We outline this issue as dilemma *4* in table 5-3. The results of experimental analyses in case 3 verify that dilemma. Replacing radial lines by transversal lines will lead to +11% increase in regular travel time variation costs.

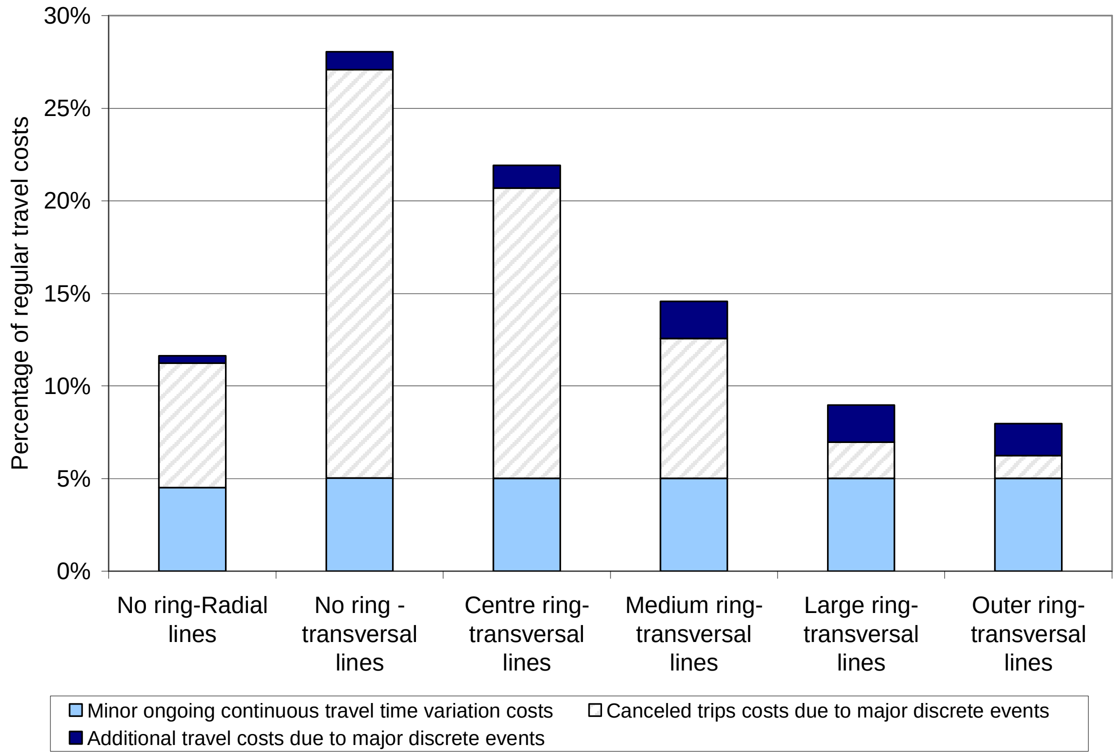

Figure 7-11: Reliability related costs for the network with transversal lines

The second measure we focus on is connectivity reliability in case of major discrete disturbing events. Figure 7-11 shows that trip cancelation costs for the networks with transversal lines are higher than for the networks with radial lines. This is due to the higher vulnerability of transversal lines (2.3 times as much as the network with radial lines) and lower possibility of operating adjustments. As shown in table 7-4, the number of times that a transversal line is affected by major discrete events is larger compared to a radial line (321 vs. 140 times per year). This is in line with dilemma *5* in chapter 5.
Moreover, the possibility of service adjustments for the operator is lower for transversal networks. This is because a transversal line is more likely to be simultaneously affected by multiple major discrete events in different locations than a radial line (115 vs. 50). This makes operating adjustments such as applying detours or implementing partial services more difficult and often impossible (dilemma 5, table 5-3).

Table 7-4: Vulnerabilities in the public transport service lines

	The radial line	**The transversal line**
The average number of line's affections per year	140	321
The average number of line's multiple affections per year	50	115

Figure 7-11 also shows that including ring lines to the network with transversal lines reduces the trip cancelation costs (from 2nd bar on the left side to the right side). For example, the network with transversal lines and a large ring line has lower reliability related costs than the network with radial lines. As indicated before, including ring lines increase service network redundancy. Since the number of trip cancelation for the network without a ring line (variant 1) is relatively high (about 9.8% of total trips on average), including the ring line especially the large ring line leads to a substantial drop in trip cancelation number. For variant 4 the number of trip cancelation is on average 1% of all trips. In other words, increasing network redundancy for the network with transversal lines enhances network connectivity reliability significantly. Of course, extra travel costs due to traversing via detour routes rise accordingly. The extra travel costs, imposed to public transport travellers in variant 4, are approximately 2.3 times as much as those in variant 1.

Figure 7-12 shows that the previous findings of overall network performance with respect to increasing network redundancy are still valid. Compared to figure 7-8, the difference between total network costs in the stochastic perspective and the deterministic perspective is higher in the network with transversal lines. This is due to the fact that trip cancelation costs are much higher in the networks with transversal lines than in the networks with radial lines (2.3 times as much as the network with radial lines).

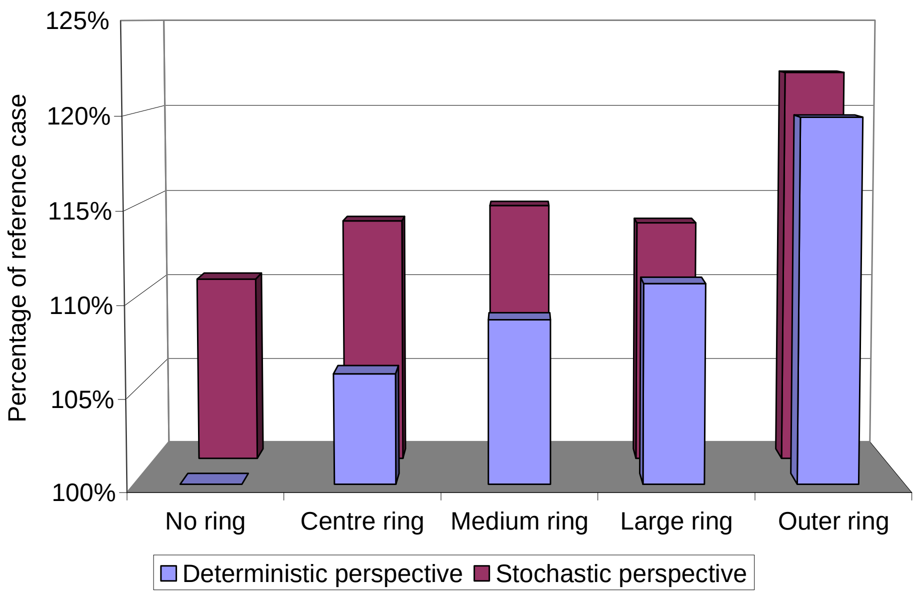

Figure 7-12: Relative total network costs for variants of the transversal line network: the deterministic perspective vs. the stochastic perspective

In general, the outcomes of the overall network assessments show that increasing the network redundancy as in the networks with radial lines won't lead to better overall network performance for the networks having transversal lines and still the network without a ring line is optimal.

In the comparison between optimal variants in the deterministic perspective and the stochastic perspective, which is variant 1 for both perspectives, results of the stochastic perspective are different from the deterministic perspective. Results of the deterministic perspective clearly showed that replacing radial lines by transversal lines leads to lower network costs due to the fact that they offer more direct services between OD pairs. However, in the stochastic perspective the result is quite different. Figure 7-13 shows the total network costs in the stochastic perspective for both network types.

In the stochastic perspective the total network costs for the network with radial lines are somewhat (1.7%) lower. This is because unreliability related costs in the network with transversal lines are much higher than in the network with radial lines. Albeit this reduction rate in the overall service performance may not sound considerable especially in practice, several researches show that in public transport network design normally there are a large number of solutions near the optimum point (Beilli et al. 2000; Van Nes 2002; Fan & Machemehl 2006).
On average about 9.8 % of the total demand is cancelled in the network with transversal lines (without ring line), while this rate decreases to 2.5 % in the network with radial lines (without ring line). These findings demonstrate that in the stochastic perspective lengthening service lines in the transit network won't be beneficial in terms of the overall network performance since their unreliability related costs rise considerably (+25%).

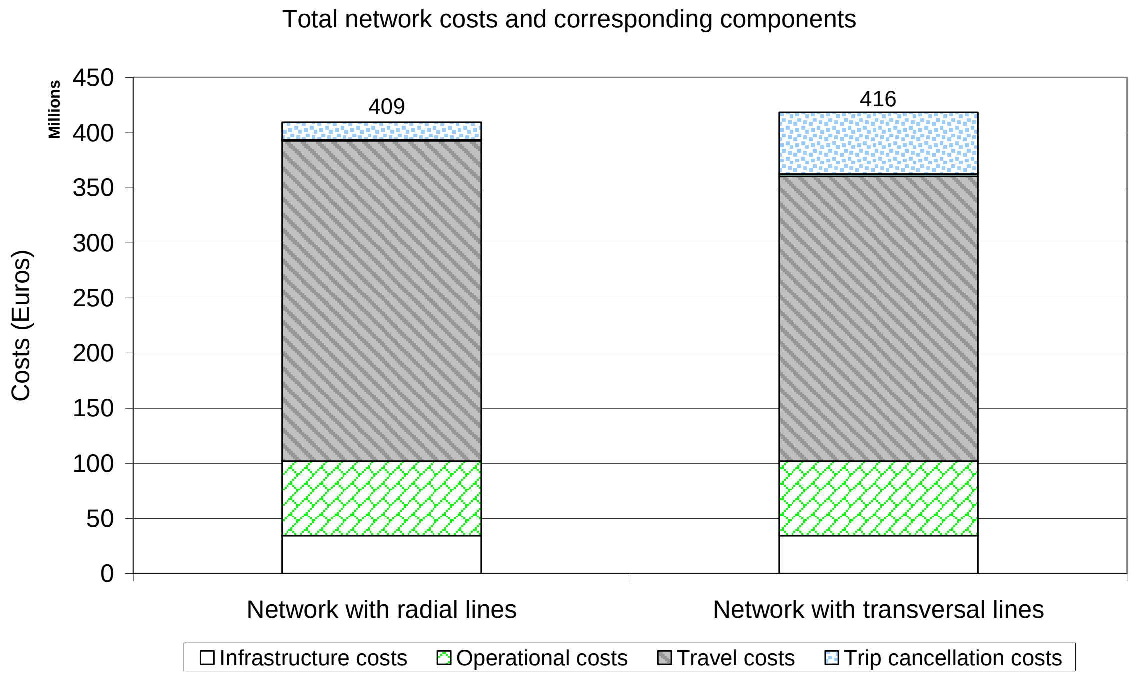

Figure 7-13: Comparison between the optimum variant (variant 1) in the network with radial lines and the network with transversal lines in the stochastic perspective

7-5-2 Synthesis

Evaluating outcomes of case 7-3 and case 7-4 yields two important conclusions:

- The traditional line density dilemma appears to be dominant in public transport network design. In other words, in the ring/radial case, radial networks without a ring line are to be preferred;
- The line length design dilemma can play a decisive role in network design and can lead to different designs in the deterministic and stochastic perspective respectively.

The findings of this experimental study demonstrate that the network with transversal lines appears preferable in the deterministic perspective, whereas in the stochastic perspective the network with radial lines is preferable.
Finally, it should be noted that these findings are reliable, since they have been validated for several different simulation seeds. The impacts of different seeds on simulation results are

large for a small number of runs (e.g.5 runs expressing 5 years). However, when the number of runs is adequate, as demonstrated in section 7-4, implementing different seeds does not influence the simulation results.

7-5-3 Sensitivity analyses

Of course, the aforementioned outcomes depend on the experimental specifications such as demand size and pattern and network size. We did several sensitivity analyses to determine whether these outcomes are adequately generic and the model is enough robust with respect to its inputs. These analyses have been arranged according to rational variations in the following network specifications:

- Demand size;
- Demand pattern;
- Network size.

Table 7-5 summarizes findings of the sensitivity analyses with respect to the aforementioned criteria. It is obvious by increasing demand size total network costs rise accordingly. The results indicate that the demand pattern and the network size can influence the outcomes of the analyses. For example, reducing the network size approximates the performance of the network with radial lines to the performance of the network with transversal lines in the stochastic perspective. This is due to the fact that transversal lines in the smaller network are less sensitive to disturbances than those of bigger network.

Table 7-5: Sensitivity analyses for the hypothetical radial arc case study

Specification / Indicator	Demand size	Demand pattern	Network size
Overall network performance	Negligible	Partly significant	Significant
Impacts of redundancy on service reliability	Negligible	Significant	Negligible
Impacts of flexibility on service reliability	Negligible	Negligible	Negligible
Vulnerability	Negligible	Negligible	Significant

Thus, the network size influences the overall network performance. More details of these sensitivity analyses can be found in appendix 4.

7-6 Summary and Conclusions

This chapter aimed at validating impacts of applying strategic measures discussed in chapter 5 on public transport network performance including reliability. We determined reliability related costs and their contributions to the overall network performance by a set of experiments. We developed a simulation tool to assess impacts of reliability enhancing measures on the overall network performance including reliability. By using this simulation tool impacts of all kinds of stochastic events on network performance were evaluated. The mechanisms and measures used in this tool are according to the extended bi-level framework and assessment criteria discussed in chapter 5 and public transport traveller’s behaviour discussed in chapter 6.

The reliability enhancing measures applied in this chapter were: reducing vulnerability in service networks, and increasing service network redundancy. We compared the performances of several public transport service networks, varying with respect to level of redundancy and vulnerability, in terms of overall network performance including service reliability. We opted for a hypothetical radial tram network as a commonly use network in urbanised areas. It was featured by different types of service lines such as radial lines, and transversal lines to generate different levels of vulnerability. To create different levels of redundancy in the service network, we combined a ring line varying with respect to location and radius with the network having radial (or transversal) lines.

Given the impacts of stochastic events on public transport networks, there are service variations in the case studies. These variations are generated by minor quasi continuous ongoing events as well as major discrete events.

We set several case studies to evaluate:

- impacts of increasing network redundancy on overall network performance including service reliability;
- impacts of decreasing service network vulnerability on overall network performance including service reliability.

The findings demonstrate that increasing service network redundancy will enhance service reliability, but it won’t lead to an improvement in the network overall performance. In other words, impacts of considering service reliability in network design, which is pursued in the stochastic network design perspective, appears not dominant enough to lead to a change in the optimally designed network in the deterministic perspective. Consequently, the deterministic design perspective seems to be dominant in transport service network design. Of course, this result is a bit indecisive and ambiguous, because it depends on the degree of vulnerability in the transit network. Sensitivity analyses demonstrate this dependency. For transit networks with high level of vulnerability, the influence of considering service reliability might be large enough to yield an optimal network.

However, the impact of service network vulnerability on service reliability is decisive. Experiments’ results demonstrate that applying longer service lines such as transversal lines in transport service networks improves overall network performance in the deterministic perspective. However, in the stochastic perspective when service reliability is accounted for, applying long service lines not only lessens service reliability, but it can also diminish the overall network performance.

Finally, based on findings of this chapter, the following noteworthy conclusions are drawn:

- Increasing network redundancy in transport service networks improves service reliability significantly; but it may not lead to better overall network performance;
- Impacts of increasing network redundancy on overall network performance depend on network vulnerability level. For the networks with high degree of vulnerability increasing network redundancy might lead to higher overall network performance;
- Reducing transport service network vulnerability may improve both service reliability, as well as overall network performance considerably.

With respect to the above conclusions, in order to achieve the benefits of improved service reliability in the analyses, we focus on creating flexibility in the service network using additional infrastructures. As indicated in chapter 5, creating network flexibility could increase network robustness and thus influence service reliability positively. Therefore, in the next chapter we use the model to deal with impacts of infrastructure flexibility on service reliability.

Finally, the findings of this chapter indicate that the public transport network pattern should be in line with the demand pattern. By considering reliability the network designer should be careful for long service lines, since they can cause critical situation in case of disruptions in the network.

8 THE ROLE OF INFRASTRUCTURE ON URBAN PUBLIC TRANSPORT SERVICE RELIABILITY

8-1 Introduction

In chapter 5 we discussed that applying prevention-oriented approaches is an appropriate way to improve service reliability at the strategic level of public transport network design. Prevention- oriented approaches consist of two strategies:

- Providing service alternatives within service networks (increasing line density and thus higher service network redundancy);
- Creating more flexibility for service networks.

We demonstrated that increasing service network redundancy as a part of prevention-oriented approaches would lead to an enhancement of service reliability, but will not improve overall network performance necessarily. These outcomes motivate us to deal with the second strategy: creating more flexibility in the service network. This is especially relevant for rail bound public transport networks which are operated only on dedicated infrastructure.

The focus of this chapter will be on creating more flexibility in the service network. By applying this approach the planner increases redundancy and flexibility in the infrastructure network in order to create more flexibility for service networks.
Additional infrastructures increase infrastructure network redundancy and thus yield higher flexibility for service networks for providing backup and emergency options. Higher flexibility in service networks increases service network robustness and thus leads to higher reliable transport networks.
Consequently in this chapter we deal with roles of additional infrastructure to improve service reliability as well as the overall network performance.

To this end we will apply the same methodology as in the hypothetical case study (introduced already in chapter 7) which consists of a tram network with 8 radial lines as well as a tram network with 4 transversal lines. The main challenge is to determine where a ring

infrastructure might be provided. This will be dealt with in this chapter by analyzing the impacts of combining different ring infrastructures into the radial transit network on service reliability and overall network performance.
The options are distinguished according to their length and location to create different levels of network flexibility. Thus, we will demonstrate that extending public transport network planning by small investment for building additional infrastructure in a smart way not only may enhance service reliability significantly, but also may have a positive impact on overall network performance. These outcomes will demonstrate the important role of infrastructure on increasing flexibility in transport service networks and thus enhancement of transit service reliability.

8-2 Ring infrastructure design and corresponding cases

In order to assess impacts of service network flexibility on service reliability as well as overall network performance, we define several network variants. These variants are based on creating different levels of flexibility in a predefined transport service network. The distinction is made according to the location and the availability of the additional infrastructure. We use the radial network pattern previously described in chapter 7. The additional infrastructure is a ring providing detour facilities for radial service lines. Thus, three different types of rings are combined with the radial service network and their impacts on the network are assessed. The cases that are going to be analysed are:

- The radial transport service network type without backup (no additional infrastructure);
- The radial transport service network type combined with a centre ring infrastructure;
- The radial transport service network type combined with a medium ring infrastructure;
- The radial transport service network type combined with a large ring infrastructure.

The option including an outer ring is not analysed, because it does not facilitate considerable number of trips given the demand pattern. Figure 8-1 illustrates the infrastructure network for corresponding variants. Note that in each case the infrastructure used by the service network plus the corresponding ring infrastructure are available. As a result it can be expected that variant 1 (no ring) will be quite sensitive to failures in infrastructure availability as, there are no possibilities for service detours (refer to the previous chapter). Depending on the location of the ring infrastructure, the other variants might be more robust. Consequently, the infrastructure costs will differ for all variants.
We define two cases by making a distinction between service lines likewise in the previous chapter 7:

- Case 8-1: ring infrastructure variants in the network with radial lines;
- Case 8-2: ring infrastructure variants in the network with transversal lines.

The annual extra investment cost for building ring shortcuts is set at 0.23 million Euros per kilometre. This cost is based on data from the Ministry of Transport, Public Works and Watermanagement (1996).

Since the ring infrastructure is only used in case of disturbances, it is possible to design the ring as a single track. Therefore, the investment and maintenance costs of the ring infrastructure will be lower than the costs of the options in the previous chapter in which the ring infrastructure is used for operating a service line. For example, the annual investment and maintenance costs for building a large ring shortcut (single track) with the radius of 6.7 km is approximately 12 million Euros less than those for building the ring service line (double track) with the same radius (infrastructure costs for the networks having ring service lines have been stated in table A3-2 in appendix 3). Table 8-1 outlines the track length, the infrastructure costs and the operation costs for the radial network variants.

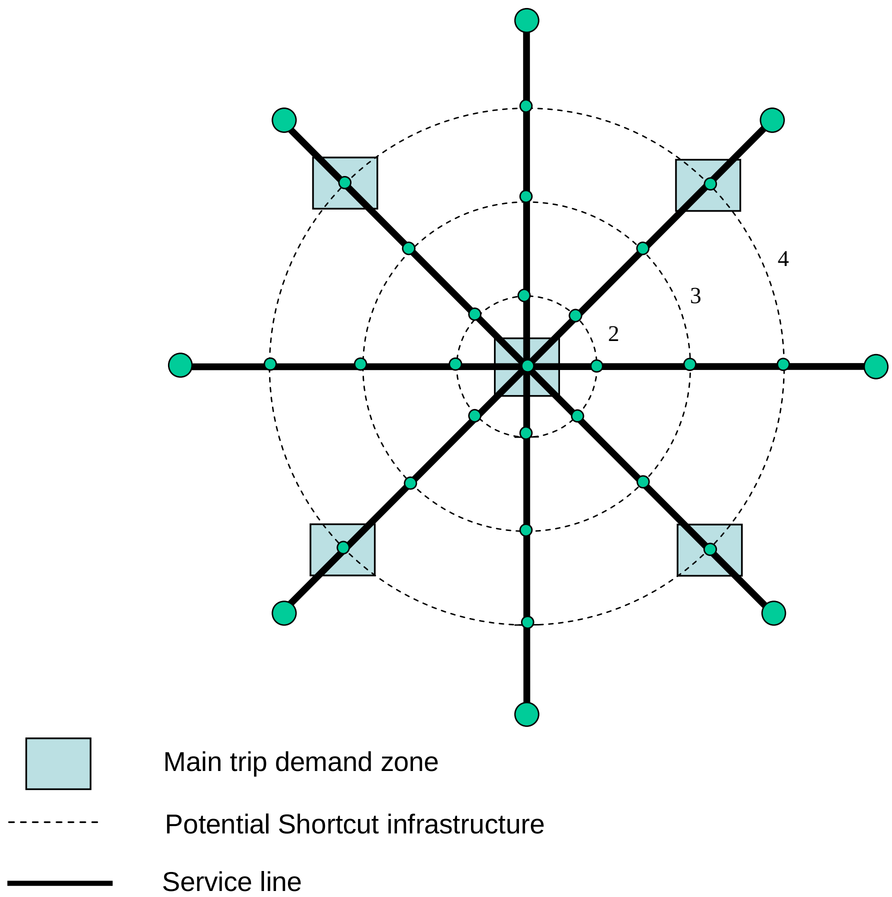

Figure 8-1: Ring infrastructure variants in the hypothetical radial network

Table 8-1: Annual infrastructure and operation costs for radial network variants (M€)

Network variant	Ring track radius (km)	Ring infrastructure costs per year*	Total track length (km)	Total network infrastructure costs per year*	Total operation costs per year
Variant 1 (no ring)	0.0	0	150.4	34.3	67.4
Variant 2 (centre ring)	1.4	1.5	158.8	35.8	67.4
Variant 3 (middle ring)	4.0	4.5	175.5	38.8	67.4
Variant 4 (large ring)	6.7	7.5	192.3	42.8	67.4

* The investment and maintenance costs per kilometre are computed based on data of the Dutch Ministry of Transport, Public Works and Watermanagement (for more detail, please refer to appendix 3).

In order to reduce the infrastructure costs further and thus improve overall network performance, it is possible to limit extra infrastructure costs. Thus, the continuous ring infrastructure could be split into four separate segments. Figure 8-2 illustrates this option for the variant with a large ring shortcut. Applying such ring infrastructure results in 50% reduction in the additional ring infrastructure costs (3.8 Million €).

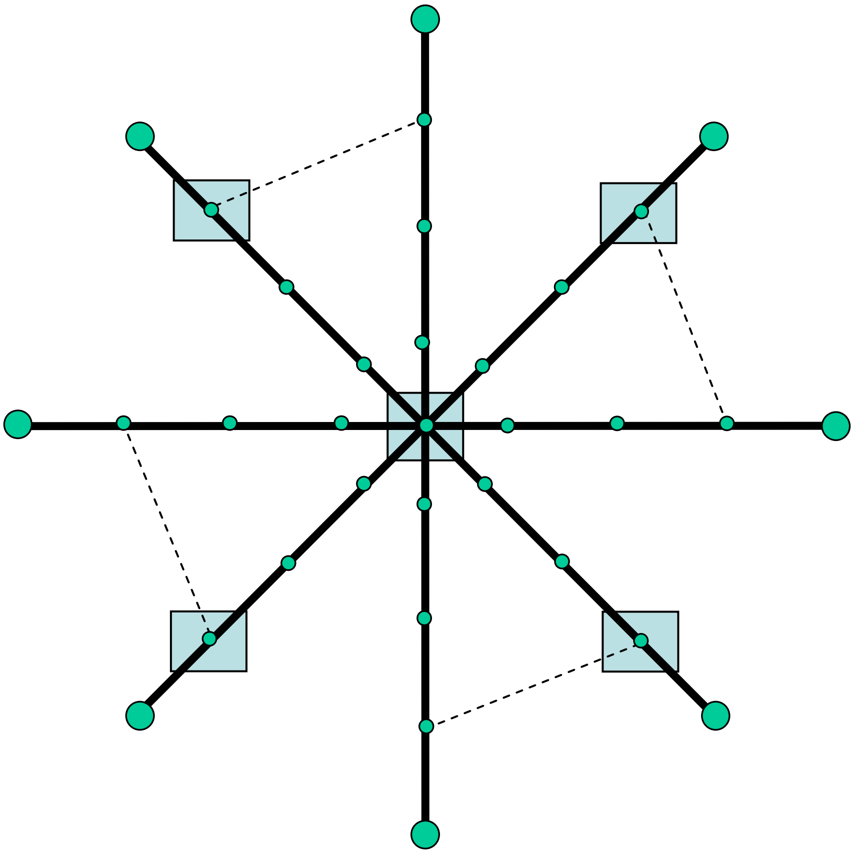

Figure 8-2: Cutting & Splitting ring infrastructure to reduce investment costs in the hypothetical network

8-3 Assessment of reliability impacts

In this section we discuss the assessment results for the defined cases to analyse the impact of service network flexibility, created by additional infrastructure, on service reliability and overall performance in different service network types. Like wise chapter 7, we use the simulation tool to assess the cases in the stochastic perspective.

8-3-1 Case 8-1: Ring infrastructure in the network with radial lines

Simulation results show that generally combining the ring infrastructure in public transport networks will increase service reliability. Figure 8-3 clearly shows that the large ring infrastructure, which provides detour facilities for larger number of trips due to larger coverage area, is the optimum design in terms of increasing network connectivity reliability, although its' length and thus its' investment costs are higher as well. These results are in line with the previous results gained in the previous chapter. Likewise chapter 7, total trip demand is set to 32 Million passenger trips per year. Given the transit demand pattern (stated in appendix 3), the large ring infrastructure could provide detours for 212.000 trips (26.6 % of affected trips) in the network with radial lines. The total number of affected trips for this variant is 583,000 trips.

Figure 8-4 shows the total network costs for the variant including the large ring infrastructure (the right column). For details of cost components computations please refer to appendix 3. Because of a substantial reduction in trip cancellation costs due to higher connectivity reliability afforded by the ring infrastructure, providing large ring infrastructure for the network results in slightly lower total network cost compared to total cost of the network without shortcuts (407 vs. 409 Million Euros/year).

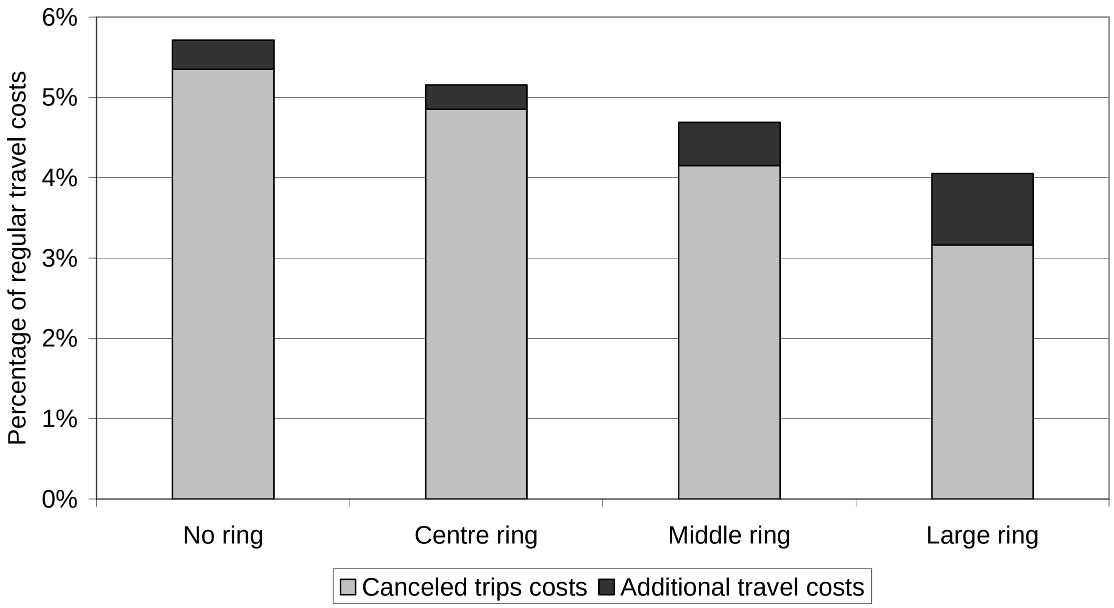

Figure 8-3: Reliability costs of including ring infrastructures in the network with radial lines as a percentage of regular travel costs

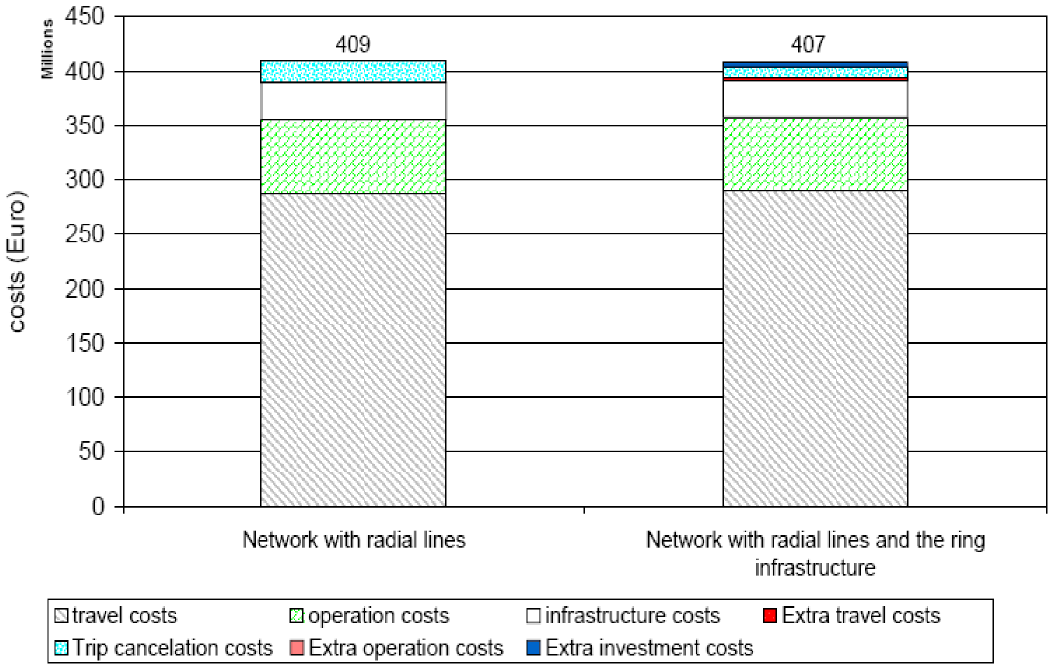

Figure 8-4: Public transport network assessment based on total yearly network costs (the network with radial lines) in millions per year

Table 8-2 outlines relevant costs for these two networks to clarify impacts of additional infrastructure on network performance assessments.

Table 8-2: Costs comparison between Network with radial lines and Network with radial lines and the ring infrastructure (Costs expressed in Million Euros)

Network type	Reliability related costs (per year)	Investment and maintenance costs for additional infrastructure (Per year)	Total network costs (per year)
Network with radial lines	19.4	0	409
Network with radial lines and the ring infrastructure	12.5	3.8	407

Thus, the impacts of service reliability improvement for networks including a ring infrastructure appear to be large enough to compensate the investment costs of additional infrastructure (19.4-12.5= 6.9 vs. 3.8).

Since the infrastructure costs play an important role in obtaining the aforementioned results, we do a sensitivity analysis regarding probable infrastructure costs variations. The sensitivity analysis demonstrates that increasing the infrastructure costs up to 40% still yields the same results. Also, increasing the PT demand size can enhance the efficiency of additional infrastructures significantly since larger number of passengers can benefit from them. In other words, facilitating the tram network with additional infrastructures is more effective in densely populated cities where trams are fully loaded and service lines' frequency is high.

8-3-2 Case 8-2: Ring infrastructure in the network with transversal lines

As discussed in chapter 7, networks having transversal lines are more vulnerable than networks having radial lines. Figure 8-4 shows trip cancelation costs and additional travel costs imposed to passengers due to disturbances for each network variant. Trip cancelation costs are clearly higher in the network with transversal lines than in the network with radial lines. (19.5 % vs. 5.3 %: Figure 8-5 vs. Figure 8-3).

Creating flexibility in the service network by introducing a large ring infrastructure provides detour facilities for about 13.2 % of affected trips and therefore leads to a reduction in the number of cancelled trips in the network having transversal lines. The improvement in connectivity reliability in the network having transversal lines is less than in the network with radial lines in which the large ring infrastructure provided detour facilities for about 26.6 % of the affected trips. This is due to the difficulty in applying detours for longer lines in case that their multiple parts are affected simultaneously.

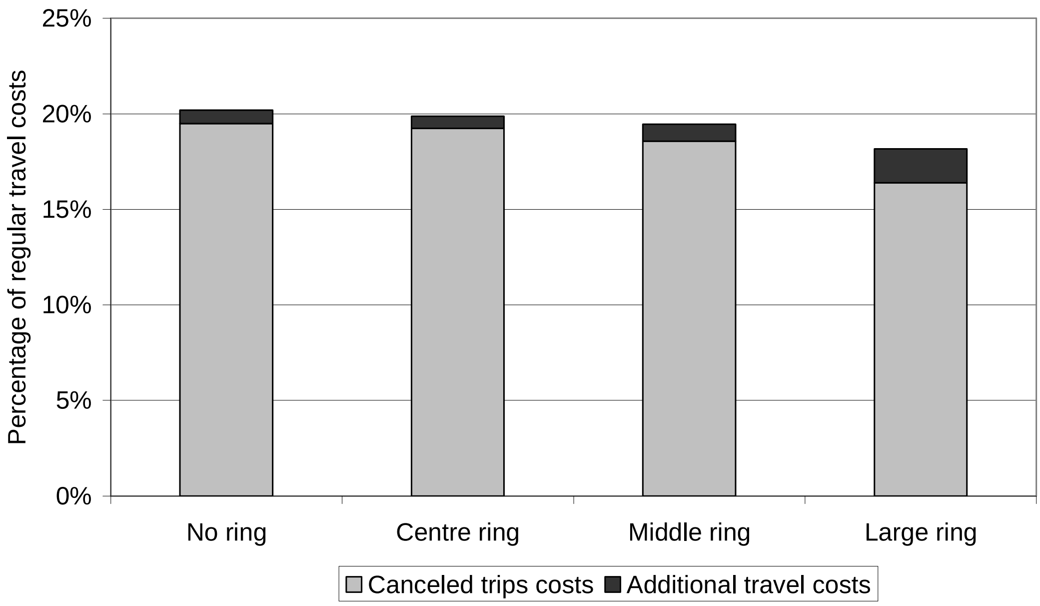

Figure 8-5: Reliability costs of including ring infrastructure in the network with transversal lines as a percentage of regular travel costs

Figure 8-6 shows the total yearly network costs for the variant including the large ring infrastructure (the right column). Equally as the network with radial lines this variant is the optimum network in terms of the overall network performance. The outcomes show that providing large ring infrastructure for the network results in slightly lower total network costs compared to those for the network without a ring infrastructure, as illustrated in the left column (415 vs. 416 Million Euros/year). This is because of the impacts of service reliability improvement for networks including a ring infrastructure appear to be large enough to compensate the investment costs of additional infrastructure (Table 8-3).

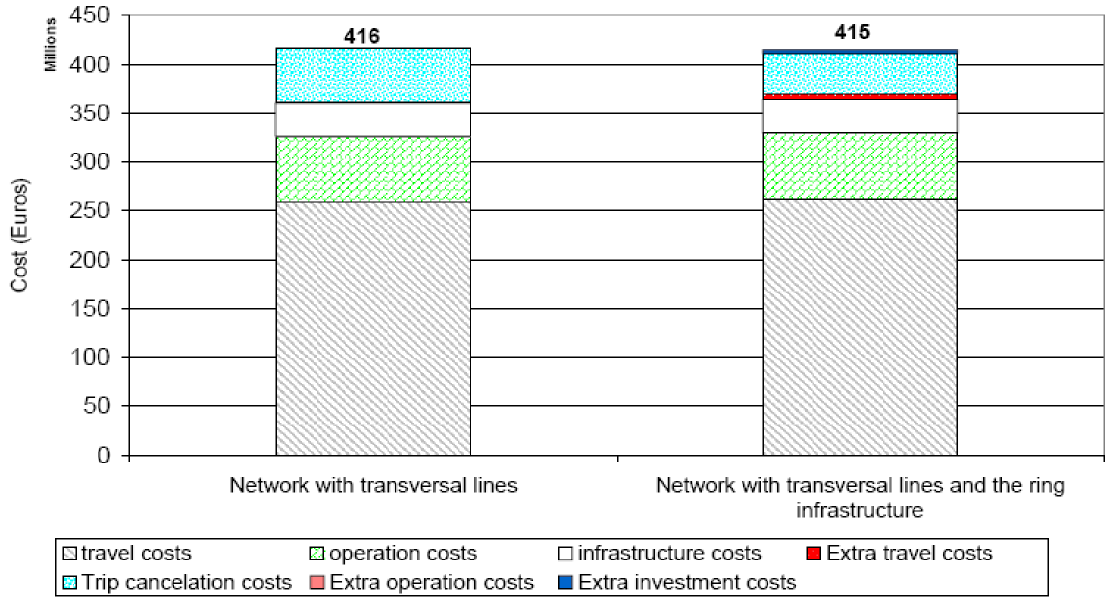

Figure 8-6: Public transport network assessment based on total yearly network costs (the network with transversal lines) in million Euros /year

Table 8-3: Costs comparison between Network with transversal lines and Network with transversal lines and the ring infrastructure (Costs expressed in Million Euros)

Network type	Reliability related costs (per year)	Investment and maintenance costs for additional infrastructure (Per year)	Total network costs (per year)
Network with transversal lines	55.9	0	416
Network with transversal lines and the ring infrastructure	46.9	3.8	415

8-4 Summary and Conclusions

In this chapter we demonstrated that providing additional infrastructure in order to create service network flexibility appears to be beneficial for service reliability as well as overall network performance in case of major discrete disturbing events. The costs for extra infrastructure are clearly outweighed by the savings in reliability costs. This is especially of concern for rail bound public transport networks which are operated on dedicated infrastructures.

The analyses for the network having radial lines as well as for the network having transversal lines demonstrate that the larger ring infrastructure creates service network flexibility significantly and will be more beneficial for service reliability improvement, although its infrastructure costs are higher. In spite of the fact that facilitating the infrastructure network by the ring infrastructure increases network investment and maintenance costs, these additional costs are outweighed by service reliability benefits.

Compared to the cases in which alternative service lines are provided by increasing the service line density (chapter 7), creating more flexibility for the service network is more straightforward, because in terms of the ratio of benefits to costs the findings are not as ambiguous as those of chapter 7. The efficiency of creating network flexibility does not depend on network vulnerability as much as increasing service network redundancy. As indicated before, flexible service networks not only enhance service reliability, but also they lead to an improvement in overall network performance. This outcome was demonstrated in both line network types (radial lines, transversal lines), although for the network having transversal lines due to the problem of multiple affections, a smaller improvement in connectivity reliability is observed.

Finally, as a recommendation for public transport network designers, accounting for reliability has consequences for infrastructure. It leads to using the existing infrastructure in a smart way. Equipping the existing infrastructure network with additional infrastructures such as shortcuts will enable transit operators to apply remedial solutions during disturbances (e.g. detours, partial runs) and help them maintain service reliability high.

The achieved outcomes in this chapter are based on typical network patterns as well as typical demand patterns. Hence, further research is needed to verify these theoretical findings in practice. An asymmetric public transport network with different configurations of service lines such as radial lines, transversal lines, and infrastructure possibilities such as turnings facilities and bypasses can be a suitable option. Hence, in the next chapter we will apply our methodology for The Hague tram network as a realistic tram network and will verify our previous experimental results.

9 ENHANCING RELIABILITY IN URBAN PUBLIC TRANSPORT NETWORKS

(A realistic case study)

9-1 Introduction

In chapters 7 and 8 we demonstrated by hypothetical case studies how public transport service reliability could be enhanced by applying strategic measures focusing on increasing service network redundancy, reducing service network vulnerability, and creating service network flexibility using additional infrastructure.
The findings of those two chapters showed that increasing service network redundancy improves service reliability, but it may not lead to better overall network performance. However, reducing service network vulnerability and creating service network flexibility may improve both service reliability and the overall network performance.

In this chapter we will extend these analyses to a reliability assessment of a realistic public transport network. We will explore multiple options for improving service reliability especially in the field of additional infrastructure.
We adopt the tram network of the city of The Hague in the Netherlands as a case study. It follows partly a radial network pattern, having radial, transversal and tangential lines. Its asymmetric pattern results in diverse vulnerability levels in service lines.
Moreover, similar to other realistic cases, the infrastructure network contains various elements such as tunnels and bridges having different levels of vulnerability. This diverse infrastructure pattern will also be more advantageous, since various types of additional infrastructure can be implemented to create service network flexibility.

The purpose of this chapter is extending the analyses of reliability enhancing measures to a realistic public transport network to validate previous findings, proposed in chapter 5 and justified in the hypothetical case study, in practice. In order to have an overview of the setup of this empirical study, firstly we describe the spatial characteristics of The Hague tram network after which we describe how to measure service reliability in the current situation.

The outcomes of this analysis will also determine the critical locations of the network in terms of service reliability.

Based on the reliability analysis of the current network, we define and test suitable cases in the context of prevention-oriented approaches to improve network robustness and consequently service reliability. These measures used in cases deal with:

- reducing service network vulnerability;
- creating service network flexibility at the critical locations of The Hague tram network.

The motivation behind the first methods is the new design dilemma related to service line length previously discussed in chapter 5 and validated in chapter 7 for the hypothetical case study. We will shorten one of the major lines in the network and re-assess the consequent impacts of newly modified configuration on service reliability and overall network performance.
In the second method, we will focus on creating service network flexibility by planning additional infrastructure. We consider different options as follows:

- adding a bypass to a vulnerable link;
- connecting terminals of two major service lines by a shortcut;
- adding a turning facility to a vulnerable service line.

Impacts of these options on service reliability and overall network performance are assessed accordingly.

Analyses in the stochastic perspective using the simulation tool will demonstrate what the consequences are of modelling reliability measures in the assessment of realistic networks. Furthermore, it leads to exploring the possibilities to improve public transport network performance.

9-2 The Hague tram network characteristics

In this section, we provide essential information of the spatial characteristics of the case study. This information will be used for assessing public transport network performance and service reliability for the current network.
The entire HTM network consists of 22 service lines, both bus and tram lines, having the following types:

- Transversal lines (10 lines);
- Radial lines (8 lines);
- Tangential lines (3 lines);
- Circumferential line (1 line).

The tram network of the city of The Hague consists of 11 service lines with a total length of 142 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%). Figure 9-1 shows a satellite image of The Hague including existing tram stops obtained from Google Earth.
Focusing on rail bound public transport the tram network has 7 transversal lines, 2 radial lines, and 2 tangential lines.

Figure 9-1: Satellite image of The Hague city including tram and LRT stops (Google Earth)

Table 9-1 outlines the current tram line configurations in the city. For more information about tram lines characteristics, appendix 5 presents the corresponding lines' itinerary, headways, and operating hours.

On the demand side, about 140 million trips are made in a year for the public transport network (HTM 2004-2005). From this amount, about 90 million trips are made by tram. Public transport demand is primarily centre oriented, while several sub centres (e.g. the cities of Delft, Rijswijk, Voorburg, Scheveningen, Wateringen and Leidschendam) also attract their share of the demand. Table A5-2 in Appendix 5 outlines trip production and attraction rates for each zone.

Given The Hague tram network, total infrastructure investment and maintenance costs, and operation costs, in the deterministic perspective are estimated as follows:

- Total infrastructure investment and maintenance costs: 65.3 Million € per year;
- Total operation costs: 130 Million € per year.

Likewise before, the value of time is set to 10€/hr.

Table 9-1: Service line classifications in city of The Hague

Line Number	Line type	From	To	Distance (km)
1	Transversal	Zwarte Pad	Delft Tanthof	19.7
2	Transversal	Kraayensteinlaan	Dillenburgsingel	13.9
3	Radial	Arnold Spoelpein	Centraal Station	8.3
4	Radial	De Uithof	Centraal Station	12.1
6	Transversal	Ziekenhuis Leyenburg	Leidsenhage	13.1
9	Transversal	Zwarte Pad	De Dreef	12.3
10	Transversal	Van Boetzelaerlaan	Voorburg Station	11.3
11	Tangential	Strandweg	Station Hollands Spoor	7.8
12	Tangential	Markenseplein	Station Hollands Spoor	7.8
(15+16)*	Transversal	Nootdorp Centrum	Dorpskade *via Centraal station*	20.1
17	Transversal	Dorpskade	Van Boetzelaerlaan	15.6

* These two lines are in fact a single line having different numbers at different part of the path

9-3 Assessing service reliability of The Hague tram Network

In this part we assess the level of service reliability in the current network. Apart from indicating this for the whole network, we will also determine service reliability indicators for individual lines and infrastructure links. Results will be used to propose options to improve network robustness and consequently to enhance service reliability.
In order to assess the reliability of the tram network of The Hague, first a schematic tram network according to the existing network is generated (Figure 9-2).

For analysing this network in the stochastic perspective, 20 different Monte Carlo simulation runs are used, each run representing a period of a year, similar to the analyses of the hypothetical networks of chapters 7 and 8. Obviously, infrastructure elements are not equally sensitive to events. Although link length is an influencing criterion, the other physical factors such as location and the level of infrastructure usage play a role as well. For instance, the bridge (link#19) and the tunnel (link#18) may be just as vulnerable as a long link (e.g. Link #6). This degree of vulnerability is because of high usage of the tunnel and bridge in combination with the regular maintenance.

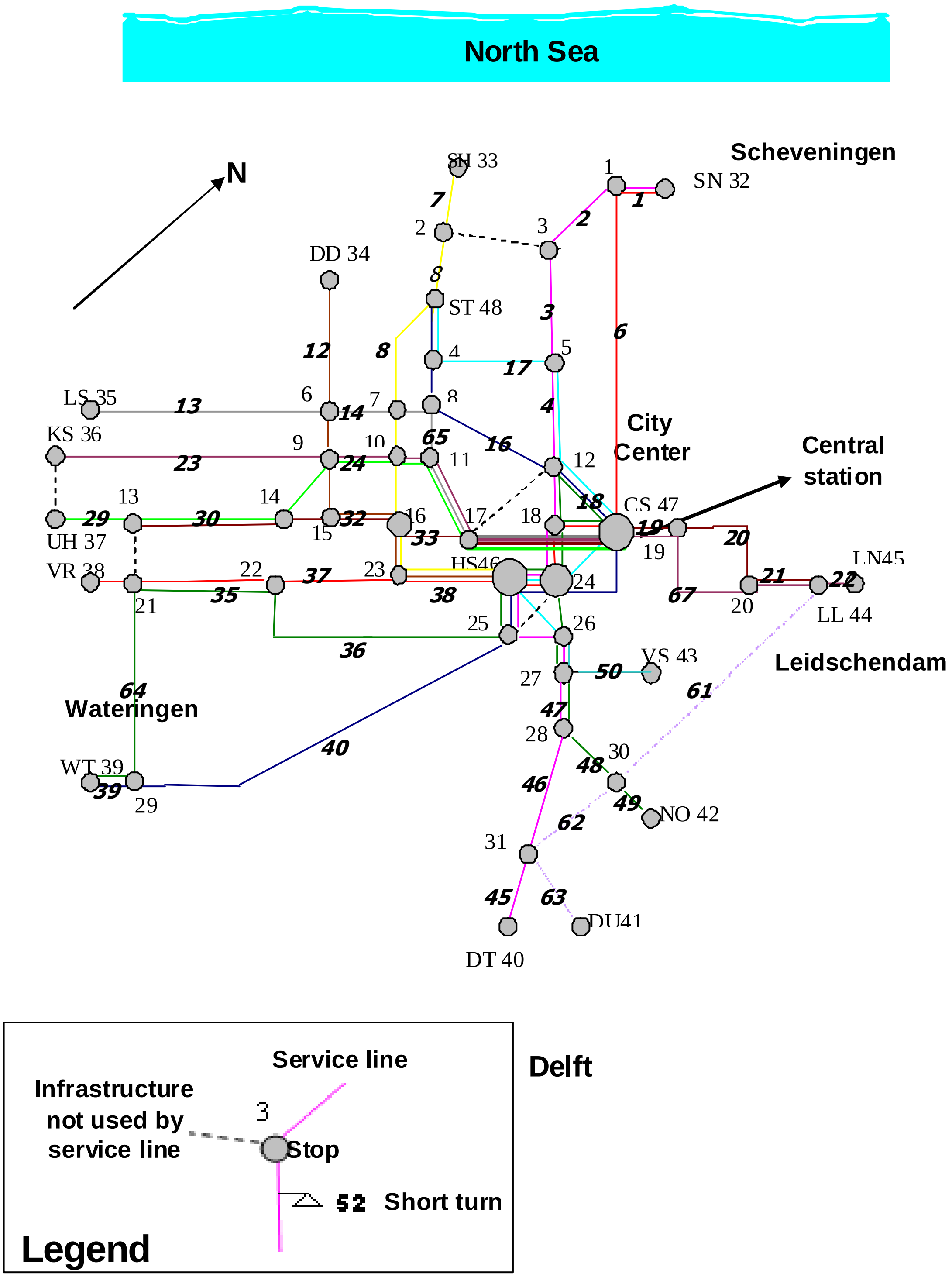

Figure 9-2: Schematic illustration of tram network of The Hague

To have an overview of the current situation of the network, after 20 simulation runs, on average the network faces disturbances in 102 days of a year (28% of a year). Due to disturbances, 89% of passenger trips are made with less than 10 minutes delay. In the aggregate level about 2.1 % of the annual trips are cancelled due to disturbances. Trip cancelation penalties depend on the origin-destination distance and availability of a bus route alternative.

Likewise chapter 7, we focus on connectivity reliability by quantifying the number of trip cancelations in case of major discrete disturbing events. Table 9-2 shows the average, the standard deviation and the coefficient of variation of the trip cancelation number at aggregate level (for the whole network) due to each type of event. The outcomes show that work zones have the highest influence on network connectivity reliability since the number of trip cancelations due to work zones is the largest.

Table 9-2: influence of events on network connectivity reliability

Event type	No. of trip cancelations as a connectivity reliability indicator		
	Mean (thousand)	STD (thousand)	COV
Bad weather	346	727	2.10
Work zone	554	343	0.62
Vehicle breakdown	48.3	11.2	0.23
Incidents	400	33.6	0.08
Public events*	41.2	-	-

*Due to the fact that public events are usually assumed to take place with a predefined pattern, the STD and the COV of connectivity reliability are zero.

By looking at the COV of network connectivity reliability the simulation results show that frequent events such as incidents affect connectivity reliability homogeneously within various years (COV = 0.08), whilst non frequent events such as work zones and bad weather with COV of 0.62 and 2.10 respectively affect network reliability unevenly and their impacts fully depend on their occurrence pattern.

At disaggregate level the connectivity reliability of The Hague network is determined by capturing the trip cancelation percentage per origin. Table 9-3 outlines the twenty most vulnerable points in terms of connectivity reliability. The result shows that terminal Delft Tanthof is the most sensitive zone in terms of connectivity reliability, because its trip cancelation percentage is the highest. The results clearly shows that the most vulnerable nodes are terminal points located at the end of service lines since no alternative(s) are available to serve them when the corresponding main lines are affected.

In addition to connectivity reliability, we determine the vulnerability of the existing lines in the network to have an overview of impacts of events on service lines. Figure 9-3 illustrates the number of affections per line due to disturbances in a whole year. It clearly shows that long lines suffer from higher vulnerability (e.g. line 15, line 1), although the lines in which there are vulnerable links for example due to heavy usage, face higher vulnerability too (e.g. line 2, line 6).

Table 9-3: The Hague tram network connectivity reliability value per origin

Origin number	Origin name	Annual percentage of trip cancelations (mean value for 20 simulation runs)
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%
33	Strandweg	2.8%
37	De Uithof	2.4%
19	Oostinje	2.3%
29	Parijsplein	2.2%
39	Dorpskade	2.2%
48	Van Boetzelaerlaan	2.0%
35	Arnold Spoelpein	1.9%
38	Vrederust	1.9%
17	Brouwersgracht	1.9%
02	Duinstraat	1.9%

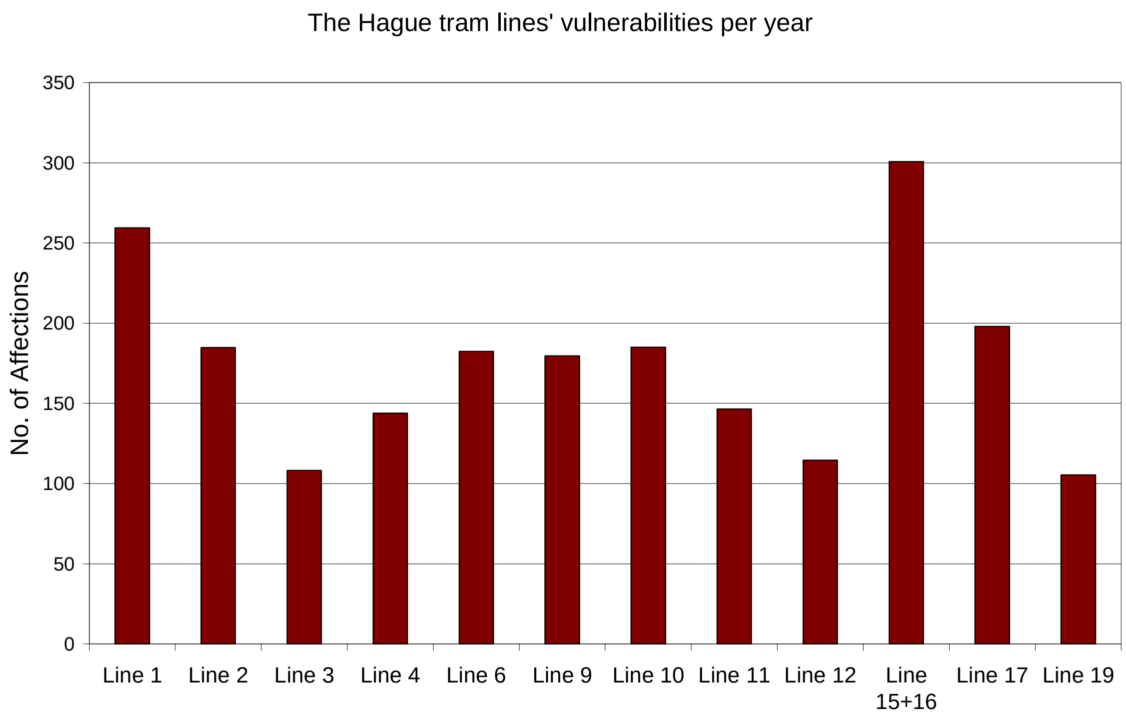

Figure 9-3: Degree of vulnerability of the tram lines of The Hague (expressed in no. of affections/year)

At a more detailed level, we quantify tram links' load during peak hours. Figure 9-4 illustrates links' load expressed by number of passengers per hour. In order to assess impacts of stochastic events on network loads, we quantify tram links' load when stochastic events cause service network variations. Figure 9-5 illustrates the relative difference in the link loads in the stochastic perspective as well as the deterministic perspective. It shows that on average some links are used up to 23% more in the stochastic perspective when stochastic events take place (e.g. links 9 and 10). This means that these links are used for detours when other links are blocked. The links which are used less in irregular conditions are the links without any function as a detour.

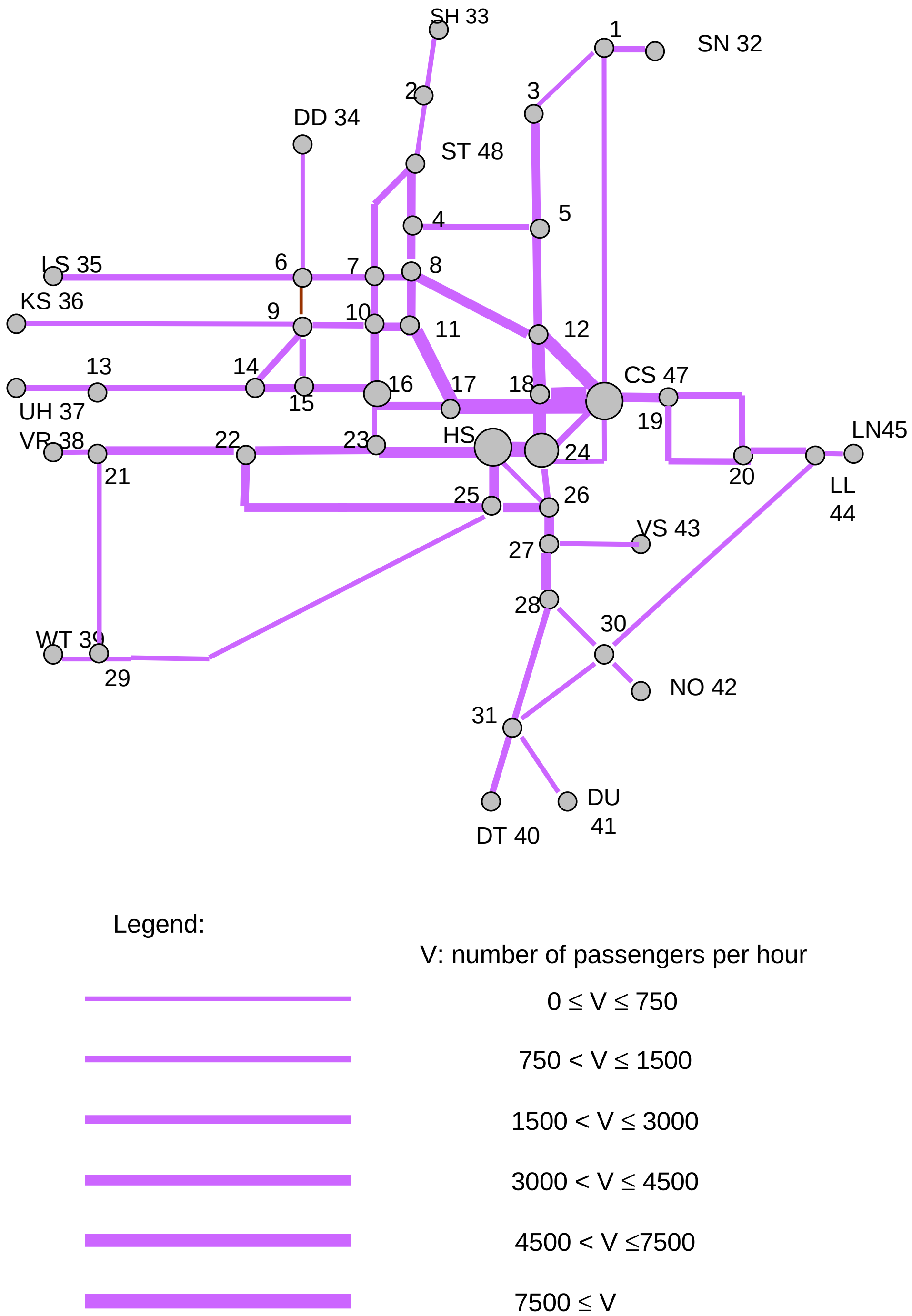

Figure 9-4: Links' load (peak hour) in The Hague tram network

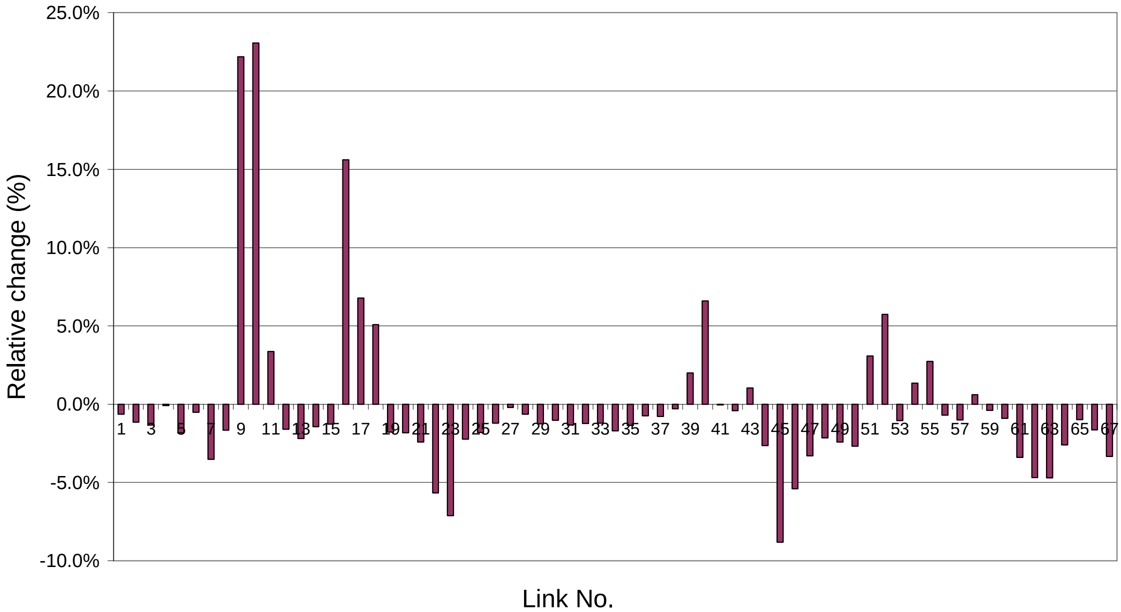

Figure 9-5: Relative changes in link loads (passengers) of the tram network of The Hague (irregular conditions compared to regular conditions)

9-4 Enhancing service reliability by reducing service network vulnerability

We demonstrated in chapter 7 that shortening long lines by splitting them into two or more parts may lead to a more reliable network and even to better network performance. We showed with the hypothetical networks that applying transversal lines, which are more vulnerable than radial lines, may reduce travel costs by 5 %; however, the associated unreliability costs are large enough to yield radial lines preferable in terms of the overall network performance. For further details, see section 7-5.
This is in fact a new transit network design dilemma regarding service network vulnerability in which service line length causes a trade-off between travel time and travel time reliability (longer service line with higher vulnerability and shorter travel times versus shorter service line with higher reliability and longer travel times: dilemma 5 in table 5-3).

In this part we intend to test this design dilemma for realistic networks and to see how shortening service lines may affect service reliability and the overall network performance. We choose the most vulnerable tram line (line 1) for this case. There are two reasons for choosing tram line 1 in the network:

- Tram line 1 is one of the most vulnerable lines in the city (Figure 9-3);
- Delft Tanthof station and Delft station, which are served only by tram line 1, are vulnerable nodes in the network in terms of connectivity reliability (table 9-3). Hence, reducing vulnerability of service line 1 could improve reliability of these stations consequently.

To reduce line vulnerability, we shorten the line by splitting it into two parts as follows:

- Line 1-A: From Scheveningen to Hollands Spoor station with the length of 7.2 km;
- Line 1-B: From to Hollands Spoor station to Abtswoudsepark Uitstap with the length of 12.5 km.

We choose the railway station Hollands Spoor as point of split because the fewest passengers will experience an additional transfer in this case. Furthermore, it provides ample accessibility for the NS Dutch train network as well as the city centre.
Splitting line 1 results in 1% reduction in the total number of cancelled trips in the entire network. Of course, this reduction rate is much higher (22%) for origin Delft Tanthof which is directly served by line 1. This result demonstrates that positive impacts of shortening a line on service reliability are much more of a regional kind.

Of course, splitting line 1 increases travel costs due to additional transfers. For instance, passengers boarding tram line to travel for example from Scheveningen to Delft need to transfer at Hollands Spoor. Thus, total travel costs in the entire network will rise up by 1.5%.

Consequently the results of the analysis show that splitting line 1 will enhance connectivity reliability for the tram network, although it increases travel costs as well. This finding demonstrates the indicated trade-off between travel time reliability vs. travel time. The net result is an increase of the total network costs of about 1%. Therefore, shortening service lines as a reliability enhancing measure might not always be a proper solution. Only if the number of additional transfers is small, this measure might be considered as a suitable option.

9-5 Creating flexibility in the service network

In this section, we focus on the role of additional infrastructure on creating service network flexibility and thus enhancing service reliability. We described in the previous chapter the impacts of additional infrastructures on improvement of service reliability in a hypothetical network. Due to special characteristics of that case study, we limited the design of additional infrastructures to a ring infrastructure at certain locations. However, in this realistic case study, impacts of other kinds of additional infrastructure such as bypasses, and turning facilities in various locations can be evaluated too.
In the upcoming subsections of this section, impacts of the following additional infrastructure types will be analysed:

- a bypass parallel to an elevated tramway to be used in case of emergency;
- a shortcut connecting two lines' terminals;
- turning facilities involving right turns and U-turns enabling services to divert to another itinerary.

The locations of the bypass and the shortcut have been predefined because of specific network conditions. We will discuss this issue for each case. However, for turning facilities, we apply a systematic search method to find the most effective location for adding the infrastructure in terms of service reliability. We will present this method in case 9-3.

9-5-1 Case 9-1: The bypass

Basically, bypasses are used as alternatives for vulnerable links. Service lines can be operated via a bypass in case of a blockade in the original path. Thus, the bypass can be used by tram service lines as the alternative itinerary.

The location of the bypass is proposed by HTM planning committee. The bypass is added parallel to the link between Centraal Station and the eastern part of the network which is an elevated tramway.
Figure 9-6 shows a schematic image of service lines merging at the Central station and the details of the infrastructure network and the proposed bypass.

The main reason of choosing the aforementioned location is the high vulnerability of link 19. In more detail there are 3 reasons that the bypass is considered to be built at this location:

1. Link 19 is a quite vulnerable line since it is heavily used. Thus, supporting the lines passing this link by an alternative will reduce service lines' failure using this link significantly.
2. In case of failure of link 19, there is no possibility for detour and thus, the connection between the north side and the east side of the city is cut. The results of the reliability assessment of The Hague tram network support this issue since centroids 44 and 45 suffer from high levels of trip cancelation (table 9-3).
3. The existing tunnel (link 28) is proved to be also a vulnerable link and furthermore, a blockade in this link will again result in a disconnection between the north side and the east side of the city. This is because there is no possibility for detour in case of tunnel blockade for lines 2 and 6 due to different height levels. Adding the bypass enables detour possibilities for these two lines.

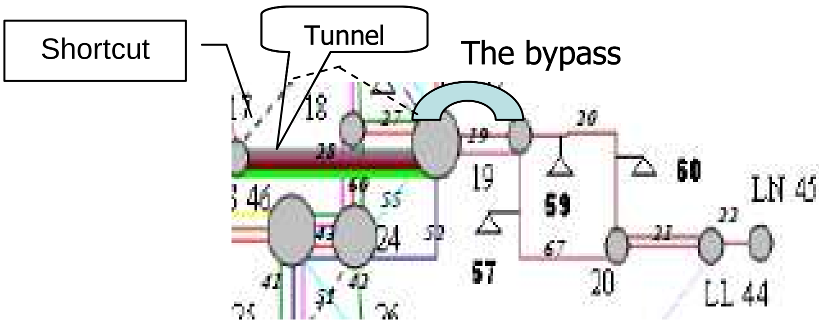

Figure 9-6: Details of network between Centraal Station and eastern part of network

By adding a bypass in parallel to link 19, impacts of disturbances are less on terminals Leidschendam Noord and Leidschenhage as well as corresponding lines 2 and 6. The reason is that when link 19 fails, all lines using this link still can be operated via the at grade bypass. Also, in case of a blockade in the tunnel, tram lines 2 and 6 can still be operated by diverting through link 18 between Centraal station and Kneuterdijk centroid and then continue through shortcut between Kneuterdijk and Brouwersgracht and finally back to the original itineraries.
Assessment results show that adding the bypass can reduce the number of trip cancelations even by 24% for some years with a mean value of 9 %. Thus, building the bypass brings benefits in terms of connectivity reliability for the entire network (e.g. for public transport travellers on other parts of the lines and the network).

The bypass decreases extra travel costs even down by 18% for some years with a mean value of 4%. This is due to a higher number of direct services provided by an improved robustness of these lines. Hence, not only is there an improvement in the network connectivity reliability, but also total travel costs are reduced sensibly due to this extra bypass.

Finally the net impact on overall network performance of adding the bypass can reduce total network costs by 0.8% for some years and on average by about 0.4%. It demonstrates that even modifying a small part of the network can positively influence the entire network performance.

9-5-2 Case 9-2: The shortcut

The outcomes of previous analyses (chapter 8) in the hypothetical networks clearly demonstrate the benefits of infrastructure shortcuts in network reliability enhancement. In this case we apply an additional shortcut infrastructure connecting two vulnerable lines (tram lines 2 and 3) and thus providing an alternative for vulnerable service lines in case of failures in one of these lines. The origins located at the end of these lines have a high level of trip cancelations (Loosduinen (LS 35) and Kraayenstein (KS36)) (see also table 9-3). The length of this shortcut is approximately 600 meters which brings 150,000 € annually for investment and maintenance costs. Figure 9-7 shows geographic characteristics of the area, the itineraries of tram lines 2 and 3 and the proposed shortcut. Note that this shortcut could be a single track since it is not heavily used unlike the bypass and thus, its construction costs could be lower than those of the bypass. The shortcut will be used in case of disturbances at links 13 or 23 (figure 9-8). In case of disturbances, these lines can be diverted from their original path via another track, skip blockade(s), back to their original itinerary using the shortcut and ultimately terminate at U-turn point illustrated in the figure 9-8.

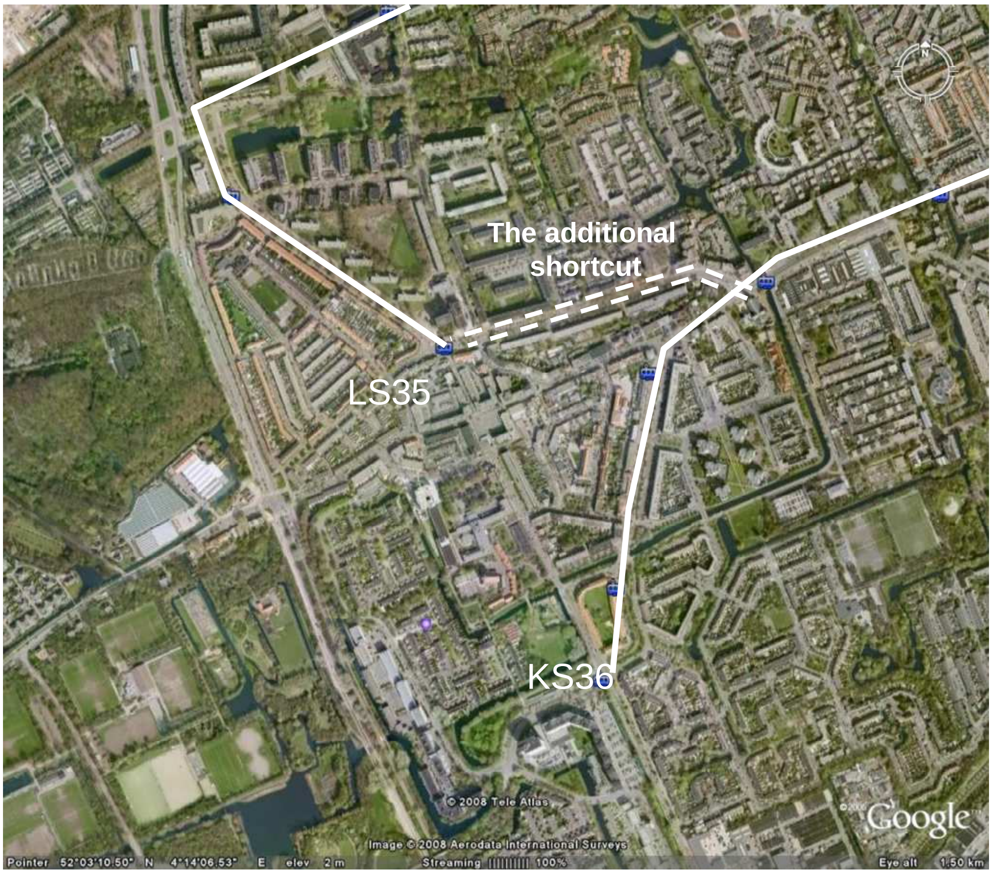

Figure 9-7: Satellite image of tram lines 2 and 3, geographic features, and the additional infrastructure shortcut

The simulation results show a 2.4 % reduction in the number of trip cancelations on average, although this rate reaches up to 12 % for some years, albeit this rate is not relevant at the strategic level of network design. Although the impact of shortcut infrastructures on connectivity reliability is less than the bypass, their infrastructure cost is also less than the bypass infrastructure cost. As a net result, applying this small shortcut in the network will lead to 0.1% reduction in the total network costs on average.

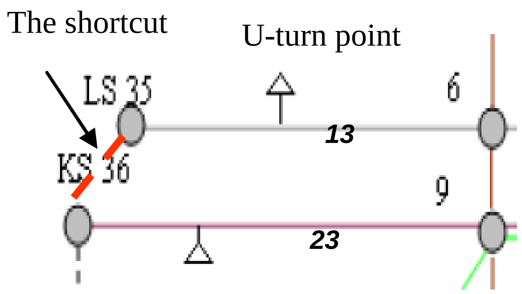

Figure 9-8: The shortcut connecting terminals KS 36 and LS 35

9-5-3 Case 9-3: The turning facility

In this case, we intend to explore attractive possibilities of adding turning facilities to the infrastructure network to create service network flexibility and thus to increase service reliability in the network. Turning facilities are especially important for rail bound transport since they enable tram and trains to switch between tracks. Moreover, they enable a short turn movement in case of necessity. To find the optimum location for installing turning facilities, we use a systematic search method based on the previous network reliability assessment stated in part 9-3. The search method consists of 4 steps as follows:

- Step 1: select the most vulnerable centroid;
- Step 2: select the most vulnerable line serving the selected centroid;
- Step 3: determine possible locations regarding the selected line for implementing additional infrastructures;
- Step 4: optimise options subject to a budget constraint for building options and select the optimum case.

Applying the aforementioned methodology will result in selecting centroid 40 (Delft Tanthof) as the most vulnerable centroid (Table 9-3). This centroid is served only by line 1 and therefore the proposed line set consists of one line only (step 2). By looking at the line configuration and geographic obstructions in detail, we find that it does not make sense to apply any type of bypass or shortcut to a part of the line. For example, providing a shortcut between Delft Tanthof (DT 40) and Delft University (DT41) will be very expensive because of the infrastructure requires crossing the canal between the Schie-Canal and the NS railway tracks. Therefore, the focus is on determining locations for turning facilities.

According to HTM report, line 1 suffers from lack of turning facilities in the following sections:

- Link 66 between Broeksloot and Herenstraat;
- Link 47 between Herenstraat and Hoornbrug/Broekpolder;
- Link 50 between Herenstraat and Voorburg station;

- Node 30 Scholekstersingel served by lines 15 and 19.

The focus of the first three options is on maintaining service within The Hague, while the last option connects The Hague to Delft. The geographic view of this part of line 1 and the selected locations for implementing turning facilities are shown in figure 9-9 and figure 9-10 schematically as well.

Figure 9-9: The geographic location of turning facilities

Analysis of these four options shows that a turning facility at node 30 is the most effective option (Figure 9-11). The assessment model shows that adding this turning facility will create more flexibility for line 1 and thus can reduce the number of cancelled transit trips by 6.1% and for some years even by 22.9%. Also, it decreases extra travel costs down by 2.6% and for some years even by with 8.9%, albeit this rate is not relevant at the strategic level of network design. These reliability benefits yield a 0.3 % decrease in total network costs for the entire tram network.

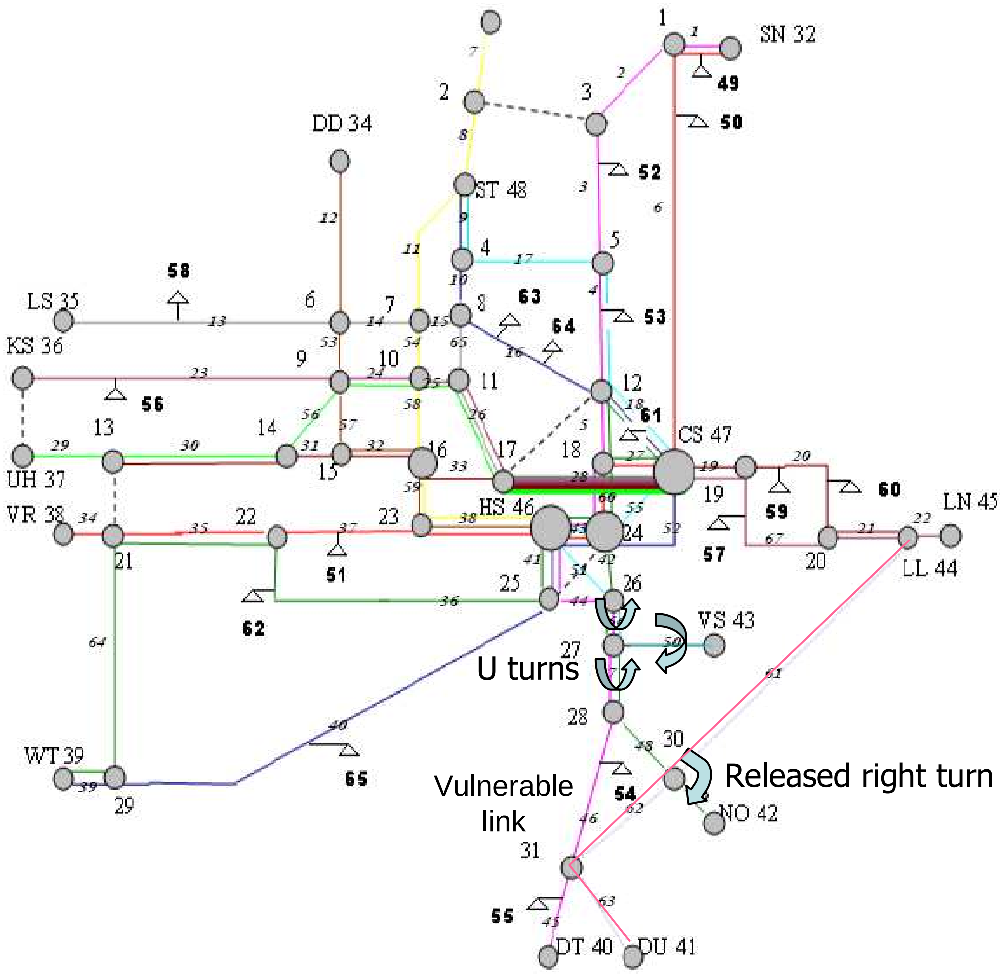

Figure 9-10: Turning facility locations in line 1 of The Hague tram network

It should be noted that the combination of cases 9-1 to 9-3 (including the bypass, the shortcut, and the turning facility simultaneously in the infrastructure network) may bring additively positive joint impacts on service reliability. The reason is those additional infrastructures are applied at different parts of the infrastructure network which are located so far away from each other. Thus, the probability of simultaneous infrastructure blockades due to major discrete disturbing events is quite small.

Furthermore, the services lines that benefit of these additional infrastructures are also different. For example, the bypass improves service reliability of lines 2 and 6, whereas the turning facility enhances service reliability of line 1. The shortcut improves service reliability of lines 2 and 3.

Finally, sensitivity analyses demonstrate that the aforementioned findings are generic and reliable. They have been validated for several different simulation seeds. The impacts of different seeds on simulation results are large for a small number of runs (e.g.5 runs expressing 5 years). However, when the number of runs is adequate (e.g. 20 runs expressing 20 years), implementing different seeds does not influence the simulation results. Furthermore, sensitivity analyses show that parameters' value (e.g. route utility function, value of time, trip cancelation penalties) do not influence the achieved outcomes significantly, albeit when trip cancelation penalties are set to higher value, the role of additional infrastructures are more outstanding.

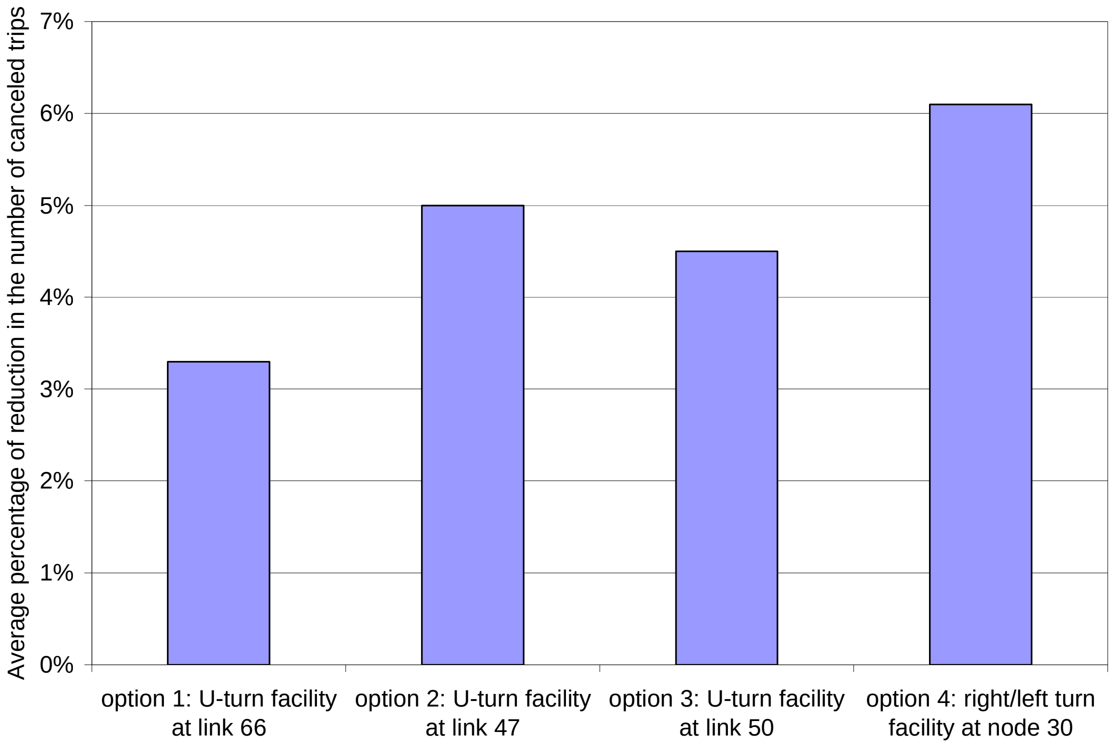

Figure 9-11: Impacts of turning facilities on connectivity reliability of The Hague tram network

9-6 Summary and Conclusions

In this chapter we extended the previous analyses of reliability assessment, discussed in chapters 7 and 8, to reliability assessment of a realistic public transport network. We explored multiple options for improving service reliability especially in the field of additional infrastructure. Thus, we validated the previous findings (obtained in the hypothetical case studies) in practice.
In this chapter we adopted the tram network of The Hague as a European medium size city. Its tram service network contains various typical service lines such as transversal lines and radial lines with different levels of vulnerability. Moreover, the diversity in the The Hague tram infrastructure network enables the planner to consider different additional infrastructure options to improve service network flexibility. Consequently, we applied several reliability enhancing measures at the strategic level of network design and assessed their impacts on service reliability and the overall network performance accordingly.

As the first step we evaluated the current situation of the existing network in terms of reliability. We determined in detail connectivity reliability between origin-destination pairs as well as service line vulnerability. The results showed that in the current situation, the average trip cancelation rate and extra travel costs are around 2.1% and 2.0% per year respectively. However, long service lines such as tram line 1 and 15+16 suffer from higher vulnerability than other lines. Based on these outcomes suggesting interesting locations, several reliability improvement options were considered and tested.

In the 1st method, we split a long service line (line no. 1) into two parts being connected at the HS train station. Applying this method will reduce service line vulnerability for line 1 and thus increase connectivity reliability for OD pairs served by this line. The case's outcomes verified the previously obtained results of the hypothetical case study. Shortening long service lines by splitting them into short lines reduces service network vulnerability and consequently enhances service reliability, although, it results in an increase in travel costs as well. The net result showed an increase in the total network costs as the overall network performance criterion. Therefore, shortening service lines as a reliability enhancing measure might not always be a proper solution. Only if the number of additional transfers is small, this measure might be considered as a suitable option.

In the 2nd method, we assessed the impacts of infrastructure redundancy on service reliability. Bypasses, shortcuts and turning facilities are three different types of additional infrastructures that can be applied in rail bound public transport networks. Implementing the aforementioned additional infrastructures in the network and assessing different cases yielded more or less similar results for different types of infrastructure. In other words, the findings demonstrate that it's possible to gain interesting achievements in terms of service reliability even with small investments and thus small changes in the infrastructure network.

Our approach truly shows that considering additional infrastructure facilities such as bypasses, shortcuts and turning facilities will enhance network connectivity reliability and have also a sensible positive impact on network performance. The analyses for the Hague tram network show that additional infrastructures can not only increase service reliability of the network, but also they can lead to a significant reduction in travel costs and even in total network costs as the overall network performance criterion. Furthermore, applying the synergic combination of the aforementioned additional infrastructures improves additively service reliability in the network.

Finally, considering reliability in the strategic transit network design results in a useful recommendation for the infrastructure planners: "using the existing infrastructure in a smart way by equipping the existing infrastructure network with additional infrastructures such as shortcuts, bypasses, and turning facilities". Combing these additional infrastructures with the existing infrastructure network for rail bound transit will facilitate operational adjustments in case of network disturbances and eventually will lead to maintaining service reliability high.

10 CONCLUSIONS

The motivation for the research presented in this thesis is to determine the impact of service reliability on urban public transport network design and assessment. This final chapter summarises the main results of this thesis. First, a short summary of the problem studied and the approach used to incorporate service reliability in urban public transport network assessment and design is given. Next, we address the questions which were raised in the introduction chapter regarding the research objective. Addressing the questions is accompanied by presenting relevant findings and the conclusions regarding urban public transport network design and assessment. Finally recommendations for further research are given.

10-1 Summary of the conducted research

This research starts with the classical public transport network design approach which is presented in *chapter 2*. In this chapter we summarise the classical public transport network design procedure and address this question: why the classical public transport service network design problem is not appropriate. A bi-level design framework based on game theory is proposed to deal with design complexities. Also, classical public transport design objective functions with different perspectives are presented. All design aspects presented in this chapter demonstrate that the classical public transport network design problem is approached according to the deterministic (opposed to stochastic) point of view by assuming fixed (opposed to random) public transport network characteristics in both demand and supply sides: travellers (demand side), the service network and infrastructure (supply side).

In *chapter 3* we look at public transport networks in a more realistic perspective. We elaborate on impacts of stochastic events on public transport networks at both supply and demand sides. We use several empirical results, obtained in several previous researches, to determine impacts of stochastic variations on infrastructure networks and transport service networks for the public transport supply side. At the demand side, we empirically establish the impacts of random events on public transport demand. Expected demand variations caused by minor ongoing quasi-continuous events, whilst demand fluctuations caused by

major discrete events. Both types of demand alterations change travel costs in the network consequently and might influence service operation costs as well.
We also show how variations in transport networks lead to adaptive adjustments and remedial solutions in public transport operation. Depending on the event type, transit operators might apply different actions to mitigate event's impacts on transit services. For minor quasi-continuously ongoing events, solutions are limited to some minor service adjustments, whilst in case of major discrete events actual remedies such as applying detour are considered by transit operators.

In *chapter 4* we deal with impacts of stochastic events discussed in chapter 3 on public transport service performance quantitatively, that is how service quality offered to travellers might change due to impacts of stochastic events in public transport network. The main service quality indicators that we consider are: running time variations, service punctuality, and service regularity.
On the demand side the question was raised what the impacts are of transit service variations on travellers' total trip time. We address this question by measuring the door-to-door trip time variations in travellers' routes.
As last issue in this chapter, the influence of service reliability on traveller's behaviour is studied. Empirical studies demonstrate that public transport service variations affect traveller's departure time and route choice behaviour directly, and mode choice and destination choice in the long run. Also, service reliability is valued highly by travellers among all other influencing factors and it impacts on their choice behaviour inevitably.

Given the consequences of stochastic events in service operations and their impacts on travellers, in *chapter 5* we elaborate on operational, and strategic measures to improve service reliability. Operational measures enable public transport operators to cope with service disturbances and to weaken their impacts on travellers. Strategic measures aim at reducing the service network vulnerability (e.g. by shortening service lines), increasing the service network redundancy (e.g. by proposing alternative routes for travellers), and creating more flexibility for applying operational measures (e.g. by applying detours, partial service lines).
Considering the aforementioned measures yield consequences for the classical network design problem in terms of design objective functions, design dilemmas, and the design framework.
We configured a conceptual framework for comparisons between public transport system properties in reality, and those calculated with the classical modelling approach and the stochastic approach. To do so, we distinguished two extreme cases of a public transport system, namely a fairly unreliable versus a highly reliable public transport system. We concluded that in an unreliable public transport system individual travel costs are higher, therefore patronage is lower and consequently production costs are higher relative to the reliable public transport system. Also, the classical approach underestimates travel costs in unreliable public transport systems, because of undermining or ignoring probable variations and distortions which happen in reality in the system. For reliable public transport systems the classical approach results in the biased estimation of real properties but not as bad as for unreliable public transport systems. However, we demonstrated that applying the stochastc model which considers impacts of minor quasi continuous ongoing events and major discrete events yields accurate estimation of real properties of the public transport systems.
Applying operational measures increase operating costs. Increasing redundancy and flexibility in the service networks need additional investment and maintenance costs. Moreover, operational adjustments impose additional travel time (costs) to travellers. Thus, the network performance assessment criterion should be extended to capture these types of costs.

Accounting for impacts of disturbances on traveller's behaviour also leads to an extended bi-level relationship between network design and traveller's behaviour. These extensions in public transport network design and assessment are discussed and elaborated in chapter 5.

With the purpose of extending the network design problem with service reliability considerations, the impact of service reliability on travel choice behaviour is accounted for in *chapter 6*. We explicitly focus on the PT-route choice problem. Thus, we elaborate on public transport route choice model concepts with respect to stochastic variations in public transport networks. To do so, we study impacts of random variations and distortions of transit services, caused by minor ongoing continuous events and major discrete events respectively, on traveller's route choice behaviour. To determine the impacts of minor continuous ongoing events on PT traveller's route choice, we include a travel time reliability indicator in the route utility function. To capture the impacts of major discrete events on traveller's route choice, both the route set generation procedure as well as traveller's choice modelling are purposefully modified.
To account for impacts of major discrete events on route choice, we make a distinction between travellers' pre-trip and en-route choice behaviours depending on the event type and availability of information for travellers. This distinction results in a more realistic modelling of PT-travellers' route choice behaviour.

By using hypothetical networks and a new dedicated simulation tool, Chapter 7 determines to what extent reliability enhancing measures lead to better overall network performance. A simulation tool with the capability of implementing different types of public transport networks (e.g. radial networks, transversal networks) has been developed for assessing public transport network performance including service reliability. By using the simulation tool, stochastic events are generated for a longer period of time (e.g. a year) and then their impacts on infrastructure availability, the public transport service network, transit demand, passenger's behaviour, and finally service quality offered to travellers are determined. Thus, public transport network performance is evaluated in the stochastic perspective.
We implement several reliability enhancing measures at the strategic level of network design in a hypothetical case study, resembling an ideal commonly used public transport network pattern (radial/arc network), and evaluate their impacts on overall network performance including service reliability. The main intention is to verify whether consideration of service reliability in the design assessment leads to significantly different outcomes of classical public transport network design.
In chapter 7, the focus is on transport service network, where we apply measures to increase service network redundancy or decrease service line vulnerability. In contrast, in *chapter 8* impacts of purposefully providing dedicated small additional infrastructures on connectivity reliability as well as on overall network performance are evaluated using a similar assessment approach as in chapter 7.

To analyse a realistic case study including natural varieties and characteristics usually observed in urban public transport networks, we apply our assessment approach on a more complex network having more spatial diversities. This was the subject of *chapter 9*. We adopt The Hague tram network as medium size European city transit network. The simulation model is applied on this network to firstly quantify the service reliability of the network in its current conditions. Thereafter, dedicated reliability improving measures (in the field of additional infrastructure consisting shortcuts, bypasses, and turning facilities) are implemented (in the model) and accordingly their consequences for the service reliability as well as overall network performance are predicted and assessed.

Additionally, shortening of a service line by splitting it into two parts at an appropriate location is another reliability enhancing measure studied in this network. It reduces service line vulnerability and thus increases network robustness and connectivity reliability. The achieved outcomes in chapter 9 are in line with the hypothetical case study's outcomes and validate the recommendations presented in chapter 5 regarding public transport network assessments and design.

10-2 Addressing the research questions & Findings

With respect to the questions we raised in chapter 1 and scientific contexts in chapters 2, 3, 4, 5, and 6 and case studies' outcomes in chapter 7, 8, and 9, our research addresses the questions raised in three themes in chapter 1.

10-2-1 Theme 1: The diagnosis issue

In this theme, by mainly using results and insights from the literature we identified causes of variations in public transport networks, impacts of events on public transport networks, and the notions of service reliability. In the context of the diagnosis issue, six questions were raised that we address accordingly as follows:

Why is classical public transport service network assessment and design not appropriate?
Due to complexities of public transport network design and assessment, several methods are in use to deal with network design problem and tackle the complexities. They mainly fit in the context of one of the three approaches addressing the public transport network design problem, namely, optimisation models, design methodologies, and decision support systems. In all these approaches, the main assumption is that public transport network characteristics are constant and do not vary over time. Thus, traditional public transport network design approaches do not evaluate network performance realistically, because they do not consider influence of potential variations caused by stochastic events on network performance.

Which are relevant random variations pertaining to urban public transport networks?
There are variations on the demand and the supply sides causing disturbances for travellers and operators in transportation networks. Many sources contribute to these variations. Basically, they might be classified as follows:

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

All kinds of forces cause stochastic choice behaviour on the individual traveller side leading to demand alterations. Infrastructure supply is impacted by stochastic events (e.g. bad weather, maintenance activities). Also, the transport service network quality varies due to traveller's behaviour, infrastructure quality, external and internal sources of variations.

We identified various types of events causing random variations in transport systems and classified these based on several criteria consisting of the event's source, frequency, location, predictability, regularity, and the event's severity. Recognizing the aforementioned criteria and the ways how these events impact public transport networks leads to a systematic and dedicated classification of events.

Which are the impacts of stochastic events on public transport network service operations?
Public transport service operation is impacted by stochastic events, and thus may deviate from the planned schedule. Service quality deviations depend on the event type.
Public transport service performance variations due to minor continuous ongoing events are limited to service running time variations and timetable deviations which are observed as regular service quality variations and are satisfactorily coped with by transit operators. Service performance variations can be measured by common operating measures such as service running time variations, punctuality, and regularity and may result in additional costs for travellers as well as the operator. For minor continuous ongoing events, operational adaptive actions are limited to some service adjustments predominantly speeding up and slowing down services.

In contrast, transit service distortions caused by major discrete events are more complicated so as not to be simply observed in transit service quality indicators. Therefore, impacts of major discrete events on transit service performance need to be studied explicitly by considering events' specific characteristics and specific ways how they impact on service operations. Connectivity reliability expressed by number of trip cancelations is proposed as a suitable criterion to measure impacts of major discrete events on public transport networks performance. In case of major discrete events actual remedies such as applying detours are considered by transit operators to mitigate consequences of disruptions.

How do transit travellers perceive service variations suffered by them?
Given public transport service performance variations, travellers suffer from trip time variations and even possibly trip cancelations. Both aspects caused by stochastic events impose additional costs to travellers mainly focusing on regular travel time variation costs, extra travel costs and trip cancelation penalties. Variations in quality of services offered to travellers in the long term form the service reliability perception in the traveller's mind.

What are relevant notions of service reliability in public transportation?
Service reliability of public transport networks predominantly deals with travel time reliability and connectivity reliability. Travel time reliability is defined as the range of travel times experienced by travellers during a long series of daily trips. Connectivity reliability is defined as the probability that network nodes are connected and can be reached. Service reliability in transportation is a performance criterion expressing long term performance; although, impacts of recent experiences on service reliability are more influencing than those of past experience.

Which are relevant impacts of PT service reliability on traveller's choice behaviour?
Service reliability affects all traveller's choice aspects. The logical order of choices based on the time scope (from short term to long time term) is:

- Departure time choice;
- Route choice;
- Mode choice;
- Destination choice.

The perception of service reliability depends on the trip purpose and the traveller's attitude in term of risk averseness. For compulsory trips (e.g. commuting trips, educational trips) service reliability is more important than for optional trips (e.g. shopping trips, and leisure trips). Also, risk averse travellers may value reliability highly compared to risk prone travellers.

10-2-2 Theme 2: The development of public transport network planning

In this theme we developed a public transport network design philosophy and procedure including new design dilemmas, extension of network performance criteria to capture service reliability, and extensions of the bi-level relationship between network design and traveller's behaviour to include impacts of stochastic events. Regarding these theme 2 objectives, five questions were raised that we addressed in this thesis as follows:

How can service reliability be improved in the PT planning stages?
At the operational level, coping-oriented approaches are applied to reduce service variations and distortions caused by minor continuous ongoing events and major discrete events respectively. In case of minor continuous ongoing events, applied strategies focus on *speeding up* and *slowing down* services. In case of major discrete events, operational remedies are:

- Adding capacity to the affected services;
- Repairing the affected service lines (e.g. detours, partial service lines);
- Informing travellers for alternative routes.

At the tactical level, increasing spare capacity in public transport timetable is a relevant approach. It leads to preventing probable delay propagation and thus reduces service vulnerability.

At the strategic level, reducing service lines vulnerability, increasing service network redundancy, and creating service networks flexibility using additional infrastructure are relevant methods to improve service reliability.

Measures that are applied at both tactical and strategic levels are in the context of prevention-oriented approaches and can facilitate operational measures.

Which are relevant consequences of reliability improving measures for the public transport network design problem?
Incorporating service reliability considerations in public transport network planning leads to extensions of the classical network design problem with respect to:

- Network design dilemmas;
- Network design objectives;
- Bi-level relation framework.

New design dilemmas originate from trade-offs between travel time versus travel time reliability, operation costs versus service reliability, and investment costs versus service reliability.

Improving service network flexibility and redundancy, and also applying operational measures to cope with disturbances will increase investment costs, operation costs, and travel costs, whilst decreasing reliability associated costs. Hence, in order to have an appropriate network design objective and assessment criteria, the objective function should be modified accordingly to capture those costs alterations considered in the stochastic perspective. Thus, formulating the generalised cost function in the stochastic condition is suggested. Consequently, the consumer surplus function, the producer surplus function, and the social welfare function have to be reformulated in the stochastic condition too.

Furthermore, considering stochastic events and according operational measures will lead to distinctions between the service network originally designed by the transit planner and the actual network experienced by travellers. Moreover, major discrete events may influence transit demand leading to a distinction between expected demand and actual transit demand as well. In other words, the bi-level relationship between network design and travellers' behaviour needs to be extended to incorporate these impacts.

Does considering service reliability lead to new network design dilemmas?
Yes, it does. As mentioned in the previous answer, new design dilemmas originate from trade-offs between travel time and travel time reliability, operation costs and service reliability, and investment costs and service reliability. These dilemmas are classified into two types according to disturbance type:

A. Design dilemmas due to considering minor quasi-continuous ongoing events:

1. Faster services with higher travel time variations vs. slow services with higher reliability;
2. Timetables with small slack times and lower unreliability vs. timetables with sufficient slack time and higher reliability;
3. Larger stop spacing with higher service reliability vs. shorter stop spacing with lower service reliability;
4. Longer service lines with larger cumulated running time variations and smaller number of transfers vs. shorter service lines with lower cumulated running time variations and larger number of transfers.

B. Design dilemmas due to considering major discrete disturbing events:

5. Longer service lines with lower connectivity reliability and smaller number of transfers vs. shorter service lines with higher connectivity reliability and larger number of transfers;
6. Lower investment costs and lower service reliability vs. higher investments costs and higher service reliability.

The first three dilemmas are primarily dealt with at the tactical planning stage, whilst the last three design dilemmas are mainly addressed at the strategic level of planning.

Does considering service reliability require an extension of the classical network design objective functions?
Yes, it does. Accounting for service reliability in public transport network assessment and design results in extended network design objective functions. Impacts of minor quasi continuous ongoing events are captured by a stochastic form of design objective functions, whereas to incorporate impacts of major discrete events, inclusion of the following new components in the classical design objectives is needed:

- Extra travel time due to major discrete events converted to costs;
- Trip cancellation penalties due to major discrete events;
- Extra operation costs for providing detours / and deploying extra vehicles in case of major discrete events;
- Extra investment costs for additional required infrastructure to provide detour and short runs.

Which are relevant consequences of considering impacts of stochastic events for the classical bi-level network design framework?

Considering service variations in the transport network due to minor continuous ongoing events as well as major discrete events, requires a distinction between the planned services and the actual services offered to travellers; and thus to a different public transport traveller's behaviour and corresponding network performance in the classical network design problem. Therefore, the classical bi-level scheme should account for impacts of these events and the corresponding operational measures as well. Furthermore, stochastic events will also affect public transport demand and cause demand fluctuations which will similarly affect network performance. Therefore, these effects should be included in the bi-level framework as well.
At the strategic level of network design, special attention to route choice is needed. Incorporating service reliability in route choice behaviour enforces modellers to apply extensions in the route choice models. In other words, in route choice models for transit travellers the route's utility function and the route set generation procedure need to be extended in such a way that impacts of service quality variations caused by minor continuous ongoing events as well as major discrete events are adequately incorporated.
Furthermore, impacts of the two aforementioned event types on route choice behaviour are significantly different. In case of minor continuous ongoing events, dealing with service reliability is limited to extending the route's utility function by including a travel time reliability indicator. In case of major discrete events, the route set generation procedure should be extended by relaxing route set generation constraints. Also, depending on the degree of passengers' awareness of disturbances and transit services conditions, different route choice behaviours (pre-trip, en-route) are accounted for.

10-2-3 Theme 3: The implementation issue

In this theme we identified, implemented and ultimately assessed the reliability improving measures at the strategic level of network design. The theme on implementation led to raising the following questions that we addressed in this research by several case studies (hypothetical and realistic):

What are promising reliability enhancing measures for the service network and infrastructure planning?
Shortening long service lines by splitting them into shorter parts is an appropriate way to reduce service line vulnerability and thus to improve service reliability. By shortening service lines, it is possible to reduce travel time variations and the probability of line failures. Reducing travel time variations leads to improvement of travel time reliability, whereas decreasing probability of line failures improves connectivity reliability. In the case study using a hypothetical radial/arc tram service network, this measure was assessed on its efficiencies in terms of service reliability and overall network performance.

Increasing line density in a certain way results in higher redundancy in the service network and consequently can improve service reliability of service network as well. It may facilitate operational remedies during disturbances (e.g. applying detours) and also offer alternative routes to transit travellers (e.g. including tangential lines in a radial service network).

At the infrastructure network level, planning for additional infrastructure such as shortcut facilities create more flexibility in the infrastructure network and consequently in the service network. It can increase network robustness and connectivity reliability by enabling transit operators to apply remedial solutions (such as applying detours, or short runs) and thereby maintain connectivity reliability high. 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 additional infrastructure. In the case study, we exemplified this approach by assuming different ring infrastructures in a radial network, varying with respect to the availability and location of the infrastructure ring.
In the realistic case study, we plan for a bypass to be installed parallel to a vulnerable link, and to be used as a backup. Also, planning for turning facilities for a vulnerable service line (Tram line 1 of The Hague) is another realistic example of creating flexibility for public transport service networks.

What are relevant outcomes of applying reliability enhancing measures at the strategic level for overall network performance?

- Reducing transport service network vulnerability may considerably improve service reliability as well as overall network performance.
- Increasing network redundancy in transport service networks may improve service reliability significantly; but it may not necessarily lead to better overall service performance.
- Creating more flexibility for the service network using additional infrastructure not only enhances service reliability, but it also leads to an improvement in the overall network performance. This outcome is demonstrated in both the hypothetical and realistic network types.

Do reliability enhancing measures at the strategic level of network planning really work for realistic cases? and if yes, what are their consequences in terms of improving overall network performance?
Yes, they do. Reliability enhancing measures at the strategic level of planning are shown to be effective and efficient for realistic transit networks.
Shortening long service lines by splitting them to short lines reduces service network vulnerability and consequently enhances service reliability; however, it results in an increase in travel costs as well. The net result shows an increase in the total network costs as an overall network performance criterion.
The results of The Hague case study truly demonstrate that creating flexibility in the service network may improve service reliability. Implementing additional infrastructure such as bypasses, shortcuts and turning facilities eases operational remedies during disturbances, thus enhances network connectivity reliability, and eventually has the positive impact on overall network performance.
The analyses for the Hague tram network demonstrate that additional infrastructures can not only increase service reliability of the network, but may also lead to a significant reduction in travel costs and even in total network costs as the overall network performance criterion.

Which are the scientific contributions of our work? What is new?
This thesis contributes to the State-of-the-Art of service reliability considerations in the public transport network design in various aspects. The main scientific achievements are:

- Establishment of an extended PT network design framework by incorporating service reliability on the supply and demand sides;
- Formulating PT network design objective functions using new stochastic modelling approach in which unreliability is explicitly considered in formulations;
- Formulation of an extended route choice model including the route set generation procedure with the capability of incorporating public transport travellers' perception of service reliability in their regular route choice behaviour and of their responses to unexpected variations;

- Establishment of new measures at the strategic level of network design for both transport service networks and infrastructure with positive impacts on network robustness and service reliability;
- Establishment of a new planning procedure for infrastructure of urban rail bound public transport network demonstrating the effective role of additional infrastructures on improvement public transport network reliability.

10-3 Conclusions for urban public transport network assessment and design

Given the outcomes of the analyses, the main conclusions of this thesis are as follows:

The classical service performance criteria which are used to assess transit network performance ignore service reliability. Therefore, a realistic estimation of network performance when random disturbances occur in the network won't be gained. In other words, the performance of transit systems is overestimated by discarding unreliability related costs.
In addition, ignoring or underrating influences of service reliability on public transport network design will result in difficulties in transit operations in case of disturbances. Strategic and tactical measures applied to enhance service reliability can facilitate operation adjustments and remedies (e.g. partial services, detours) during disturbances.
Furthermore, if the influence of service reliability on travellers' behaviour is disregarded, the full potential of a transit network in terms of patronage won't be used and in the long term its share of travel demand in competition with private modes will reduce.

Considering service reliability as an influential factor in urban public transport network design will bring consequences for service network design. Consequences will predominantly relate to the service network redundancy and the service line length. Networks having service redundancy appear to have a higher degree of service reliability, albeit their overall performance might not be improved.
The service line length is another point of attention. Longer service lines usually are more vulnerable and thus keeping them operating during disturbances is more difficult for transit operates. Shortening long service lines by splitting them into shorter lines can improve service reliability. If the number of additional transfers imposed to passengers due to splitting lines is small, this measure might improve the overall network performance as well.

Finally, accounting for reliability has consequences for the required infrastructure. It leads to using the existing infrastructure in a smart way. Extending the existing infrastructure network with small dedicated additional infrastructures such as shortcuts, bypasses, and turning facilities will enable transit operators to apply remedial solutions during disturbances (e.g. detours, partial runs) and help them maintain service reliability high.

Our study truly shows that considering additional infrastructure facilities such as bypasses, shortcuts and turning facilities in a smart way will not only enhance network connectivity reliability, but will also have a sensible positive impact on network performance. The analyses for the case studies show that investment for building additional infrastructures in transit networks can lead to a significant reduction in reliability related costs, and travel costs. These reductions are large enough to compensate investments costs for building additional infrastructures. The net result can be a sensible reduction in total network costs as the overall network performance criterion.

Focusing on practitioners’ perspective, they should check the vulnerability of the transit system. If there are links with high vulnerability in the infrastructure network or links that are commonly used by a number of service lines, transit planners should provide backup options for those links. The backup options could be shortcuts, bypasses, and turning facilities. Thus, in case that original links are blocked by stochastic events (e.g. incidents, maintenance works), service lines using those links can still be operated through backups.
Also, public transport network designers should pay attention to long service lines. Our findings demonstrate that long lines suffer basically from higher vulnerability than short lines. Thus, we advise transit network designers to avoid planning of long lines. If the demand pattern is in such a way that shortening service lines by splitting them into short parts does not impose a large number of transfers to passengers, it’s worthwhile to check this option.

Applying both options (shortening long service lines, and providing backup infrastructures for transit networks) will improve service reliability for public transport travellers, will lead to higher degree of passengers’ satisfaction, and eventually yield higher public transport patronage.

10-4 Recommendations for further elaboration

This research can be extended further by elaborating more on the model and implementing more complicated applications.

The capacity constraint for services can be included into the model. Thus, in case of disturbances in the network the probability of overloading due to insufficient capacity can be accounted for as well especially for passengers using alternative routes. In the developed simulation tool, passengers can switch between services freely regardless of considering service capacity limitations. The developed model could estimate the number of on board passengers as well as the number of waiting public transport travellers at each stop and then based on service capacity, compute how many passengers confront overloading services. Thus, additional costs imposed to the waiting travellers, are accounted for as well. These additional costs are added to the total network costs to provide better insight on overall network performance.

Applying other types of urban transit modes (e.g. bus, train) is another option for further research. Compared to trams networks, these types of transit networks have different characteristics for operational adjustments.
For bus networks operational adjustments seem to be much easier. In case of major disturbances there are more options for remedies, because of less operational dependency on dedicated infrastructure as well as higher freedom in operations. However, there might be still restrictions hampering remedial adjustments. For instance, entering residential districts might not be possible due to regulations and also road network geometrical constraints.
For train networks, the operational adjustments are not as straightforward as tram networks because of more operational constraints especially due to safety measures. Implementing train network applications, representing the aforementioned constraints and measures, require accounting for the service timetable as well. Thus, in case of disturbances, there are additional limitations such as a minimum headway between services hampering service adjustments. Therefore, applying reliability enhancing measures at the strategic level might be lead to different results for these types of transit networks.

Eventually, addressing multilevel transit systems is recommended too. Multilevel transit systems contain transit modes that are predominantly working together supplementarily. In such system, transit travellers can switch between transit modes at transfer points to reach their destination conveniently. An example is the transit network in the Netherlands containing the NS train network as the interurban transit and urban transit consisting bus, tram, LRT and metro. Switching from the higher level network to the lower level network requires a transfer. Thus, service reliability of multilevel transit becomes point of higher concern, if connections are missed. It is remarkable that the reliability of multilevel public transport in particular has received scarce attention in the literature, and has not been studied in the systematic way. Hence, implementing a multilevel transit network having at least two different transit levels would be relevant to deal with realistic situations which exist in many countries.

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APPENDIX 1: LIST OF SYMBOLS

Symbol	Unit	Explanation	Indices	Explanation
B	€	Operator budget		
C	€	Costs		Generalised travel costs
			o	Operation cost
			oe	Extra operation cost
			tv	Regular travel variation cost
			te	Extra travel cost
			tc	Trip cancellation cost
			t	Travel cost
			im	Infrastructure and maintenance costs
			ime	Extra infrastructure and maintenance costs
			n	Total network costs
CS		Route set of OD pair		
D	*min*	Disturbance duration		
F	*/h*	Frequency	*i*	Line *i* service frequency
P	*trip*	Demand	*e*	Trip demand forced to use detour routes
			n	Trip demand use normal routes
			c	Trip demand failed to travel
			wl	Trip demand using walking legs
			e	Trip demand traversing via alternative routes
PRDM		Irregularity indicator		
Pr_{ζ}	%	Percentage of missing a service		
PS	€	Producer surplus		
PST		Path size term used in the route utility function		

Symbol	Unit	Explanation	Indices	Explanation
R	€	Operator's revenue		
T	*min*	Generalised travel time		
			s	Generalised travel time in the stochastic perspective
U	€	Utility function	*r*	Route *r* utility
			ij	Trip utility between *i,j*
VOT	*€/hr*	Value of time	*1*	Normal value of time
			2	Extra value of time
WP	€	Walking penalty		

Symbol	Unit	Explanation	Indices	Explanation
c	€	Cost factor	*o*	Operation cost per vehicle per service
			cij	Cancellation cost between points i, j
			im	Investment costs for infrastructure per unit of length (km)
l	*km*	Length	*a*	Link *a* length
			i	Line *i* length
n		Number	*ds*	Total number of disturbances
			l	Total number of service lines in the transit network
			t	Total number of transfers
			vi	Total number of vehicles in line i
h	*min*	Headway	*p*	Planned headway
			a	Actual headway
t	*min*	time	*a*	Access time
			w	Waiting time
			in	In-vehicle time
			t	Transfer time
			e	Egress time
			wl	Walking time
			rn	Regular service running time
			rd	Detour service running time
			r	Travel time reliability
p	*min*	Average punctuality		
r	€	fare	*t*	Fare paid by travellers

Symbol	Unit	Explanation	Indices	Explanation
α	€	constant		PT mode preference constant
β		Weights	*a*	Access time weight
			w	Waiting time weight
			in	In-vehicle time weight
			nt	Transfer weight
			t	Transfer waiting time weight
			a	Access time weight
			e	Egress time weight
δ	*0/1*	Dummy variable	*ids*	Whether line *i* affected by disturbance or not
			ah	Whether link *a* is part of route *h* or not
Δ	*min**	Threshold	*wl*	Walking threshold
			nt	Transfer number threshold
			ovp	Overlap criterion threshold
Γ		Link set indicator		
μ	*min*	Expected mean	*d*	Event's duration
			p	Event's interval
Θ		Threshold	*cmp*	Comparability threshold
			det	Detour criterion threshold
σ	*min*	The std	*d*	Standard deviation of events duration

* For walking threshold *(wl)* only

APPENDIX 2: IMPACTS OF MAJOR DISCRETE EVENTS ON SERVICE RUNNING TIME VARIATIONS (AN EXPERIMENTAL STUDY)

In order to have a comparison between impacts of minor continuous ongoing events and major discrete events on service running time, we performed an experimental analysis in a hypothetical public transport line containing two end terminals and seven middle stops (figure A2-1). The line's characteristics are compatible with a transversal line in a medium size city. The length of the line is set to be 10 Km.

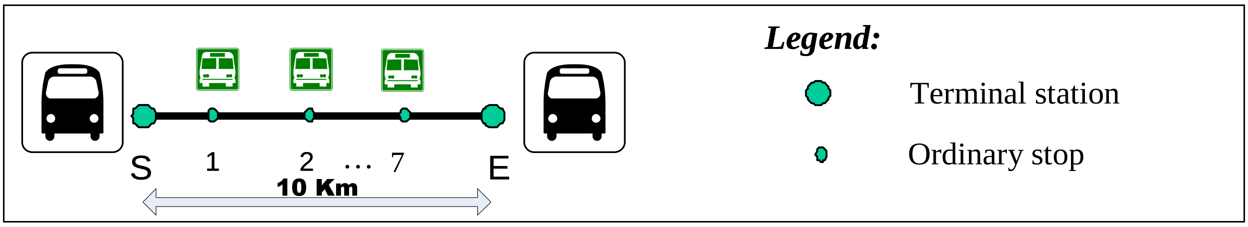

Figure A2-1: The hypothetical service line

We will assess the influence of probable disruptions on the public transport line in terms of service running time and service running time variations. We choose the mean and the standard deviation of running time respectively as two relevant indicators.

Van Oort and Van Nes (2006) already demonstrated that regular service running time variations caused by minor continuous ongoing events lead the 11.1 s /km standard deviation of travel time for tram networks. Similar findings have been already stated in several empirical researches as well (Turner and Wardrop 1951; Herman and Lam 1974; Richardson and Taylor 1978; Bovy 1996).

However, in case of major discrete events the situation is quite different and usually more cumbersome. Transit infrastructure links might be blocked by major discrete events such as

incidents. Simulation results demonstrate that on average each transit link is blocked affected by major discrete events totally 48 hours per year.
Due to probable blockades, service path might change to keep working (e.g. via detour, split into different parts, or partial service line). In the former case, service running time increases consequently.
In this experiment, impacts of major discrete events, which is an increase in running time, is generated uniformly and then imposes variations in the regular running time distribution. The corresponding computations are presented in the next section.

Computation details

Expected running time =28 min
V= 21.5 km/h (Average speed considering dwell time based on The Hague tram network)
STD: 11.1 s/km (regular travel time variations due to minor ongoing continuous variations)
Thus: STD of travel time in the whole line: 1.72 min

In case of major discrete events:
Duration:
Total blockade duration per link per year: 48 hrs

Total number of trip cancelation due to blockade per year:
On average 367 times trip cancellation

Total number of applying detour services in case of disturbances per year:
On average 367 times detour possibility (uniform distribution for extra time, with the range of min: 0; & max: 20min)

The result of simulation has been illustrated in figure A2-2 for different probability distributions consisting of: Normal distribution, Lognormal distribution, and Weibull distribution.
Variations in the mean running time and the standard deviation of running time have been outlined in table A2-1 and A2-2 respectively.

Table A2-1: The mean running time and the STD of running time in case of disturbances in the line

	The mean running time (min)	STD of running time
Log Normal Dist.	28.13	2.045
Normal Dist	28.10	2.067
Weibull Dist	28.12	2.082

Table A2-2: The ratio of mean running time and the STD of running time in regular condition to irregular condition

	The mean running time ratio	The STD of running time ratio
Normal Dist	1.002	1.204
Log Normal Dist.	1.003	1.196
Weibull Dist	1.002	1.178

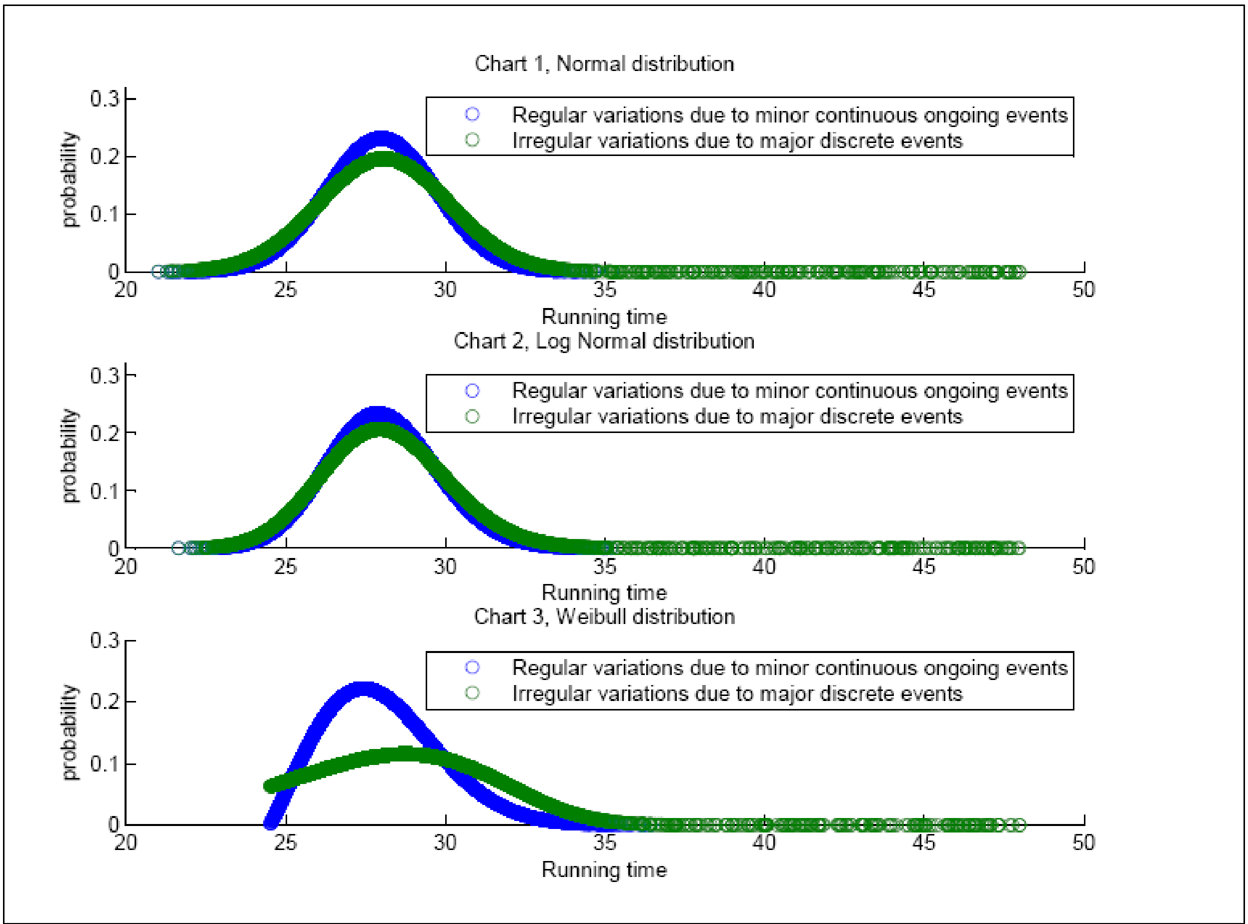

Figure A2-2: The travel time probability distributions for the tram network

Statistical test results:

Evaluating the simulation results leads to the following findings:

1. In case of disturbances caused by major discrete events the Kolmogorov-Smirnov test rejects the null hypothesis stating the service running time still follows the pre-defined probability distribution.
2. Variations of the expected travel time due to major discrete events on average per year are negligible.
3. There is a 20% increase in the STD of service running time due to major discrete events.
4. The Weibull distribution is not a relevant candidate for expressing running time distribution due to high sensitivity in left side of curve to disturbances.

Regarding the test results, we expected that the KS statistic test rejects the null hypothesis beforehand. This is due to irregular variations in running time at the right tail of the running time distribution curve. However, the main part of curve still follows the predefined probability distributions.

With respect to the service running time distribution patterns in illustrated figure A2-2, negligible variations in average running time in case of major discrete events are observed, whereas for the STD of travel time variations are considerable. Major discrete events increase the STD of running time up to 20% for the tram line.

APPENDIX 3: MODELLING AND EXPERIMENTAL SETUP

As stated in chapter 7 the simulation model that we use to assess public transport network performance consists of two phases as follows:

- The deterministic phase;
- The stochastic phase.

Figure A3-1 illustrates the model algorithm in each phase which contains several steps. In this appendix details in the aforementioned phases are explained.

I1: Phase 1- Step 1: Public transport network input

As main input of the model, an urban public transport network is implemented to the model. The simulation model has the capability to deal with urban public transport networks in which service running is monitored on sight and not by automatic control systems commonly used in train/metro networks. Thus, the theory of blocking systems for deploying successive vehicles is not the case.

We opt for a tram network with the symmetric radial pattern. The length of radial infrastructure is 9.4 km. The total number of centroids representing stops is 33. The total number of links in the network is 32.
The tram network contains eight radial lines. In the alternative case study, they are replaced by four transversal lines. Figure A3-2 shows these two networks. In the network with radial lines, terminal points at city centre are allocated to the lines separately (Figure A3-2 A). Thus, there are 8 terminal points in the city centre. Obviously required facilities for tram cars depot and turning movements are provided in each terminal.

The lines' service frequency (headway) is equal for all service lines. Lines' service frequency during peak hours is set to 6 veh/hr; whereas, during off peak hours and weekends it is set to 4 veh/hr. The operating hours is set to 18 hrs daily.

Combination of ring service lines with the radial or transversal lines creates alternative networks (Figure A3-2 C).

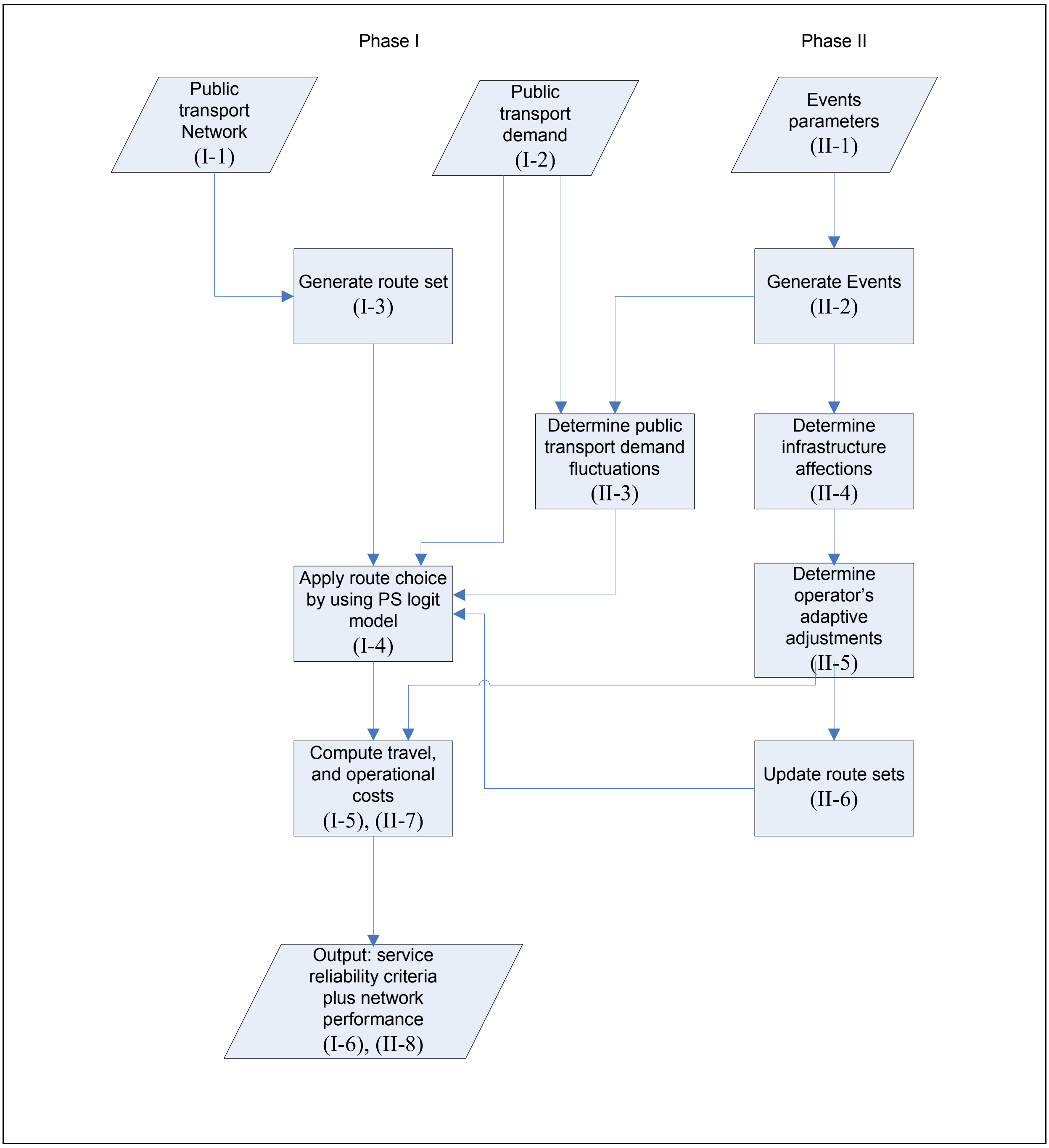

Figure A3-1: Algorithm of the network assessment model

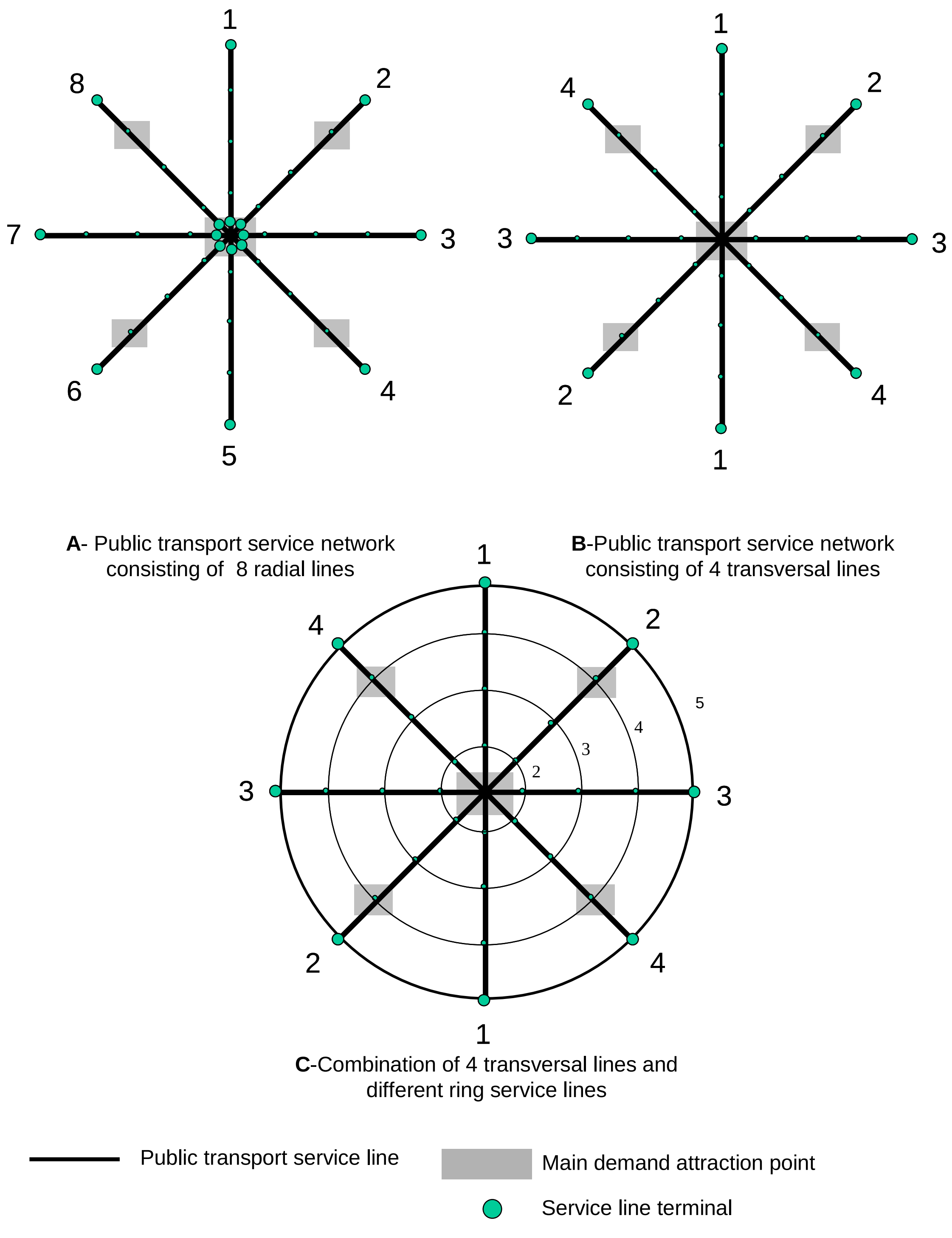

Figure A3-2: The hypothetical case study configurations

The investment and maintenance costs are based on data of the Dutch Ministry of Transport, Public Works and Watermanagement (1996). Similar data has been stated in British source TSU (2009) too. For computing the infrastructure costs, the investment and maintenance costs are amortised over a period of 30 years using a discount rate of 4%, yielding an annual payment of 5.8%. The yearly maintenance costs are estimated as 3% of the investment costs. Table A3-1 outlines infrastructure cost components for Tram.

Table A3-1: Investment and maintenance cost for tram

	Tram
Investment costs (price level 2000) [M€ per km]	2.61
Annual payment factor [%]	5.8%
Maintenance factor [%]	3.0%
Total annual payments [%]	8.8%
Annual costs [M€ per km]	0.23

Table A3-2 outlines network length, infrastructure costs, and operation costs for radial network variants.

Table A3-2: Annual infrastructure and operation costs for radial network variants (M€)

Network variant	Total track length (km)	Total infrastructure costs per year	Total operation costs per year
Variant 1 (no ring)	150.4	34.6	67.4
Variant 2 (centre ring line)	167.2	38.5	67.4
Variant 3 (middle ring line)	200.6	46.1	67.4
Variant 4 (large ring line)	233.1	53.6	67.4
Variant 5 (outer ring line)	267.6	61.5	67.4

I2: Phase 1- Step 2: Public transport demand

Public transport demand in zones can be estimated through traditional 4-stages transport models (stage 1-3). In this research, these steps are preliminary determined and thus public transport demand is pre-determined as an input for the model. Trip demand attraction and production for all zones are assumed to be equal. Table A3-3 outlines trip attraction for zones.

Table A3-3: Number of trip attractions to each zone

Zone Number	Trip attraction number (per year)
1 (Centre)	8,000,000
2	285,714
3	285,714
4	4,000,000
5	285,714
6	285,714
7	285,714
8	285,714
9	285,714
10	285,714
11	285,714
12	4,000,000
13	285,714
14	285,714
15	285,714
16	285,714
17	285,714
18	285,714
19	285,714
20	4,000,000
21	285,714
22	285,714
23	285,714
24	285,714
25	285,714
26	285,714
27	285,714
28	4,000,000
29	285,714
30	285,714
31	285,714
32	285,714
33	285,714

I3: Phase 1- Step 3: Generating route sets between OD pairs

We stated in chapter 6 that in the route set generation procedure, several criteria should be accounted for. Table A3-4 outlines these criteria and the parameters value used in the route set generation model.

Table A3-4: Route set generation parameters value

Parameter	Parameter value
Detour threshold	100%
Behavioural criteria- max walking time	20 min
Behavioural criteria- max number of transfers	2
Overlap threshold	0.7
Comparability threshold	1
Choice set size	6

I4: Phase 1- Step 4: Applying route choice model

Route Utility Function

Given the discussion in chapter 6, a route utility function based on generalised travel cost is formulated as follows:

$$U = VOT \cdot (\beta_a t_a + \beta_w t_w + \beta_{in} \sum_{j=1}^{n_t+1} t_{in,j} + \beta_{nt} n_t + \beta_t \sum_{i=1}^{n_t} t_{ti} + \beta_r t_r + \beta_e t_e) + r_t + \alpha \tag{A3-1}$$

Where:

t_a = Access time;

t_w = Waiting time at the first boarding

t_{inj} = Corresponding in- vehicle time (in leg number *j)*

n_t = Total number of transfers during trip

t_t = Corresponding transfer time (at transfer point *i)*

t_r = Travel time reliability indicator

t_e = Egress time

ß = Corresponding weight(s)

r_t= Fare paid by travellers

α= PT mode preference constant

For units of the parameters refer to appendix 1. We define centroids as representatives of the corresponding zones containing stops. This leads to skipping access time as well as egress time.

The weight of utility function components are set based on realistic surveys' outcomes. For instance, Van der Waard in 1989 in a Dutch survey found that waiting time is perceived by public transport travellers as 1.54 times as much as in-vehicle time. For transfer penalty this rate was 8.2. He found that transfer waiting time is perceived 20% higher than in-vehicle time.

The first Dutch national study estimates public transport users' value of transfer time 2.1, 1.6, and 1.6 times as much as in-vehicle time for trip purposes of commuting, business, and other respectively (Gunn & Rohr 1996).
British evidence demonstrates that waiting time is perceived 1.47 as much as in-vehicle time (Wardman 2001). Wardman (2004) demonstrates that for overall trip purposes waiting time is perceived 1.8 as much as in vehicle time for urban trips. For urban trips access time is perceived by public transport travellers 40% higher than in-vehicle time. The same study shows that for interurban trips waiting time is perceived 1.7 as much as in vehicle time. Note that waiting time and transfer time values can be expected to vary according to a wide range of socioeconomic and situational factors.
Thus, all the aforementioned values are not generically valid. There is little evidence on how the values vary with factors other than trip purposes (Wardman 2004).

Based on travel time components' weights found by Van der Waard (1989), and Wardman (2004), and travel time reliability perception found by Tseng et al (2004), the implied route utility function is formulated as follows:

$$U = 1.5t_w + 1\sum_{j=1}^{n_t+1} t_{in,j} + 8.2n_t + 1.2\sum_{i=1}^{n_t} t_{ti} + 1.7t_r + \varepsilon \qquad \text{(A3-2)}$$

For simplicity sake we considered fixed fare system regardless of route length and thus eliminated it in the route choice model.
The regular travel variation cost is approximated for each route based on travel time components' regular variations:

$$t_r = \sqrt{\sum_{k=1}^{n_t+1} \sigma_{in,k}^2 + \sigma_w^2 + \sum_{j=1}^{n_t} \sigma_{t,j}^2} \qquad \text{(A3-3)}$$

Where:
$\sigma_{in,k}^2$ = Variance of the in-vehicle travel time in leg *k* of route *r*
σ_w^2 = Variance of waiting time
$\sigma_{t,j}^2$ = Variance of transfer time at transfer point *j*
n_t = Total number of required transfers during trip

Route Choice Model

With respect to methods for dealing with the overlap problem, outlined in table 6-1, we opt for Path Size logit model. The route choice application is formulated as follows:

$$P(r \mid CS) = \frac{e^{(U_r + Ln(PST_r))}}{\sum_{h \in CS} e^{(U_h + Ln(PST_h))}} \qquad \text{(A3-4)}$$

where:
r = Route *r*
CS= Route set indicator

PST= Path size term formulated as follows:

$$PST_r = \sum_{a \in \Gamma_r} \frac{l_a}{d_r} \cdot \frac{1}{\sum_{h \in CS} \frac{d_r}{d_h} \cdot \delta_{ah}} \qquad \text{(A3-5)}$$

where:
l_a= Length of common link a
d_r= Total length of route r
δ_{ah} = Binary variable (0/1) indicating whether link a is part of route h or not

I5: Phase 1- Step 5: Computing travel and operation costs

Travel Costs

Travel cost is computed for each traveller between an OD pair. In the aggregate level total travel cost is accumulated as follows:

$$C_t = \sum_{i=1}^{O} \sum_{j=1}^{D} P^n{}_{ij} \cdot U_{ij} \cdot VOT_1 \qquad \text{(A3-6)}$$

Where:
$P^n{}_{ij}$ = Trip demand between point i and point j made their trip
U_{ij} = Corresponding route utility function between point i and point j
VOT_1 = Value of time (10€/hr)

Table A3-5 outlines total travel costs for network variants.

Table A3-5: Total travel costs for all network variants (M€)

Network variant	Total travel costs per year
Variant 1 (radial lines-no ring)	295
Variant 2 (radial lines- centre ring)	313
Variant 3 (radial lines -middle ring)	320
Variant 4 (radial lines -large ring)	322
Variant 5 (radial lines- outer ring)	349
Variant 6 (transversal lines -no ring)	287
Variant 7 (transversal lines- centre ring)	306
Variant 8 (transversal lines- middle ring)	310
Variant 9 (transversal lines- large ring)	315
Variant 10 (transversal lines- outer ring)	337

Operation costs

The total operation cost for operating the transit network per year is computed as follows:

$$C_o = 365 \cdot \sum_{i=1}^{n_l} n_{v,i} \cdot doh_i \cdot c_o \qquad \text{(A3-7)}$$

Where:
doh_i = Daily operation hour for line i (for the case study it is the same for all lines and is set to 18 hours per day)
n_l = Total number of existing lines
i = Line number
$n_{v,i}$= Total number of vehicles in line i operated to have service frequency F_i
F_i = Service frequency of line i
c_o = Operation costs per vehicle per service (C_o depends on line length and alignment. For radial lines, the operation cost is set to 125€/hr, whilst for ring lines it is set to 150 €/hr)

The main input for quantifying the operational costs per vehicle hour is derived by Van Goeverden & Schoemaker (2000). Costs include personnel costs, those are driving staff and other service related personnel, and vehicle costs, consisting of investment, maintenance and operating costs. As stated in table A3-2, total operation costs for all network types are equal to 67.4 Million Euros per year.

I6: Phase 1- Step 6: Output- overall network performance

As the main output, the total network costs containing travel cost, operation cost, and infrastructure costs expresses overall network performance. It is formulated as follows:

$$C_n = C_t + C_o + C_{im} \qquad \text{(A3-8)}$$

Where:
C_n = Total network costs
C_{im} = Investment and maintenance costs for infrastructures

The investment and maintenance costs for providing suitable infrastructure for urban public transport networks can be formulated as follows:

$$C_{im} = c_{im} \cdot \sum_{i=1}^{n_l} l_i \qquad \text{(A3-9)}$$

Where:
c_{im} = Infrastructure and maintenance costs of service lines per unit of length
n_l = Total number of service lines in the transit network
l_i = Corresponding line length (km)

The investment and maintenance costs are set based on data of the Ministry of Transport, Public Works, and Watermanagement (1996). The investment costs are amortised over a period of 30 years using a discount rate of 4%, yielding an annual payment of 5.8%. The yearly maintenance costs are estimated as 3% of the investment costs. Thus, annual costs for tram infrastructure is 11M€/km.

II1-2: Phase 2- Step 1 & 2: Events parameter & generation model

Major discrete events causing disturbances in the network are classified based on their time, duration, occurrence location, and seasonal impacts (table 3-5 in chapter 3)

The simulation tool creates several types of major discrete events. Events interval and duration are formulated based on the exponential distribution and the Log-Normal distribution respectively:

Interval: (exponential distribution)

$$g(x,\mu_p) = (\frac{1}{\mu_p}) \cdot e^{(-\frac{1}{\mu_p})x} \qquad \text{(A3-10)}$$

Where:

$\mu_p =$ Expected mean of interval between the same types of events. [Parameter *p* denotes period]

Duration: (Log-normal distribution)

$$d(y,\mu_d,\sigma_d) = \frac{e^{\frac{-(Ln(y-\mu_d))^2}{2\sigma_d{}^2}}}{y \cdot \sigma_d \cdot \sqrt{2\pi}} \qquad \text{(A3-11)}$$

Where:

$\mu_d =$ Expected mean of event's duration [Parameter *d* denotes duration]

$\sigma_d =$ Standard deviation of event's duration

Table A3-6 summarises the absolute values for μ_p, μ_d, and σ_d for each type of event. Since the public event(s) repeat with the same time pattern every year, it is not included in the table. It should be noted that due to seasonal affects, there might be some changes in the aforementioned parameters for incidents. For simplicity sake, we do not state these changes.

Table A3-6: Absolute values for parameters of events interval and duration

Events	μ_p	μ_d	σ_d
Incidents	0.89	2.48	0.50
Storm	180.00	1.55	0.40
Snow*	180.00	1.55	0.40
Ice*	18.00	2.30	0.40
Thunderstorm	180.00	1.55	0.40
Vehicle breakdown	7.00	2.19	0.30
Work zone	60.00	2.60	0.30

* Occurrence in winter only

II3: Phase 2- Step 3: Public Transport demand fluctuations

Demand fluctuations are irregular demand alterations arising due to some events. Bad weather and public events are two main events influencing travellers' mode and route choice decisions and causing significant increase or decrease in public transport demand at the time of occurrence. Table A3-7 classifies public transport demand fluctuations according to event types and trip purposes.

Table A3-7: Demand fluctuations due to major discrete events

	Bad weather	Public events
Commuting/Business	+40%	0 %
Education	+40%	-10%
Shopping/Leisure	-20%	+30%

II4: Phase 2- Step 4: Events' impacts and Infrastructure affection

This step determines which link(s) of the infrastructure network are affected by major discrete events. Please note that in case of service network failure such as vehicle breakdown, infrastructure network is affected accordingly. This is especially the case for rail networks. Depending on the event type, one or more links might fail. In case of public events, we assume fixed events' locations. Thus, corresponding segments that are affected can be identified beforehand. For events with extensive geographical impacts such as snow and storm a part of network involving a number of links are affected simultaneously, whereas for other types of events such as incidents only a link is blocked at the time of incident.
A Monte-Carlo approach is used to select failing links, while for simplicity sake no correlation between failing links for events with minor impact area is assumed. Probability of link affections depends on link length and other factor such as link sensitivity to failures. Thus, links located in the city centre are more sensitive to some events such as incidents and public event than other links. Furthermore, the correlation between events is accounted. We apply it for bad weather and incidents. In other words, during bad weather conditions the probability of incidents rises as much as 100%.

II5: Phase 2- Step 5: Operator adaptive adjustments

As discussed in chapter 5, we do not address network resilience in this research. So, the transition phase from commencement of adjustments till implementation on the service network is not considered. After service disturbances arise due to major discrete events, the operators carry out service adjusting tactics. The priority order is: applying detour, and other remedial solutions consisting of splitting services, and applying partial services.
The applied detour threshold for the experiment is set to 100%. In other words, the length of the alternative path must not exceed than 200% of regular line length.
Note that a minimum excess time is applied to account for the possibility that there is sufficient buffer time in the schedule. This is according to the timetable design dilemma discussed in chapter 5.
If applying detours is not possible, the operator splits service lines into independent lines or to apply short runs. Depending on the location of event(s), the service path could be split into several parts. In the experiment we allow splitting a service line into maximum 2 parts.
To deal with higher transit demand that might occur due to some events such as bad weather, transit operators follow the raising capacity strategy that is achieved usually by increasing service frequency using their reserved vehicles. In the experiment, the additional demand is accommodated by deploying high capacity vehicles having 40% extra capacity.

And finally, if a transit line affected at different locations simultaneously or there is no possibility for detour or line splitting, the service line is cancelled during the event. In this case, the operator provides information for travellers to travel via alternatives routes.

II6: Phase 2- Step 6: Updating route set for travellers

In case of major discrete events, affected travellers might accept routes with higher disutility, for example routes with longer in-vehicle time, extra transfer(s), and longer waiting times. They might even opt for public transport routes including long walking legs.
In this situation a new route search procedure with the relaxed constraints as discussed in chapter 6 is applied for the travellers facing services' disturbance.
In the experiment we allow 1 more transfer. We also add 10 extra minutes to the maximum walking time, yielding 30 minutes. Finally we relax the detour threshold by increasing 50 % to the directional constraint.

In the experiment the en-route choice behaviour is applied only during incidents and vehicle breakdown. At the point of incident, the route generation set algorithm with relaxed constraint searches and then generates alternative routes for the affected travellers.

II7: Phase 2- Step 7: Computing travel and operational costs

In case of disturbances caused by major discrete events in the network, there are additional costs imposed to travellers and operators. This section will elaborate on these additional costs. In valuing extra travel time, we expect that the value of time for the additional travel time is higher due to the related uncertainty. In the context of public transport British Rail suggested that lateness costs are 2.5 times higher than scheduled travel time costs (British Rail 1986). Rietveld et al (2001) introduce an 'uncertainty minute' which is weighed as a factor 2.4 higher than a certain minute. According to Dutch empirics, Tseng et al, (2004) value the standard deviation of travel time as 1.7 of in-vehicle travel time. Wardman (2004) demonstrates empirically that the schedule delay being more and less highly valued than in-vehicle time for public transport travellers. A penalty for cancelled trips is included in the travel costs as well a cancellation penalty based on origin-destination distance, thus accounting for the costs of using alternative modes.

Extra travel costs in case of service disturbances

Travellers suffer from extra travel costs when travelling via alternative routes or detoured lines. The extra travel cost in case of service disturbances caused by major discrete events is formulated as such:

$$C_{te} = \sum_{i=1}^{O}\sum_{j=1}^{D}[\mu_e P_{ij}^{e} \cdot (U_{ij}^{e} - U_{ij}) \cdot VOT_2 + \mu_{wl}(P_{ij}^{wl} \cdot (U_{ij}^{wl} - U_{ij}) \cdot VOT_2 + P_{ij}^{wl} \cdot WP)] \quad \text{(A3-12)}$$

If $U_{ij}^{e} \geq U_{ij}$ μ_e=1; μ_e=0 otherwise

If $U_{ij}^{wl} > U_{ij}$ μ_{wl} =1; μ_{wl} =0 otherwise

Where:

P_{ij}^{e} = Trip demand between point *i* and point *j* in the irregular condition suffering from events consequences and use either detour or partial services

U_{ij}^{e} = Utility of route alternatives

P_{ij}^{wl} = Trip demand between point *i* and point *j* in the irregular condition walking between stops as a trip leg

VOT_2= Value of time in case of major discrete events (20€/hr)

WP= Walking penalty (7€)

$$U_{ij} \leq U_{ij}^{e} \leq U_{ij}^{Max}$$

Table A3-8 outlines extra travel costs for network variants.

Table A3-8: Extra travel costs for all network variants (M€)

Network variant	Total extra travel costs per year
Variant 1 (radial lines-no ring)	1.2
Variant 2 (radial lines- centre ring)	1.0
Variant 3 (radial lines -middle ring)	1.1
Variant 4 (radial lines -large ring)	1.9
Variant 5 (radial lines- outer ring)	2.9
Variant 6 (transversal lines -no ring)	2.8
Variant 7 (transversal lines- centre ring)	3.7
Variant 8 (transversal lines- middle ring)	9.5
Variant 9 (transversal lines- large ring)	6.2
Variant 10 (transversal lines- outer ring)	5.8

Trip cancelation cost

If no route alternative is available for travellers, they might cancel their trip or switch to other transport modes. In both conditions, trip cancelation penalties are imposed to them. We formulate trip cancelation cost as such:

$$C_{tc} = \sum_{i=1}^{O} \sum_{j=1}^{D} P_{ij}^{c} \cdot c_{cij} \qquad \text{(A3-13)}$$

Where:

P_{ij}^{c} = Trip demand between point *i* and point *j* in the irregular condition which is cancelled;

c_{cij} = Trip cancellation penalty between points *i* and *j*. It depends on the distance between the OD pair (average value 20 €)

Note that in computing regular travel cost stated in formula A3-6 the trip demand which can not be made has to be reduced from the total demand. Thus:

$$P^{n}_{ij} = P_{ij} - P_{ij}^{c}$$

Where:

P_{ij}= Total trip demand
P_{ij}^{c} = Trip demand between point *i* and point *j* in the irregular condition which is cancelled

Table A3-9 outlines trip cancelation costs for network variants. The outcomes show trip cancelation costs decreases by increasing radius of ring line. It is also higher for the network having transversal lines.

Table A3-9: Trip cancelation costs for all network variants (M€)

Network variant	Total trip cancelation costs per year
Variant 1 (radial lines-no ring)	19.8
Variant 2 (radial lines- centre ring)	14.5
Variant 3 (radial lines -middle ring)	8.8
Variant 4 (radial lines -large ring)	5.6
Variant 5 (radial lines- outer ring)	4.1
Variant 6 (transversal lines -no ring)	63.3
Variant 7 (transversal lines- centre ring)	48
Variant 8 (transversal lines- middle ring)	23.4
Variant 9 (transversal lines- large ring)	6.0
Variant 10 (transversal lines- outer ring)	4.1

Extra operation costs in case of major discrete events

Applying operational adjustments in case of disturbances caused buy major discrete events in a public transport network imposes some extra costs to the operator. Extra operation costs in case of events can be formulated as follow:

$$C_{oe} = \sum_{ds=1}^{n_{ds}} \sum_{i=1}^{n_l} \delta_{ids} \cdot D_{ds} \cdot \frac{t_{rd}}{t_{rn}} \cdot n_{v,i} \cdot c_o \tag{A3-14}$$

Where:
n_{ds}= Total number of disturbances
n_l = Total number of lines
D_{ds} = Corresponding disturbance *ds* duration
$\delta_{i,ds}$ = Dummy variable equal to 1, if the line i has been affected by disturbance *ds*; 0 otherwise
t_{rd} = Detour running time
t_{rn} = Service normal running time
$n_{v,i}$ = Total number of vehicles allocated to line *i* to have service frequency F_i

II8: Phase 2 - Step 8: Output: Reliability criteria plus network performance

At the end of simulation period the model provides service reliability criteria as well as overall network performance. With respect to connectivity reliability, the number of cancelled trips between each OD pair is derived. In the aggregate level, the total number of trip cancelation in the network is computed too.

Moreover, the number of disturbances affecting the network is computed for each service line individually. In order to have better insight on service line vulnerability, the number of multiple affections affecting simultaneously each line is determined too.
Overall network performance in this phase is determined by combining all cost components. The following formulation expresses the overall network performance calculation in the stochastic perspective:

$$C_n = (C_t + C_o + C_{im}) + (C_{tv} + C_{te} + C_{tc}) + (C_{oe}) + (C_{ime}) \qquad \text{(A3-15)}$$

Where:
C_{tv}= Regular travel variation costs due to minor quasi ongoing continuous events
C_{ime}= Extra investment cost for providing additional infrastructure

$$C_{tv} = t_r \cdot VOT_1 \qquad \text{(A3-16)}$$

t_r is computed based on formula (A3-3) stated already.

Extra investment costs *(C_{ime})* for providing additional infrastructure is computed likewise investment and maintenance costs (C_{im}) of regular infrastructure stated by Equation A3-9, however in some cases such as adding infrastructure shortcut to the transit network, the term c_{im} might be smaller than normal infrastructure. This is because of lightly usage of additional infrastructure which leads to lower maintenance costs.

APPENDIX 4: SENSITIVITY ANALYSES FOR THE HYPOTHETICAL CASE STUDY

Variables

We did a set of sensitivity analyses to check whether the findings of the hypothetical case study are generic. The analyses have been arranged based on rational variations in the following network specifications:

- Demand size;
- Demand pattern;
- Network size.

The aforementioned network characteristics play decisive roles in transit network formation. In other words, altering these characteristics can configure different network patterns which may exist in urbanised areas. Table A4-1 outlines the aforementioned variables and their changes.

Table A4-1: The variables and corresponding change(s) for sensitivity analyses of the hypothetical case study

Variable	Corresponding change(s)
Demand size	+ 50% , -50%
Demand pattern	Changing to centre oriented
Network size	-50 %

We increase and decrease the demand size by 50% to evaluate impacts of these variations on service reliability. Albeit, this rate is arbitrary it could be considered as maximum changes in the demand pattern in the mid-term scope (Khattak & Le Colletter 1994).

Also, in another sensitivity analysis we change the demand pattern from the regionally distributed pattern to the centre-oriented pattern. This pattern is observed in many medium size European cities having CBD in the city centre.

The network that we used as the hypothetical case study is a radial network with 9.4 km radius expressing a rather large city (e.g. Frankfurt). Therefore, we decrease the size of the network approximately 50% to check impacts of reliability enhancing measures for smaller networks with radius of 5 km.

Results of sensitivity analyses

The results of the assessment are outlined as follows:

Demand size:

1. The demand size does not influence significantly on impacts of the redundancy measure on service reliability.
2. The demand size does not significantly change the impacts of network flexibility, created by shortcut ring infrastructures, on service reliability. Hence, the service reliability patterns for the radial network and the transversal network illustrated by figures 8-2 and 8-4 respectively remain unchanged.
3. Increasing demand size enhances the efficiency of network flexibility significantly. This is because a larger number of passengers benefit from additional infrastructures and retrieve their trips.
4. Obviously, increasing demand size increases total network costs as the overall network performance criterion accordingly. 50% increase of the demand size increases total network costs by 32.5%. Likewise, 50% reduction in demand size decreases total network costs by 32.5%.

Demand pattern:

1. The demand pattern may influence on impacts of the redundancy measure on overall network performance. If the demand pattern is centre-oriented, variant 1 (the radial network without ring) and variant 6 (the transversal network without ring) are still optimum in terms of overall network performance. However, the difference between overall network performance for the following variants reduces significantly:
   - The network having radial lines and the large ring line and the network having transversal lines and the outer ring line (illustrated in chart 7-6);
   - The network having transversal lines and the large ring line and the network having transversal lines and the outer ring line (illustrated in chart 7-12).

   This is due to significant reduction in number of trips between regional zones.

2. The demand pattern does not significantly change the impacts of network flexibility, created by shortcut ring infrastructures, on service reliability. Hence, the service reliability patterns for the radial network and the transversal network illustrated by figures 8-2 and 8-4 respectively remain unchanged.

Network size:

1. 50% reduction in the network size does not lead to any change in the optimum service network variant. With respect to service network redundancy, networks without ring lines are still optimum variants.
2. 50% reduction in the network size does not lead to any change in the optimum variant in terms of service reliability with respect to redundancy level. Still variants having the outer ring line provide higher network redundancy and lead to the highest service reliability criteria (figures 7-7 and 7-11).

3. 50% reduction in the network size does not lead to any change in the optimum variant in terms of service reliability with respect to flexibility. Still variant with large infrastructure ring in the network with radial lines and in the network with transversal lines provide higher network flexibility and lead to the highest service reliability criteria (figure 8-2 and figure 8-4).
4. 50% reduction in the network size leads to changes in the preference between the network with radial lines and the network with transversal lines in the stochastic perspective. In our case study, the analyses' outcomes show that in the deterministic perspective the network with transversal lines is more efficient than the network with radial lines in terms of overall network performance (figure 7-10). However, results show that in the stochastic perspective, the situation is different and the network with radial lines is optimum this time (figure 7-13). The 2% difference between the optimum variants in terms of total network cost is observed (figure 7-13). If the network size is halved, this percentage decreases down to 0.2% which means there is roughly no difference between the overall performance of the network including transversal lines and the network including radial lines. This is due to a significant reduction in the associated unreliability costs. As indicated in chapter 4 the service line length is a decisive factor influencing line vulnerability and thus service reliability.

APPENDIX 5: THE HAGUE TRAM NETWORK SPECIFICATIONS

The tram network in the Hague serves almost everywhere in Haaglanden region which embraces The Hague, Delft, Rijswijk, Voorburg, Leidschendam, Nootdorp, Wateringen, Leidschenveen, and Zoetermeer (HTM 2008). The following lines itinerary (Table A5-1) provides a good overview of all our routes. Note that line 19 has not been inaugurated yet. Meanwhile, note that each indicated stop may be a representative of some stops which are aggregated to a centroid. The aggregated trip demand production and attraction stated by table A5-2, is according to travel demand forecast for next ten years.

Table A5-1: The Hague tram lines characteristics

Line 1	Line 2	Line 3	Line 4	Line 6	Line 9
Zwarte Pad	Kraayen steinlaan	Arnold Spoelpein	De Uithof	Ziekenhuis Leyenburg	Zwarte Pad
Circustheater	De La Reyweg	Goudenregenstr aat	Ziekenhuis Leyenburg	Dierenselaan	Circus theater
Duinstraat	Monstersestraat	Laan van Meerdervoort	Dierenselaan	Paul Krugerplein	Centraal Station
World Forum	MCH Westeinde	Statenplein	De La Reyweg	Hobbemaplein	Centrum
Kneuterdijk	Brouwersgracht	MCH Westeinde	Monsterse straat	Brouwers gracht	Rijswijksеплеi n
Centrum	Centraal Station	Brouwersgracht	MCH Westeinde	Centraal Station	Station Hollands Spoor
Rijswijkseplein	Oostinje	Centraal Station	Brouwers gracht	Oostinje	Wouwermanst raat
Station Hollands Spoor	Essesteijn		Centraal Station	Essesteijn	Loevesteinlaan
Lorentzplein	Leidsenhage			Leidsenhage	Leggelostraat
Broeksloot	Dillenburgsingel				De Dreef
Herenstraat					
Hoornbrug/Broe kpolder					
Delft Station					
Tanthof					
Total line length	**Total line length**	**Total line length**	**Total line length**	**Total line length**	**Total line length**
19.7 (km)	*13.9 (km)*	*8.3(km)*	*12.3(km)*	*12.1(km)*	*13.1(km)*
Headway	**Headway**	**Headway**	**Headway**	**Headway**	**Headway**
10 min, 15min	8-15 min	10 min, 15min	10-15 min	10-20 min	5-20 min
Operating hours	**Operating hours**	**Operating hours**	**Operating hours**	**Operating hours**	**Operating hours**
17-19 hrs	17-19 hrs	17-19 hrs	17-19 hrs	16-18 hrs	16-18 hrs
Number of required vehicles	**Number of required vehicles**	**Number of required vehicles**	**Number of required vehicles**	**Number of required vehicles**	**Number of required vehicles**
15	14	26	24	11	19

Table A5-1 (Cont'd): The Hague tram lines characteristics

Line 10	Line 11	Line 12	Line 15+16	Line 17	Line 19
Van Boetzelaerlaan	Strandweg	Markenseplein	Dorpskade	Dorpskade	Delft TU
Statenplein	Duinstraat	Goudenregen straat	Parijsplein	Parijsplein	Delft Station
World Forum	Van Boetzelaerlaan	Zevensprong	Leggelostraat	Lorentzplein	Scholekster singel
Kneuterdijk	Laan van Meerdervoort	Paul Krugerplein	Loevesteinlaan	Station Hollands Spoor	Leidsenhag e
Centraal Station	Loosduinseweg	Hobbemaplein	Lorentzplein	Rijswijkseplein	
Rijswijkseplein	Hobbemaplein	Wouwerman straat	Station Hollands Spoor	Centraal Station	
Station Hollands Spoor	Wouwermanstraat	Station Hollands Spoor	Rijswijkseplein	Kneuterdijk	
Broeksloot	Station Hollands Spoor		Centrum	Waldeck Pyrmontkade	
Herenstraat			Kneuterdijk	Statenplein	
Voorburg Station			Centraal Station	Van Boetzelaerlaan	
			Centrum		
			Rijswijkseplein		
			Broeksloot		
			Herenstraat		
			Hoornbrug/Broe kpolder		
			Scholekster singel		
			Nootdorp Centrum		
Total line length	**Total line length**	**Total line length**	**Total line length**	**Total line length**	**Total line length**
11.3 (km)	*7.8 (km)*	*7.8 (km)*	*19.7 (km)*	*15.6 (km)*	*16.0 (km)*
Headway	**Headway**	**Headway**	**Headway**	**Headway**	**Headway**
10 min	10 min, 15 min	8-15 min	10-20 min	5-20 min	-
Operating hours	**Operating hours**	**Operating hours**	**Operating hours**	**Operating hours**	**Operating hours**
6 hrs	17-19 hrs	16-18 hrs	16-18 hrs	16-18 hrs	-
Number of required vehicles	**Number of required vehicles**	**Number of required vehicles**	**Number of required vehicles**	**Number of required vehicles**	**Number of required vehicles**
9	6	8	17	15	--

Table A5-2: Trip production and attraction (passengers per year)

Zone number	Trip production	Trip attraction
1	3,071,520	3,395,520
2	2,028,240	2,352,240
3	1,555,200	1,879,200
4	1,788,480	2,112,480
5	1,872,720	2,196,720
6	2,345,760	2,669,760
7	2,332,800	2,656,800
8	2,151,360	2,475,360
9	2,501,280	2,825,280
10	3,006,720	3,330,720
11	2,695,680	3,019,680
12	9,136,800	9,460,800
13	2,144,880	2,468,880
14	2,268,000	2,592,000
15	2,268,000	2,592,000
16	3,065,040	3,389,040
17	14,450,400	7,128,000
18	17,366,400	8,488,800
19	3,032,640	3,356,640
20	2,391,120	2,715,120
21	2,151,360	2,540,160
22	2,216,160	2,669,760
23	2,967,840	3,291,840
24	3,045,600	3,045,600
25	2,255,040	2,579,040
26	2,093,040	2,546,640
27	2,216,160	2,669,760
28	2,209,680	2,663,280
29	1,814,400	2,268,000
30	2,455,920	2,909,520
31	2,715,120	3,168,720
32	2,455,920	2,779,920
33	2,391,120	2,715,120
34	1,924,560	2,248,560
35	2,060,640	2,514,240
36	2,209,680	2,663,280
37	2,203,200	2,656,800
38	1,982,880	2,566,080
39	1,730,160	2,183,760
40	2,131,920	2,585,520
41	2,138,400	2,592,000
42	2,047,680	2,501,280
43	1,782,000	2,235,600
44	3,538,080	3,862,080
45	2,216,160	2,540,160
46	11,858,400	11,858,400
47	11,016,000	11,016,000
48	3,149,280	3,473,280

Summary

Reliability in urban public transport network assessment and design

Shahram Tahmasseby

Public transport reliability has become more and more important aspect for assessing the performance of public transport networks. Unreliability in public transport services leads to uncertainty and resulting delays aggravating inconveniences for public transport users. Moreover, it increases operating costs due to lower fleet and crew utilisation. With respect to the importance of reliability, the question might be raised how the impacts of reliability might be accounted for in public transport network assessment and design? As a result, does considering reliability as an influential factor lead to extensions in public transport network assessment and design?

Evaluating public transport 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 the demand pattern varies between hours and over days, while transport supply varies as well. In reality there are a large number of regular and irregular variations influencing public transport infrastructure availability and service operations. The question thus is how such stochasticity in supply and demand might be included in the public transport network assessment and thus how assessment feedbacks may influence public transport network design.

Basically, there are random variations in transport systems which are caused by various types of events. They can be distinguished and classified based on several criteria such as the event's source, event's frequency, event's location, event's predictability and event's

regularity. Depending on ways stochastic events impact transport systems, they can be classified to minor continuous ongoing events and major discrete events. Minor continuous ongoing events are defined as regular ongoing events which take place in pre-defined patterns and cause minor variations in public transport networks (e.g. regular travel demand variations). Major discrete events are defined as events that take place in transport networks normally without any predefined pattern and cause major distortions in the network (e.g. traffic accidents).

Impacts of the aforementioned event types on travellers are different. In case of minor continuous ongoing events, travel time variations are experienced by travellers. This can be seen as the usual variation in quality. However, in case of major discrete events, the effects are so different that they are not properly captured in. Travellers must choose other routes, and sometimes do not reach their destination.

Public transport operators have a wide range of measures to reduce and control the size and impacts of service variations. Depending on the event type transit operators might apply different remedial solutions to lessen event's impacts on transit services. In the case of minor continuous ongoing events, they can slow down and speed up services to reduce service running times and headway variations as much as possible. Commonly used indicators are regularity and punctuality.
However, in case of major discrete events service disturbances are observed not only in service running time variations, but also in the service line itinerary as well as the associated service frequency. Implementing detours to avoid a blocked path is a commonly used strategy. Thus, public transport services will be maintained as effectively as possible by diverting the path using the available infrastructure. In case implementing detours is not feasible, service lines may be temporarily shortened or split into two or more different parts. If none of the aforementioned measures is applicable, in the worst case, service lines are temporarily cancelled. Furthermore, to cope with demand fluctuations, for example in the case of a substantial rise in public transport demand, the service frequency may be temporarily increased.

Stochastic events and adaptive operational adjustments bring in consequences for public transport travellers. Indicators for such situations are the extra travel time and the number of trip cancelation. In the long run both types of events provide the service reliability perception for travellers.

To improve service reliability of public transport networks there is a variety of measures. The measures can be categorised into preventing measures and coping measures. The above operational measures are typical examples of the latter category. Preventing measures, however, often have a relationship with the strategic and tactical planning of public transport. These measures facilitate operational measures applied in case of service disturbances. Shortening service lines in transit networks is an appropriate way to reduce service network vulnerability. Increasing redundancy in the service network can improve connectivity reliability. Service network redundancy can be achieved by increasing service line density which offers multiple routes for passengers travelling between origins and destinations. In case of disturbances in the network, it also increases the probability of service restoration for the operator. To increase service network redundancy, required infrastructure has to be available. In case of rail bound public transport network, increasing service network redundancy requires improving infrastructure network redundancy as well.

In addition to network redundancy, creating flexibility in the infrastructure network and thus in the service network is another method for improving network robustness. Service network flexibility can be achieved through planning extra infrastructures which are used as backup facilities in case of disruptions in the network. Creating service network flexibility requires extra infrastructures and thus might lead to increase of infrastructure network redundancy as well.

Applying the aforementioned tactics results in extensions in the classical network design problem. Thus, incorporating service reliability considerations in the strategic network design stage requires extensions of the classical network design problem with respect to:

- New network design dilemmas;
- Extended network design objectives;
- More complex relationship between network design and traveller’s behaviour in the bi-level design problem.

The new design dilemmas are the result of a trade-off between travel time and service reliability and between service reliability and network costs. For instance, by increasing service running time, the operator has more options to improve the quality of service performance standards. The consequence for travellers will be slower public transport services but more reliable.

Classical public transport network design objective functions contain general components: travel time (cost), operating costs and investment costs. In the classical objective functions service reliability is disregarded. The more realistic approach takes into account the reliability of transport services. Including service reliability into the network design objective functions adds additional cost components to the cost function and thus increase total costs. These additional cost components capture regular travel time (cost) variations, extra travel time (costs), trip cancelation (costs), extra operating costs, and extra investment costs for the investing on additional infrastructure used in case of major disturbances. This extended function enables the designer to make a comprehensive assessment of all relevant components of a public transport network.

The network design problem is often described as a bi-level problem in which one decision maker, that is the network designer, has full knowledge of the decisions of the second decision maker, that is the traveller, and uses this knowledge to achieve his own objectives. Adding reliability-related components to the objective function calls for additional attention to the modelling of traveller’s behaviour. Public transport travellers do not react on a static network, but on a network under the influence of various regularly changing events. Depending on the nature of service disturbances, different methods maybe applied to incorporate service reliability on traveller’s behaviour.
In case of minor continuous ongoing events, traditional methods propose that the impact of service variations on choice behaviour is captured by including a travel time reliability indicator into the routes’ utility function. The standard deviation of travel time is a commonly used travel time reliability indicator.
In case of major discrete events occurring, disturbances are large enough to impact travellers’ behaviour as well. Due to major discrete events, transit services are not operated as usual. Detoured lines, partial lines, and temporarily cancelled services are typical consequences seen in service quality. Due to these changes in transit service quality offered to passengers, passengers are assumed to consider different route sets, and to exhibit different route choice behaviours depending on the availability and adequacy of information about the transit

network situation. If passengers are informed sufficiently beforehand about transit service changes, they make a decision pre-trip. However, if passengers are not aware of disturbances in transit services in advance, they make choices as they normally do and during their trip, they might be obliged to make a route choice again en-route. In this condition, they may suffer from additional travel time, or involve in a diverted service path and walk longer. To model all these phenomena, simulation is proposed.

A number of case studies for a typical (ring) radial tram network are applied to examine impacts of preventing measures on the reliability of public transport network and the overall network performance. The findings demonstrate that increasing network redundancy in transport service networks improves service reliability significantly by reducing the number of cancelled trips; however it may not always lead to better overall network performance which is expressed by the sum of all involved costs (travel costs, operating costs, and infrastructure costs including reliability-related components).
Reducing the vulnerability of a network by shortening service lines may increase the number of required transfers for passengers. However, its positive impact on service reliability is significant. Depending on the probability of major discrete events occurrence it can lead to a better overall network performance.
The third option, increasing the redundancy in the infrastructure network, facilitates operational adjustments to maintain original service network in case of disturbances. Positive impact is found for both service reliability and the overall network performance. Analysis of the tram network in The Hague confirmed the findings of the analysis with the hypothetical (ring) radial network.

The result of this research clearly shows that there are opportunities for improving service reliability and the overall network performance in public transport network design. In some situations shortening long service lines is recommended, although the demand pattern plays a major role. The main contribution may be expected from smart investments in infrastructure to increase service network flexibility. Examples include bypasses for vulnerable links, shortcuts between adjacent lines and turning facilities at strategic points. The analysis is developed in this framework and the tool is specifically tailored to select easily the most effective measures.

Samenvatting

Betrouwbaarheid in openbaarvervoernetwerkanalyse en –ontwerp

Shahram Tahmasseby

De betrouwbaarheid van openbaar vervoer is een steeds belangrijker aspect bij de beoordeling van openbaarvervoernetwerken. Onbetrouwbaarheid van openbaarvervoerdiensten leidt tot onzekerheid bij openbaarvervoerreizigers terwijl de resulterende vertragingen bovendien tot duidelijke ongemakken leiden. Daarnaast stijgen de exploitatiekosten door omrijden en inefficiëntie in inzet van materieel en personeel. Gezien het grote belang van betrouwbaarheid is de vraag gerechtvaardigd hoe de gevolgen van betrouwbaarheid een rol spelen bij de analyse en het ontwerp van openbaarvervoernetwerken. Anders gezegd, leidt het in beschouwing nemen van betrouwbaarheid tot wijzigingen en uitbreidingen in openbaarvervoernetwerkanalyse en –ontwerp?

In het algemeen worden openbaarvervoernetwerken geanalyseerd vanuit een deterministisch perspectief. Alle typen invoergegevens worden verondersteld exact bekend te zijn en constant in de tijd. Dit zijn geen reële veronderstellingen aangezien de vervoervaag varieert van uur tot uur en ook tussen de dagen. Daarnaast varieert het aanbod van vervoerdiensten voortdurend. In de praktijk beïnvloedt een groot aantal regelmatige en onregelmatige gebeurtenissen zowel de uitvoering van openbaarvervoerdiensten als de beschikbaarheid van infrastructuur. De vraag is dan ook hoe deze stochastische processen in vraag en aanbod kunnen worden meegenomen in openbaarvervoernetwerkanalyse en hoe deze het ontwerp van openbaarvervoernetwerken beïnvloeden.

De variatie in transportsystemen wordt veroorzaakt door diverse typen van gebeurtenissen, die kunnen worden ingedeeld op basis van criteria zoals oorzaak, frequentie van voorkomen, locatie, duur, voorspelbaarheid en eventuele regelmaat. Afhankelijk van de manier waarop deze gebeurtenissen het transportsysteem beïnvloeden, kan onderscheid worden gemaakt tussen kleine voortdurend doorgaande gebeurtenissen voorvallen en grote discrete gebeurtenissen of incidenten.

Variatie in openbaarvervoerdienstuitvoering veroorzaakt door kleine voortdurend doorgaande gebeurtenissen blijft beperkt tot variatie in rijtijden en afwijkingen van geplande vertrektijden. Deze kunnen worden gezien als de gebruikelijke variatie in kwaliteit. Bij grote discrete gebeurtenissen zijn de effecten echter zo verschillend dat deze niet met de gebruikelijke kwaliteitsindicatoren kunnen worden geanalyseerd: reizigers moeten andere routes kiezen en kunnen soms hun bestemming niet bereiken.

Openbaarvervoerbedrijven beschikken over een breed scala aan maatregelen om de grootte en de consequenties van deze variaties te beheersen. In het geval van kleine voortdurend doorgaande gebeurtenissen kunnen ze voertuigen vertragen en versnellen om de variatie in rijtijden en vooral in vertrektijden zo klein mogelijk te houden. Veel gebruikte indicatoren zijn hierbij regelmaat en stiptheid. Bij grote discrete gebeurtenissen hebben de maatregelen een veel ingrijpender karakter. Lijnen kunnen tijdelijk een andere route krijgen of kunnen worden ingekort. In het geval van een grotere vervoervraag kan de frequentie tijdelijk worden verhoogd. In het ergste geval kunnen lijnen tijdelijk uitvallen. Indicatoren voor dergelijke situaties zijn de extra reistijd voor reizigers en het aantal reizigers dat zijn verplaatsing niet meer met het openbaar vervoer kan maken. Op de langere termijn bepalen beide typen gebeurtenissen de perceptie van de betrouwbaarheid van de dienstverlening voor de reiziger.

De maatregelen die openbaarvervoerbedrijven kunnen nemen kunnen worden onderverdeeld in preventieve maatregelen en beheersmaatregelen. De hiervoor genoemde maatregelen zijn typische voorbeelden van de laatste categorie: gegeven de variaties als gevolg van allerlei gebeurtenissen een zo goed mogelijk vervoerdienst leveren. Dit zijn dan ook operationele maatregelen. Preventieve maatregelen daarentegen hebben vaak een relatie met de strategische en tactische planning van openbaar vervoer. Binnen deze maatregelen kan onderscheid worden gemaakt tussen maatregelen die voorkomen dat een gebeurtenis het openbaar vervoer beïnvloedt, bijvoorbeeld vrije banen, en maatregelen die het voor de reiziger en het vervoerbedrijf gemakkelijker maken om met de effecten van gebeurtenissen om te gaan. Redundantie in het openbaarvervoerdienstennetwerk betekent dat reizigers alternatieve routes tot hun beschikking hebben als er tijdelijk een lijn uitvalt. Analoog kan ook het infrastructuurnetwerk het gemakkelijker maken operationele maatregelen toe te passen. Met name bij railgebonden openbaar vervoer zijn voorzieningen nodig om alternatieve routes te kunnen aanbieden of om lijnen tijdelijk in te korten. Voorbeelden hiervan zijn wissels, keerlussen, of kortsluitingen tussen parallelle routes. De voorbeelden laten zien dat al bij het ontwerp van openbaarvervoernetwerken, zowel bij het ontwerpen van het diensten- als het infrastructuurnetwerk, de betrouwbaarheid wordt beïnvloed.

Het integraal meenemen van het aspect betrouwbaarheid in het netwerkontwerp voor openbaar vervoer, leidt tot drie uitbreidingen op het klassieke netwerkontwerpprobleem:

- Nieuwe ontwerpdilemma’s;
- Uitgebreidere doelstellingsfuncties;
- Complexere relatie tussen netwerkontwerp en netwerkgebruik in het bi-level ontwerpprobleem.

De nieuwe ontwerpdilemma's zijn het gevolg van een trade-off tussen reistijd en betrouwbaarheid en tussen betrouwbaarheid en netwerkkosten. Langere rijtijden bijvoorbeeld geven de exploitant meer mogelijkheden om de kwaliteit van de dienstuitvoering te handhaven. Ze maken het openbaar vervoer langzamer maar wel betrouwbaarder.

Klassieke doelstellingsfuncties bestaan in het algemeen uit componenten voor de reistijd, de exploitatiekosten en de investeringskosten. Componenten die met betrouwbaarheid te maken hebben worden dan buiten beschouwing gelaten. De meer realistische aanpak die ook rekening houdt met de betrouwbaarheid van de vervoerdiensten, zal ook de kosten van de onbetrouwbaarheid mee moeten nemen, zoals de grootte van de variatie van de reistijden, de extra reistijden als gevolg van tijdelijke routewijzigingen, de reizigers die tijdelijk hun verplaatsing niet met het openbaar vervoer kunnen maken en de investeringskosten voor infrastructuurvoorzieningen. Op deze wijze kan de ontwerper een integrale afweging maken tussen alle relevante componenten van een openbaar vervoernetwerk.

Het netwerkontwerpprobleem wordt vaak geschetst als een bi-level probleem waarin aan de ene kant het netwerkontwerp zelf centraal staat, d.w.z. hoe ziet het netwerk eruit, en aan de andere kant het gebruik van het netwerk door de reizigers. Het toevoegen van allerlei betrouwbaarheid gerelateerde componenten aan de doelstellingsfunctie vraagt extra aandacht bij het modelleren van het gebruik van het netwerk. Reizigers reageren niet meer op een statisch netwerk maar op een netwerk dat onder invloed van allerlei gebeurtenissen regelmatig verandert. Afhankelijk van het type gebeurtenis zal het vervoerbedrijf immers proberen de dienstverlening zo goed mogelijk uit te voeren. Bij de modellering hiervan is het eerder gemaakte onderscheid tussen kleine voortdurend doorgaande gebeurtenissen en grote discrete gebeurtenissen van belang. Bij de eerste categorie gaat om een continu aanwezige variatie van reistijden die bijvoorbeeld kan worden gekwantificeerd met de variantie van de reistijden. Bij de tweede categorie gaat het om discrete gebeurtenissen waarop het openbaar vervoerbedrijf afhankelijk van het type gebeurtenis, de duur en de locatie het dienstennetwerk zal aanpassen. Reizigers zullen gedwongen worden hun routekeuzen te herzien indien hun oorspronkelijk gekozen route niet langer mogelijk is. Nieuwe alternatieven moeten worden gezocht en nieuwe keuzen moeten worden gemaakt. Als de reiziger voor vertrek al weet dat het netwerk tijdelijk is gewijzigd, kan dit keuzeproces voor vertrek plaats vinden, in andere situaties zal de reizigers gedurende zijn reis zijn route moeten aanpassen. Om al deze fenomenen te kunnen modelleren is een simulatieaanpak noodzakelijk.

Met behulp van een aantal casestudies voor een typisch (ring-)radiaal tramnetwerk is nagegaan in hoeverre een aantal typen preventieve maatregelen de betrouwbaarheid van het openbaar vervoernetwerk en de totale prestatie van het netwerk beïnvloeden. De resultaten suggereren dat het vergroten van de redundantie van het openbaarvervoerdienstennetwerk wel de betrouwbaarheid vergroot, met name het aantal verplaatsingen dat tijdelijk niet met het openbaar vervoer gemaakt kan worden neemt sterk af, maar dat de totale netwerkprestatie gemeten in de som van alle aan het netwerk verbonden kosten (reiskosten, exploitatiekosten en investeringskosten, inclusief aan betrouwbaarheid gerelateerde componenten) niet altijd beter wordt. Het beperken van de kwetsbaarheid door een netwerk op te bouwen met korte lijnen heeft als nadeel dat reizigers vaker moeten overstappen. Daar staat tegenover dat de betrouwbaarheid van de dienstuitvoering groter is. Afhankelijk van de kans op grote discrete gebeurtenissen kan dit leiden tot een betere totale netwerkprestatie. De derde mogelijkheid, het vergroten van de redundantie in het infrastructuurnetwerk, vergroot de flexibiliteit voor het vervoerbedrijf om zijn netwerk tijdelijk aan te passen, terwijl het oorspronkelijke dienstennetwerk gehandhaafd blijft. Hierbij blijken er goede mogelijkheden te zijn om zowel de betrouwbaarheid als de totale netwerkprestatie te verbeteren. Analyses van het tramnetwerk van Den Haag bevestigen de bevindingen van de analyses met het hypothetische (ring-) radiale netwerk.

Het resultaat van dit onderzoek laat duidelijk zien dat er kansen liggen om al bij het ontwerp van het openbaarvervoernetwerk mogelijkheden te creëren om op efficiënte wijze de betrouwbaarheid van het openbaar vervoer te vergroten tezamen met de totale netwerkprestatie. In sommige situaties kan het raadzaam zijn lange lijnen te splitsen in kortere lijnen. Hierbij speelt het vraagpatroon een grote rol. De belangrijkste bijdrage mag worden verwacht van slimme investeringen in de infrastructuur waardoor vervoerbedrijven veel flexibeler hun vervoerdiensten kunnen aanpassen. Voorbeelden hiervan zijn bypasses bij kwetsbare trajecten, kortsluitingen tussen nabijgelegen lijnen en keerfaciliteiten op strategische punten. Het in dit onderzoek ontwikkelde analyseraamwerk en –instrumentarium is specifiek toegesneden om effecten van dit soort maatregelen te beoordelen, zodat de meest effectieve maatregelen gemakkelijk kunnen worden geselecteerd.

Curriculum Vitae

Shahram Tahmasseby was born on February 16, 1976, in Tehran, Iran. He finished his pre-university education in 1993 at Kamal high school in Tehran. In the same year he could start his bachelor study at the Faculty of Engineering of University of Tehran after passing the national entrance examination competition for Iranian universities and being ranked 108th among 200,000 participants. He received his bachelor degree in Civil Engineering in 1998. Afterwards, he continued his master study in Transportation Engineering in Sharif University of Technology in Iran. He received his master degree in early 2001. Upon completion of his MSc. he started to work at TCTTS Company for almost three years. During this period he involved in several multidisciplinary research projects mostly oriented to comprehensive traffic and transportation studies.
In 2004 he joined the British Engineering Group Halcrow and contributed in several traffic impact study projects in the fast growing city of Dubai in the United Arab Emirates.

In November 2005, he was affiliated with the Transport and Planning Department of the Faculty of Civil Engineering and Geosciences of Delft University of Technology and started his Ph.D. study under the supervision of Professor dr. ir. P.H.L. Bovy. His Ph.D. research topic is: "Reliability in urban public transport network assessment and design". During his study, he presented various papers in national and international conferences.

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