Service Reliability and Urban Public Transport Design

Niels van Oort

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Urban Public Transport Design

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“I know that I know nothing”
Socrates

Preface

One of the things I knew for sure when I graduated in 2003 was that I didn't want to do a PhD research. After my study I really wanted to jump into the real world to solve real problems. At HTM I found a nice job with great colleagues who really taught me what public transport was about. It was already during my first year that I discovered that doing research also contributes to practical improvements. I was especially interested in improving the planning of public transport by using actual vehicle data. Although I worked at a research and development department, the time was limited to do in-depth research and really understand the mechanisms between planning and operations. Within a few years I realized that performing a part-time PhD research was a great opportunity for me to do practical oriented research to achieve a higher quality level of public transport operations. The result of this research is this thesis, of which I am very proud. In the end, I am glad that I made that choice, back then.

I am really thankful to all people who facilitated the combination of working and doing research. First of all my regards to HTM, especially the board members Ton Kaper and Piet Jansen and my former manager, Peter Tros. They supported and encouraged me to start this adventure. I owe many thanks to my daily supervisor, Rob van Nes and my promotor, Piet Bovy, who arranged this opportunity at the side of the university. I would like to thank Alfons Schaafsma as well, who inspired me to do a PhD research next to a regular job.

The topic of service reliability was not that hard to choose. My father, not really a public transport fan, always told me that working in the field of public transport was a good choice, since there is so much to improve. At least concerning service reliability he is completely right. Although it is very simple to found (policy) documents stating that service reliability is important and should be improved, I am still surprised about the little attention this topic gets in both the scientific and practical world. In the field of heavy railways, much more attention is paid to service reliability, but the focus on passengers is quite new there as well. As a public transport researcher, consultant and frequent user, I am convinced that during the planning stages of public transport many cost-effective opportunities exist to improve the level of service reliability. Together with the application of operational instruments, this will lead to highly reliable services.

Although I learned a lot these last years and I really gained insights into the interaction between planning and operations, I also discovered that there is so much we still don't know concerning the topic of service reliability. I hope research on this topic will continue and I would like to contribute to this, both by performing scientific research and practical projects. I think it is important that the public transport sector in the Netherlands should invest more in research to minimize costs and maximize passenger benefits. The decentralization and tender structure didn't contribute much to such a shared research objective. I think that from a perspective of the universities, this topic should be higher on the research agenda as well. During my research in the group of Nigel Wilson at MIT in Boston, I was surprised by so much excellent research of public transport planning and operations. Although the level of public transport in Europe is much higher than in the US, the level of comprehensive practical oriented research is much higher. In Europe and in the Netherlands, we should learn from this and conduct more practical oriented research with regard to public transport. Being in Boston and cooperating with Nigel Wilson and Peter Furth and their staff was great, thank you all.

I enjoyed this PhD research very much. It was great to find out how planning and operations are connected and it was nice to travel over the world to discuss my research findings with fellow researchers. I am grateful to a lot of people who helped me with this research and with this thesis. First of all my promotor, Piet Bovy, who was amazingly quick and accurate in his feedback on this thesis and my research. Rob van Nes, my daily supervisor also helped me much by discussing about research directions, writing papers and finishing this thesis. I would like to thank all my committee members for their valuable comments. Their feedback really improved this thesis. It is partly based on (inter)national papers presented at conferences and published in journals. The reviewers of these papers also contributed substantially by sharing their comments.

I would like to thank the board and management of HTM to facilitate this research. My colleagues at the department of research and development were of great help by discussing my research results. The colleagues at the planning department and control room taught me a lot as well. Special thanks go to Anne Wil Boterman. It was great to have a colleague who is interested in the same issues in public transport as I am. Marc Drost, you were a great roommate and fellow researcher. It is great that you both supported me in the last stage of this research as well. Several students also helped me with my research. Thank you, Gijs van Eck, Winston Sukawati, Hilbert Veldhoen, Yilin Huang and Dirk Versluis. I would also like thank the colleagues who helped me to relax after all the hard working: Ronald Coelman, Sophia van Iperen, Menno Post and Robert Renzema. The last HTM colleague I want to mention is Peter Tros, my former manager. He was a nice boss, but overall a great man, who always supported and inspired me to continue my research.

After great years at HTM I changed jobs and started to work at Goudappel Coffeng in 2010. I would like to thank the board and management for their support and trust concerning my PhD research. My new colleagues were of great help during the last stage of my research as well. Next to my employers, Railforum and TRAIL also supported me, for which I am very thankful. Although I didn’t visit Delft that much, I enjoyed being at the department. It was also nice to meet my TU Delft colleagues far away from home at a conference and finally find time to have a proper talk. Special thanks to Paul Wiggenraad and Winnie Daamen for reviewing my thesis. Concerning the English writing I would like to thank Karen Drake. It is wonderful you helped me so well, even without knowing me. Maybe, we will meet sometime. As part of my research, I conducted an international survey on service reliability. I would like to express my gratitude to all participants for their contributions. This survey really helped me to put my research results of The Hague in a broader perspective.

Concerning my friends and family, I am sorry that I had to skip so many parties, holidays and other nice events, especially during the last year. But thanks for all the support and interest you all had in my work. Finally I would thank my father, mother and brother for their unlimited support and trust. Although the stage of being “almost finished” was quite long, it was great to know you always were there for me. The last ones who I would like to thank are Elana and Maaike. Without your endless patience and understanding I could not have finished this thesis. It was hard to skip so many nice activities and to sit weekends on a row at my desk, but I am really thankful that you encouraged me to continue and that you were able to put everything in a good perspective. In the meantime Elana has finished several projects and school presentations. Mine is now ready as well.

Niels van Oort

Leidschendam, April 2011

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1. Introduction

1.1 Research background

The last few decades have shown a substantial increase in personal mobility. Not only in interurban travel but as well in the urban environment traffic and transport volumes have been increasing for years. However, the share of public transport in this mobility growth did not change much and still remains rather limited. To ensure accessibility and liveability of our cities for future generations however, a substantial quality leap in public transport is necessary. This will facilitate a desired modal shift from car traffic towards public transport, which is safer, cleaner and produces less congestion. In this thesis, we demonstrate that several promising opportunities exist to improve service reliability, being one of the most important quality aspects of public transport. We will present several planning instruments enabling enhanced service reliability. In addition, we will show forecasting tools we developed and we will introduce a new indicator that expresses the impacts of service reliability more effectively than traditional indicators. This way, the assessment of public transport benefits will be substantially improved, thereby enabling cost-effective quality improvements.

When we look at the developments in mobility, we see that between 2000 and 2008, the number of traveller kilometres on the road increased by 5% in the Netherlands (Ministry of Transport 2009). The main reasons for expansion in road traffic are the increasing number of (working) people and an increase of (social) activities further away from home. In addition, more people own cars due to higher incomes and lower car prices (Ministry of Transport 2009). In contrast, the overall figures regarding public transport show almost no visible increase over the last 15 years, as shown in Figure 1.1. Also, the limited share of public transport is illustrated by this figure.

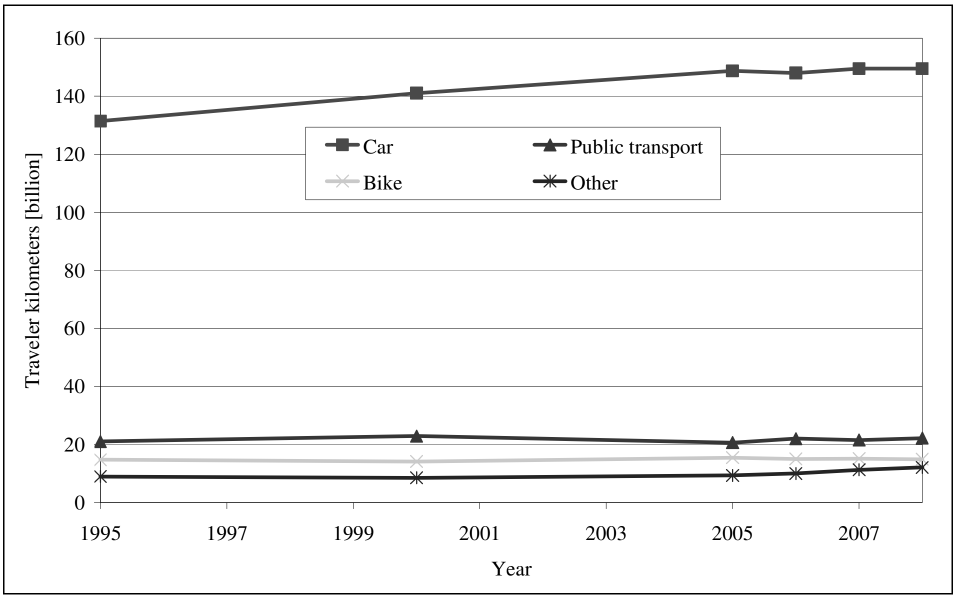


Figure 1.1: Travel kilometres per mode over the years in the Netherlands between 1995 and 2008 (source: Ministry of Transport 2009)

Although the traveller kilometres by public transport did not grow substantially, the national railroads in the Netherlands did experience a 9% growth between 2000 and 2007. However, considering the low share of rail transport in total mobility, this increase is rather limited. Figure 1.2 (Ministry of Transport 2009) shows the difference in train use and the other modes of public transport (bus, tram and metro). This figure demonstrates an increase of train use, while other modes of public transport remain more or less unchanged measured in traveller kilometres. Whereas other modes are growing, as shown by Figure 1, the share of public transport decreases.

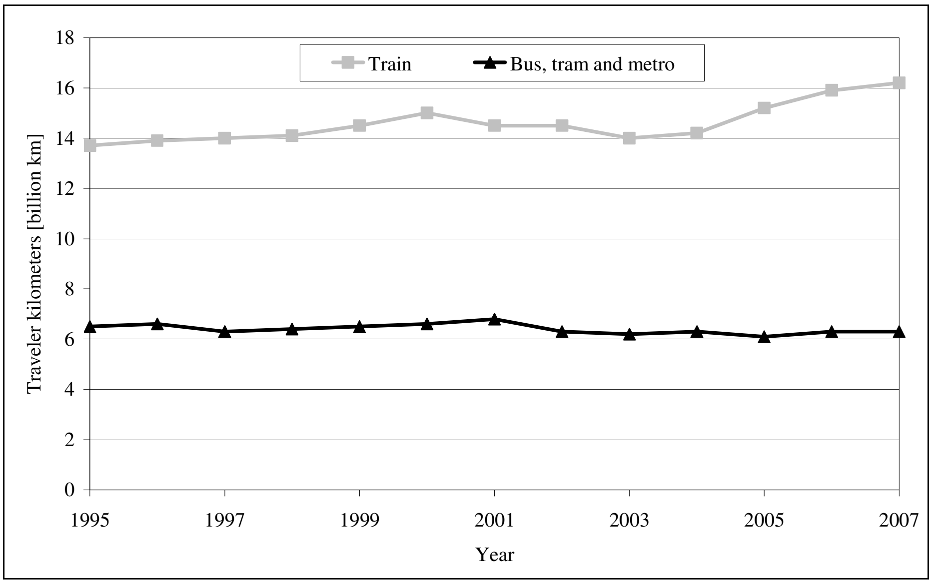


Figure 1.2: Development of traveller kilometres of railways and public transport in the Netherlands between 1995 and 2007 (source: Ministry of Transport 2009)

Other countries and continents exhibit similar developments as shown above (European Commission 2001). Figure 1.3 shows the modal split (forecast) in Europe between 2000 and 2020 expressed in travelled kilometres (Larsson 2009). It illustrates a decrease of the share of public transport. The urban modes bus, tram and metro will experience a market share decrease from 10% in 2000 to 7% in 2020. When focusing on numbers of trips, similar trends are expected. The low share of public transport in Europe may even be considered high in comparison to America and Australia where the car is by far the main mode of transportation, as shown by Figure 1.4 (Kenworthy and Laube 2001). Only in Asia, public transport achieves a higher level of market share than in Europe. In Europe as well as in Asia (especially in China) walking and cycling have a fair share in total mobility as well.

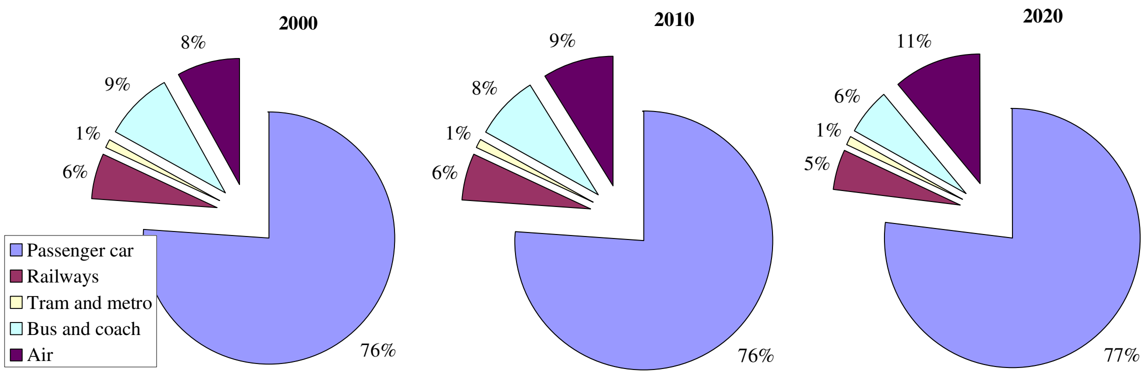


Figure 1.3: Development and prediction of modal split (traveller kilometres) in the European Union from 2000 to 2020 (source: Larsson 2009)

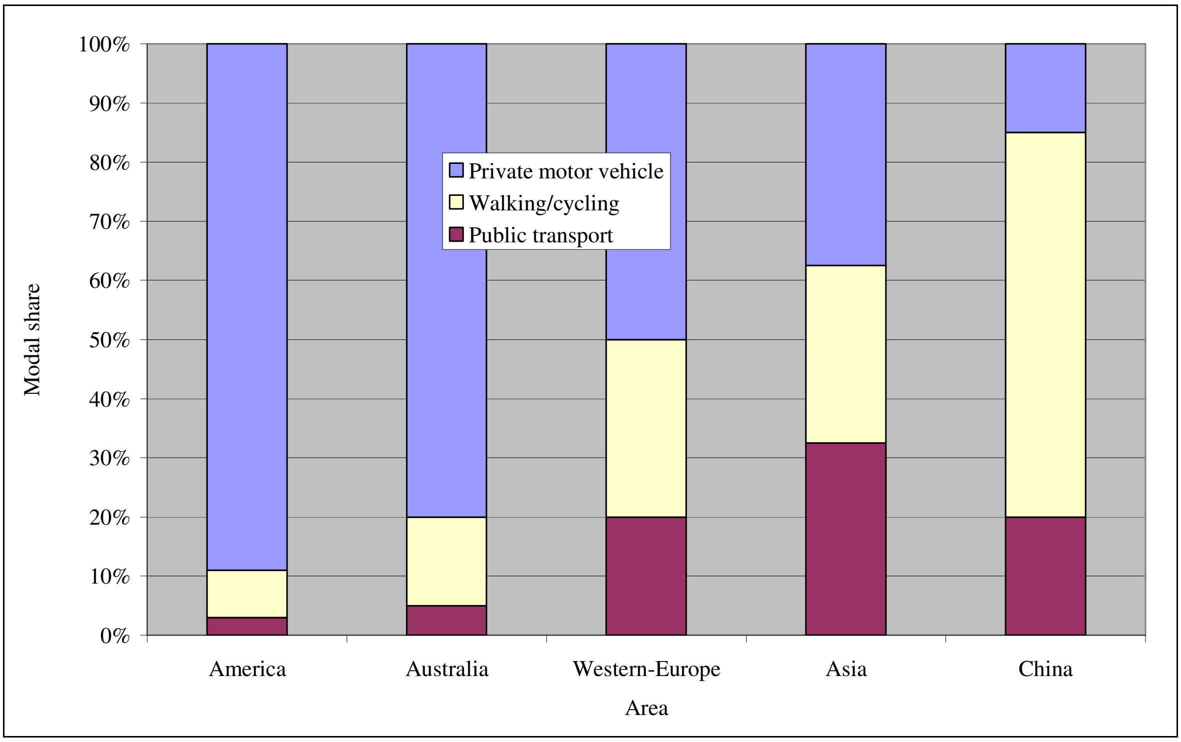


Figure 1.4: Modal split in the world in year 2001 (number of travellers; source: Kenworthy and Laube 2001)

Due to the growth of personal mobility and the small part of public transport in this growth, the societal costs of mobility also increased severely. In addition to space usage and energy consumption, the main aspects are loss of time due to congestion, probability of getting injured, and damage to the environment due to emission and noise. In 2008 the estimated costs of congestion were 2.8 to 3.7 billion Euros, just for the Netherlands. Between 2000 and 2008, these costs increased by 78% (Ministry of Transport 2009). The estimated costs of unsafe mobility in the Netherlands are approximately 10.4 to 13.6 billion Euros (Ministry of Transport 2009). These costs consist of medical costs (e.g. hospitals), production loss, physical damage (e.g. cars), emotional damage and delays due to incidents and blockings of infrastructure. The estimated costs of environmental damage were about 2 to 8.5 billion Euros in 2008 (Ministry of Transport 2009).

To reduce these external costs, public transport may play an important role. In Raad voor Verkeer en Waterstaat (Advising organ for Dutch Ministry of Transport) (2004) it is stated that a public transport user causes about half the damage to the environment compared to a car user. The policy of the Dutch government, among other governments in the world, is to improve public transport to ensure accessibility and liveability of cities and to reduce car mobility. To increase the role of public transport in total mobility, a substantial quality improvement is necessary (Raad voor Verkeer en Waterstaat 2004). Service reliability is one of the main factors determining the quality of public transport, setting the main focus of this thesis.

Since public transport is able to improve and ensure accessibility and liveability of cities, and since public transport might create a reduction of the negative impacts of increased car mobility, a leap in quality of public transport is necessary. Focusing on the quality of public transport, we distinguish the following main quality aspects:

- *Price*
  The main part of the price is the ticket of the transport service. However, the price of parking the car or bike at the origin stop may also affect the total price of the complete trip.
- *Accessibility*
  - In time
    This is the number of possible departures provided within a certain time frame. This number depends on both the frequency of the service and on the operating hours. Usually, availability in time is high during peak hours. In between these periods and in the evening the availability drops and during the night limited or no public transport services are offered.
  - In space
    Availability in space depends on the distance of the origin to the closest relevant stop and the distance between the destination and the closest relevant stop.
- *Travel time*
  This is the total time spent travelling from origin to destination. A journey consists of several parts. Note that accessibility, as mentioned above, affects travel time to a large extent.
- *Comfort*
  Comfort expresses the level of passenger wellbeing. The level of comfort is an important quality aspect and is relevant to both the vehicle and the stop. Different kinds of travellers appreciate this aspect differently. First class facilities in trains show that some people are willing to pay more to raise their level of comfort.
- *Image*
  The image of the public transport system determines whether people would like to use it, without this reflecting badly on them.
- *Service reliability*
  Service reliability expresses whether the actual passenger journey meets the expected quality aspects such as waiting, travel time and comfort. This issue is the focus of this thesis.

To prioritize the quality factors in public transport, Peek and Van Hagen (2002) introduced the “pyramid of Maslow for public transport”, shown in Figure 1.5.

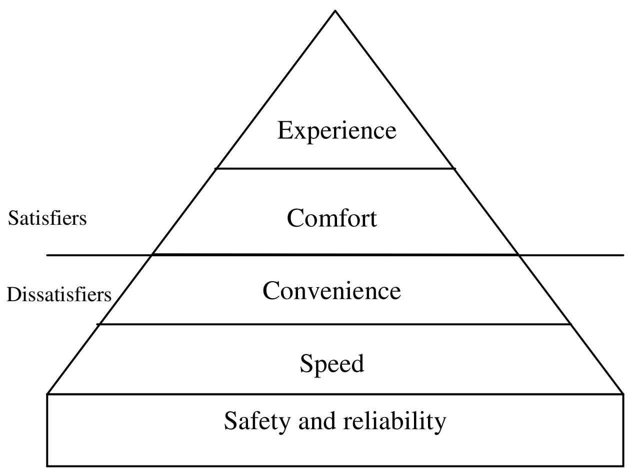


Figure 1.5: Quality factors in public transport presented in pyramid of Maslow (source: Peek and Van Hagen 2002)

This pyramid consists of different layers, representing requirements set by the public transport customers. The lower part shows the dissatisfiers which are elements that must be sufficient without doubt. If not, passengers will be dissatisfied and they are likely to avoid using public transport (they do not travel or change their travel mode). The upper part shows the satisfiers which are additional quality aspects. These aspects satisfy travellers. An important part of the satisfiers is the experience of passengers: how do they perceive the complete journey, including waiting and transferring for example (see for instance Baker and Cameron 1996 and Van Hagen et al. 2007). The elements safety, reliability and speed form the base of the pyramid, stressing the importance of service reliability.

Earlier research (Brons and Rietveld 2007) yielded the passenger appreciations related to the importance of quality aspects in public transport. Figure 1.6 shows their findings from frequent passengers (illustrating both the passenger satisfaction and perceived importance of several quality aspects). This figure demonstrates that service reliability is considered very important by them, while their appreciation of it is limited however. Non-frequent users assign the same importance to service reliability, while their appreciation of it is a little higher. Their satisfaction score is 6.0 out of 10, which is still relatively low.

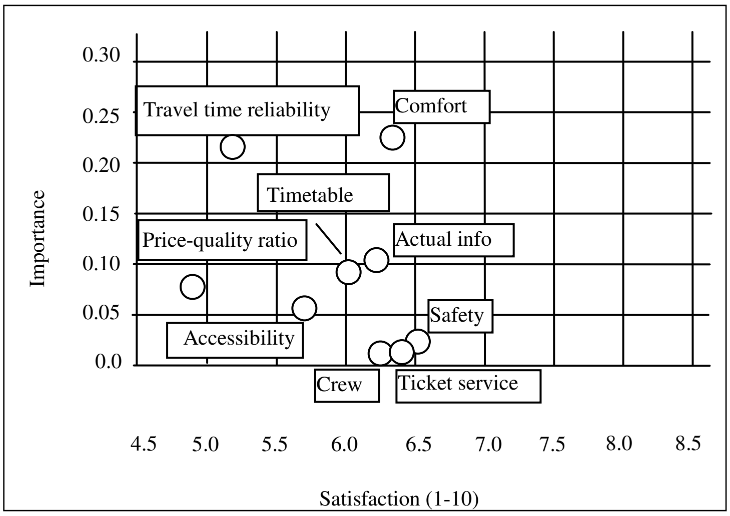


Figure 1.6: Satisfaction and importance of quality aspects of frequent public transport users (source: Brons and Rietveld 2007)

In several studies reliability-related attributes have been found among the most important service attributes in a variety of situations (Prashkar 1977, Jackson and Jucker 1981, Black and Towriss 1991, Rand and AVV 2005). Balcombe et al. (2004) report that service reliability is considered twice as important as frequency by passengers. Tahmasseby (2009) states that the sustained growth of the economy and the continued improvements in the quality of life lead to an increase in the value of time and value of service reliability. König and Axhausen (2002) conclude that the research done over the last decade shows that the reliability of the transportation system is a decisive factor in the choice behaviour of people.

The Dutch policy of improving mobility and public transport use focuses on reliability of travel time (Ministry of Transport and Ministry of VROM 2004, Ministry of Transport 2008a). The main policy report regarding traffic and transport in the Netherlands (Ministry of Transport and Ministry of VROM 2004), considers service reliability one of the main aspects of quality in public transport and has chosen this aspect as one of the main pillars of future policy. In Ministry of Transport 2008a the Dutch government states that more robust networks must be developed to decrease vulnerability and to increase service reliability. Winsemius (2005) concludes that the level of service reliability is not sufficient at this moment. This contributes to the low level of competition offered by public transport to car use. In Raad voor Verkeer en Waterstaat (2004) an analysis demonstrates that, besides travel time savings, improving service reliability is the main objective of most new public transport projects in the Netherlands and the world.

In Rand and AVV (2005) a method of comparing travel time and service reliability is presented indicating the value of reliability. The ratio of value of time and the value of reliability for all public transport (both urban and inter-urban) proved to be 1.4 (i.e. passengers consider the value of 1 minute of travel time standard deviation reduction 1.4 times higher than the value of 1 minute of average travel time reduction), illustrating the importance of service reliability from a passenger perspective.

The discussion above clearly shows the importance of service reliability. This section also shows that the modal share of public transport in (the growth of) total mobility is rather limited. Enhanced service reliability is one of the promising ways to increase the attractiveness and consequently the share of public transport. In this thesis we investigate how service reliability might be improved in a cost-effective way.

1.2 Research objectives

As stated in the previous section, service reliability is one of the main quality aspects considered by travellers and therefore preferably might be improved to achieve a more attractive and competitive public transport. This reflection leads to the goal of this research, which is contributing to improving service reliability of urban public transport. First of all, this will increase the quality of public transport and thereby improve its attractiveness in general and its competitiveness relative to the other modes, for instance the car. This leads to more welfare gains, higher ridership and higher revenues. Secondly, more reliable services allow more efficient operations, resulting in a more positive cost-benefit ratio for the operator. Improving service reliability in public transport is not a new research topic. In railways, much attention has already been paid to this topic for years (see for instance Landex 2008, Lüthi 2009 and Goverde 2005). Literature shows that in urban public transport, substantial attention is given to ways to improve service reliability at the operational level. At this level, as soon as service problems occur, instruments are applied to prevent negative effects (Osuna and Newell 1972, Muller and Furth 2000, Vuchic 2005 and Ceder 2007). Examples of such instruments are conditional priority (giving priority only to vehicles that are late) and dispatching of vehicles by a central post or by employees at main stops. In theory and practice, much attention is paid to the supply side of public transport, thereby partly neglecting the passenger effects.

However, an ounce of preventing is worth a pound of curing, as the saying goes. It is not clear how and to what extent strategic and tactical design decisions in public transport systems might affect service reliability. We expect that instruments at these planning levels enable high-quality services at the operational level, especially with regard to service reliability. This hypothesis requires further study while special attention to impacts on passengers is necessary. In addition, another hypothesis of our study is that at these planning stages use of operational information is necessary to optimize the network and timetable regarding service reliability. These hypotheses lead to the following main research questions:

- How and to what extent may operational service reliability be improved by enhanced strategic and tactical design of urban public transport?
- How may operational service data be incorporated in the tactical and strategic design of urban public transport, thereby improving (forecasts of) operations?

To achieve a more reliable and more efficient public transport system, the following sub questions need to be answered:

- How large is the variability of vehicle trip time in practice, what are its causes and what are its impacts?
- What is the best way to express the impacts of service variability and unreliability on passengers?
- How do network and timetable design affect the level of service reliability and service variability?
- Which instruments may an operator and/or authority apply to achieve a higher level of service reliability?
- To what extent will instruments and design choices at the strategic and tactical level of urban public transport have an impact on service reliability?

While most research so far focused on the service supply side when analyzing service reliability, we provide in this thesis a translation of service supply side indicators into demand side impacts.

1.3 Conditions and constraints

In this thesis, we deal with urban public transport, being defined as bus, tram and light rail services. Trains and metros are not part of the research scope; much attention has already been paid to their service reliability (e.g. Breusegem and Bastin 1991, Campion et al. 1985, Schmöcker et al. 2005 and Martinez et al. 2007 with regard to metro research and for instance Schaafsma 2001, Hansen 2004 and Geraets et al. 2007 concerning research on train traffic and transport). The main source of empirical data used in our research is the HTM Company, the urban public transport company in The Hague, the Netherlands. We performed empirical research to identify and to describe the general mechanisms with concern to service reliability. Furthermore, we conducted an international survey among urban public transport companies and authorities regarding service reliability of their urban public transport to support our (empirical) research and to set research objectives with regard to public transport systems in other cities as well. In addition to the actual case studies, we performed theoretical research, in which we investigated hypothetical lines, enabling controllable variables. This way, the research we present is valuable for cities all over the world.

In our research, we look at existing public transport networks in existing cities. Extending or adjusting the network, schedule or service is the main concern. In literature, several kinds of reliability are distinguished, for instance technical reliability of vehicles and infrastructure, reliability of the prices, availability of a seat and adherence to the promised schedule (Vrije Universiteit 1998 and Centrum voor omgevingspsychologie 1998). In our research, we investigate service reliability being the matching degree of the schedule and actual operations, and its impacts on passengers. Analyzing service reliability, we only address daily, recurrent delays, also known as systematic delays (AVV 2004, Cham and Wilson 2006). Non-recurrent delays are less frequent and imply unavailability of parts of the infrastructure (Bates et al. 2001, Noland and Polak, 2002). Unavailability of the infrastructure is not considered. For instance, Tahmasseby (2009) deals with service reliability when infrastructure is incidentally not available.

1.4 Contributions

The research presented in this thesis contributes in several ways to the understanding of service reliability related to public transport planning. In addition, our research contributes to a sophisticated consideration of service reliability in both network and timetable design of urban public transport and it enables calculation of travel time impacts of service variability on passengers. Below, the main contributions of the research in this dissertation are concisely summarized from a scientific and a practical perspective respectively.

Scientific contributions

- Identification and description of mechanisms concerning the interaction of service variability (vehicle perspective) and service reliability (passenger perspective);
- Establishment of a control framework to calculate service reliability as a function of network (both infrastructure and service) and timetable design;
- The establishment of a new indicator that expresses passenger effects of service unreliability more effectively than traditional indicators can do, namely the average additional travel time per passenger;
- A systematic Overview of causes of service variability and unreliability;
- A systematic Overview of instruments improving service reliability at strategic, tactical and operational level.

Practical contributions

- Establishment of a number of promising planning instruments, concerning infrastructure, service network and timetable design, enabling improved service reliability, in both existing and extensions of networks;
- Establishment of a methodology to optimize network and timetable design with regard to service reliability by incorporating service dynamics in the design process;
- Establishment of a control framework that enables cost-benefit analyses, with regard to passenger impacts of the level of service reliability.

Given these outcomes, the following categories of practitioners, in addition to researchers, will gain from the presented research:

- *Public transport network planners (operators or authorities (depending on agreements between them))* will benefit from the strategic planning instruments we present, next to tools we developed to calculate the expected effects of network designs on passenger travel time;
- *Public transport timetable planners (operators or authorities (depending on agreements between them))* will benefit from the tactical planning instruments we present, next to tools we developed to calculate the expected effects of timetable designs on passenger travel time;
- *Urban infrastructure planners* will benefit from our research, since we provide insights into the impacts of infrastructure design on passenger travel time.
- *Economists* will benefit from our insights we provide into the impacts of service reliability improvement instruments on passenger travel times and our new indicator that support cost-benefit analyses concerning service reliability benefits.

1.5 Scientific and societal relevance

This thesis provides insights into the subject of service reliability in public transport and presents a fundamental analysis of variability in vehicle trip times of urban public transport and of its consequences for passenger travel times. It addresses both causes and effects resulting in a control framework enabling enhanced public transport design, which is beneficial for both practitioners and scientists. We will explore the opportunities available in network and timetable design stages for improving the level of service reliability in operations. Our research is beneficial for several parties involved in public transport. Increased service reliability (and thus quality) of public transport will lead to shorter passenger waiting and travel times, less crowding and improved accessibility. This will decrease the resistance to travel by public transport. Besides, the appreciation of public transport will increase. This is beneficial to public transport operators and society, since the modal share of public transport may be increased as may welfare gains.

Operators and authorities may find instruments and tools analyzed in this thesis helping them to improve the level of quality of their public transport system. Both theoretical and practical research is presented that demonstrate the possibilities of enhanced network design and timetable planning. In addition, we present a literature review on service reliability in public transport. The mechanisms of service variability and service reliability are presented and clarified as well enabling further scientific research in this field. We show the relationship between the supply side, the actual services and the impact on passengers. Besides traditional methods of dealing with service reliability, a new indicator is introduced, shifting the focus from supply-side measuring to demand-side measuring. A case study shows that traditional indicators do not present the level of unreliability from a passenger perspective. We will introduce a new indicator, namely the average additional travel time per passenger, being the extra time passengers on average need for travelling from origin to destination due to service variability. We will demonstrate that service variability extends the average travel time per passenger, mainly due to increased waiting time. This indicator supports a proper cost-benefit analysis (CBA) of public transport in general and service reliability instruments in particular.

In conclusion, this thesis helps researchers, operators and authorities to understand causes and remedies for unreliability in public transport services. It provides methods to quantify unreliability effectively. We offer instruments to improve the level of service reliability of urban public transport, resulting in a higher customer satisfaction (and thus increased market share) and enhanced efficiency.

1.6 Thesis outline

Figure 1.7 illustrates the outline of our thesis. After this introductory chapter, in which the importance of service reliability in urban public transport is shown, two chapters continue with a description of the notion of service reliability in urban public transport. Chapter 2 presents a conceptual analysis of service reliability. The relationships between the supply side of public transport and the passengers are explained and it is shown what service reliability is and how it may be quantified. We also demonstrate how service reliability may be expressed in a more proper way with respect to the impacts for passengers.

In Chapter 3, the discussion on service reliability is based on practical experiences, partly using new insights presented in Chapter 2. The city of The Hague in the Netherlands and its public transport system is introduced as the base for cases studies in later chapters. Our international survey on service reliability and planning is introduced as well. In Chapter 3, empirical research is presented, showing the level of service variability and unreliability prevailing nowadays. The analysis of the empirical data shows the magnitudes of variability of different trip time components such as driving, unplanned stopping and dwelling. In Chapter 4, we use these insights to determine causes for unreliability and find possible remedial solutions.

Chapter 4 provides a number of planning instruments which may be implemented to decrease the level of unreliability. To select proper instruments, an analysis of causes of service variability and unreliability is presented, based on the findings of Chapters 2 and 3. To support the hypothesis that traditional instruments are not capable to solve the unreliability problem of urban public transport sufficiently, a case of an extensive service reliability improvement program in The Hague is presented. Although impressive results are achieved, unreliability and related problems are still not removed sufficiently. In this chapter, a feedforward mechanism is presented enabling enhanced service reliability due to improved planning. In this chapter, we identify and select potential planning instruments that facilitate enhanced service reliability.

Chapters 5 and 6 analyze the selected remedial instruments proposed in Chapter 4 in detail. Chapter 5 focuses on the design of the network, both the infrastructure and service network. Instruments that are investigated are terminal design, line coordination and line length. Both case studies using actual data of public transport lines in The Hague and theoretical analyses demonstrate the impacts of these planning instruments. This chapter shows that in the network design, promising opportunities exist to improve service reliability substantially.

The timetable also affects the match of planning and actual operations. Chapter 6 elaborates on this issue at the tactical level. Two instruments are presented, being trip time determination and vehicle holding. It is demonstrated that service reliability is affected by design choices. Theoretical and practical analyses are performed to demonstrate the benefits of these instruments.

Chapter 7 presents a synthesis of this thesis. The instruments discussed in Chapters 5 and 6 are analyzed in terms of their impacts on costs, welfare gains and ridership and a tentative cost-effectiveness assessment is provided. We explore the opportunities to combine instruments and to construct the best set of instruments improving the level of service reliability. The assumptions of the research are also discussed in this chapter.

This thesis ends with conclusions and recommendations in Chapter 8. This chapter also provides future research directions, related to service reliability in public transport.

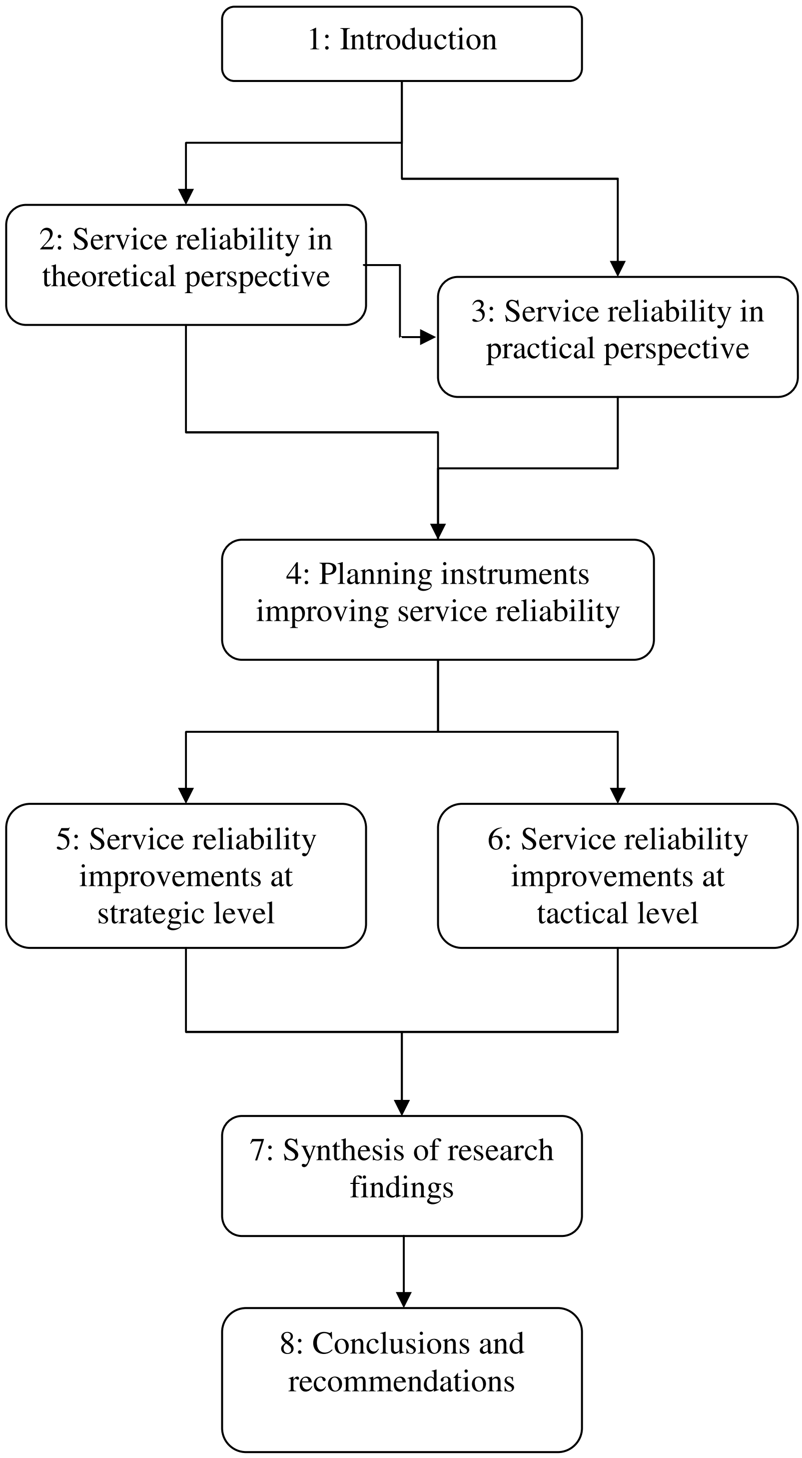


Figure 1.7: Thesis outline

2. Service reliability in theoretical perspective

2.1 Introduction

The introductory chapter showed the increased interest in improving quality of public transport in general and, more specifically, the increased focus of authorities and operators on improving service reliability. The objective of our research is to provide instruments for public transport planners to improve the level of service reliability. To achieve this, it is important to understand what service reliability is and how to assess it in a quantitative way. We define service reliability as the certainty of service aspects compared to the schedule (such as travel time (including waiting), arrival time and seat availability) as perceived by the user. In this chapter, we present a description of service reliability in urban public transport, from a theoretical perspective. Public transport service operations are compared to production processes. This comparison shows that the level of reliability depends on the variability of the system itself and the customer expectation of this variability. In order to determine quality standards concerning reliability, it is important to consider how the customer, i.e. the passenger, perceives service variability and reacts to it. In order to gain insights into the interaction process of variability and reliability, a conceptual description of the supply and demand sides of public transport is provided. The main issue in this chapter is the impact of unreliability on passengers. Our research question is how do mechanisms causing unreliability in public transport operations work and how are passengers affected by these? A control framework will be presented enabling the analysis of service reliability while considering the effects on passengers. This framework makes it possible to improve service reliability through appropriately designing public transport networks and schedules.

When investigating mechanisms of service reliability, it is important to understand production processes in public transport. In general, production processes convert input into output. If the output does not have a constant value, but is varying in time it is called variability of the output. If the output does not meet the standards of the customers the production process is considered to be unreliable. In this chapter, we deal with service variability and reliability of urban public transport services. In this case, the timetable is crucial as it sets the standards for vehicle trips in time and space while often, actual operations do not completely match this reference. Unreliability arises when the customer (i.e. the passenger) does not get the service he expects given the schedule. This chapter will demonstrate that a decreased level of service reliability affects the following three aspects of the passenger journey in the following way:

- The average total travel time per passenger will be extended;
- The variation of the total travel time per passenger will increase;
- The probability to find a seat in the vehicle will decrease as vehicles will become more crowded.

These consequences do not only affect the journey itself, but will also influence several choices made by passengers during and prior to their journey, for instance choice of route, departure time, and mode.

To assess and improve service reliability in both planning and monitoring it is necessary to set proper indicators quantifying the actual and expected level. Nowadays used indicators mainly focus on the variability of the supply side thereby neglecting the impacts of and effects on the demand side. In our research we show that passenger patterns and the difference of being late or early strongly affect passenger perception of service reliability. This chapter introduces new indicators enabling proper quantification of the effects of service reliability mentioned above, including the interaction of supply and demand. These new indicators, namely additional travel time and reliability buffer time, help to evaluate new instruments and design choices aiming at enhanced service reliability. Using these improved indicators, it is easier to consider service reliability explicitly during the design of public transport systems, since the effects on passenger reliability perception may be incorporated in the decision making process.

This chapter starts with a general system description of production processes and public transport operations in Section 2.2. In addition, an analysis of the supply side of public transport is presented, focusing on the variability in the service. This chapter shows that dealing with both the supply and demand sides is necessary when reducing variability, being a first step to improve service reliability. An analysis of the demand side is provided in Section 2.3 where the interaction of supply and demand is presented gaining insights into service reliability of public transport. In the next sections the impacts of service reliability on passengers and their choice behaviour are shown (Section 2.4) and the new indicators are proposed, quantifying these impacts (Section 2.5). After this theoretical description of service reliability, we continue in Section 2.6 with introducing general control methods in relation with the processes of planning and operations of public transport. Finally, this chapter presents a control framework enabling to consider service reliability in the planning of public transport. This framework will be used to assess the impacts of design choices on service reliability. Finally, conclusions of this chapter will be presented in Section 2.7.

Chapter 3 then will provide empirical supply and demand data illustrating and supporting the theoretical view in this chapter. Chapter 4 analyses the causes of service variability and studies instruments improving service reliability at all levels of public transport planning.

2.2 Production processes and reliability

2.2.1 Introduction

This section reflects on variability and reliability in production processes. First, a general description of production systems is presented. Subsequently, the focus is narrowed to the scope of our research being urban public transport. This section helps to understand the general principles of variability and reliability. The next section will elaborate on service reliability in public transport in more detail.

2.2.2 Public transport production process

Following cybernetics (Heylighen and Joslyn 2001), a production process, seen as a black box, converts input into output, as illustrated in Figure 2.1. The process has a certain performance which has to match the requirements. In an ideal environment, no external disturbances appear, but in practice they will arise. Next to these external disturbances, the process itself may deviate from the ideal state due to for instance human behaviour. If the output is not a constant value but is diffuse, it is called variability of the output. The process is not deterministic anymore but stochastic. If this variability is not desired or more than expected, it results in unreliability. Unreliability means that the actual output is not equal to the promised (or expected) output. Customers will suffer from this, since they may experience a reduction in quality. In addition, the producer may suffer as well, since he may need additional resources or instruments to reduce or mitigate the effects of reduced quality. Often, the focus is on the excess variability, which is the variability which is greater than a bandwidth accepted by the producer, expressed in the system's requirements.

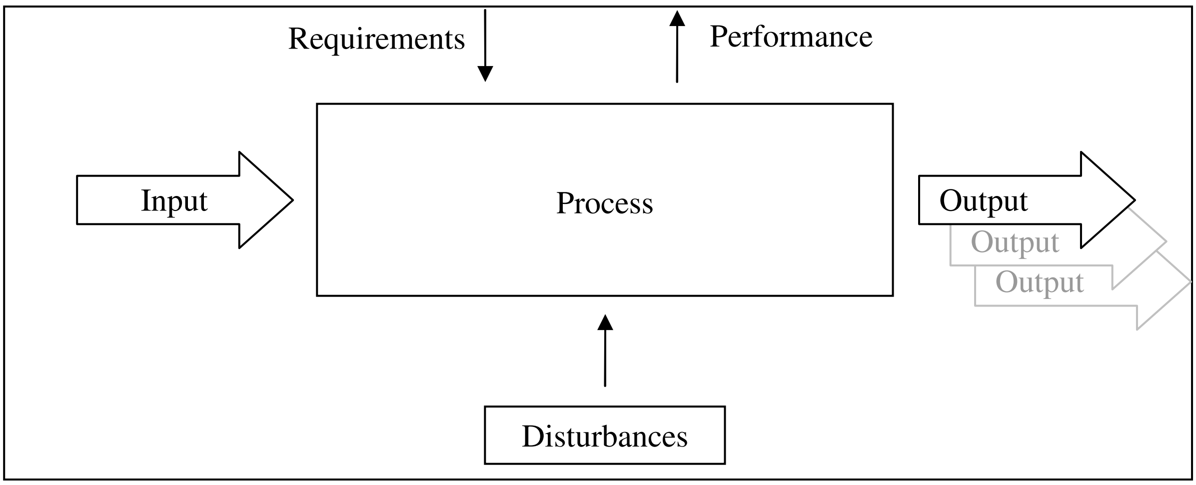


Figure 2.1: General production process (including output variability)

In public transport, the main process is the operation that is driving vehicles enabling passengers to travel from origin stop to destination stop within a specified time frame. The input of the process is a network, consisting of infrastructure and service lines, a schedule, crew and vehicles. The output of the process are actual vehicle trips from stop to stop, including actual departure and arrival times. The schedule shows the intended output, namely trips planned in time and space. However, the actual output is often not exactly as planned since amongst others, human behaviour (of both passengers and crew), weather and traffic circumstances (both public transport and other traffic) lead to variability in output. We define service variability as the distribution of output values of the supply side of public transport, such as vehicle trip time, vehicle departure time and headways. Often, requirements are set concerning excess variability, mostly in terms of bandwidths. Chapter 3 will show that these requirements differ much per public transport system. The variability of the system also affects the reliability as perceived by passengers. In transportation, service reliability may generally be 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 and Wakabayashi 1989). Which function, which conditions, and which period of time needs to be specified? For instance, the function could relate to transportation with a specified travel time and quality, or to offering connections between origins and destinations, or to facilitating transport for certain levels of demand. Conditions could be regular or exceptional, while the period of time could be a specific peak hour or a full year. In our research we will focus on specified travel times and departure times in regular conditions (when the infrastructure is fully available) in homogeneous periods.

Public transport systems are more than just operations. Prior to operations there is the design process which specifies the timetable and schedule. In the design process two levels may be distinguished namely strategic and tactical. Figure 2.2 shows the levels of public transport planning and operations.

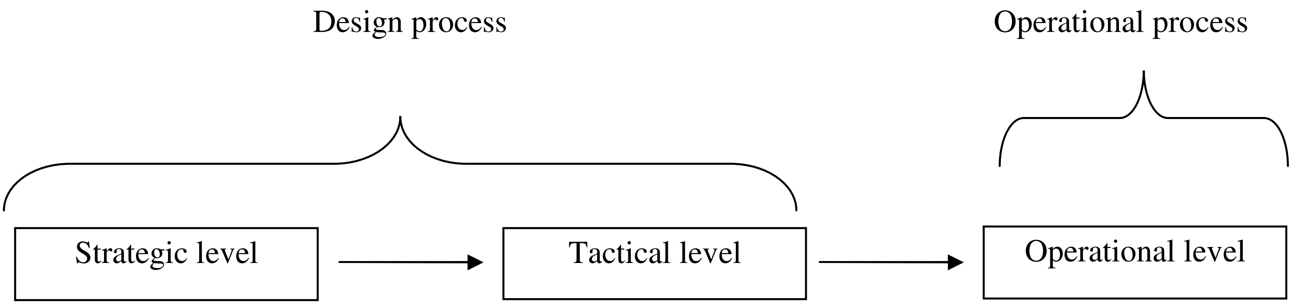


Figure 2.2: Stages at urban public transport planning and operations

At the strategic level the network is designed. Expected ridership, budget, and geographical characteristics are input for the design of the service line network, consisting of lines and main frequencies. At the strategic level, the infrastructure network (curves, locations of switches, terminals, etc.) is either used as an input or is designed as well. Both types of networks are used at the tactical level, at which the detailed timetable is constructed. Both the public timetable and the schedule for vehicles and crew are the output of this stage. The design and operational processes thus are strongly related to each other and although service variability and reliability are mainly an issue occurring in the operation process, it is strongly affected by the design process as well. Nevertheless, there is a strong focus on improving service reliability at the operational level only and not much attention is paid to the design process regarding improving service reliability (Van Oort and Van Nes 2004). In our research, the link between these two processes is investigated and possibilities of reducing service variability and improving service reliability in the design process are presented.

2.2.3 Conclusions

The production process of public transport consists of two parts. Prior to the actual operations, the network and schedule are designed, being input for the operational level. At the operational level, the actual product is provided to the passengers, being trips in time and space. In practice, variability of these trips often occurs, which, depending on the magnitude of the variability, leads to service unreliability, since actual operations do not match the plan sufficiently. In dealing with service reliability in practice, the focus is mainly on the level at which the effects occurs, namely the operational level. In our research though, we investigate opportunities to consider and improve service reliability already in the planning stages.

2.3 Service reliability in public transport

2.3.1 Introduction

The previous section showed the general principles of the concept of reliability. In this section, service reliability in public transport will be analyzed in more detail. Concerning service reliability, both the supply side and the demand side of public transport are important, since unreliability is caused by the interaction of both sides. The supply side consists of the service provided by the operator, being trips in time and space. The demand side is defined as the passenger side including their behaviour and experiences. This section describes both sides as well as the interaction between them, which affects the actual level of service reliability and the impacts on passengers. The insights gained in this section concerning service reliability will be used in the following sections to assess the impacts on passengers and to create enhanced indicators of service reliability. Finally, a control framework will be presented in Section 2.6 aiming at improving service reliability through enhanced planning.

2.3.2 Public transport supply

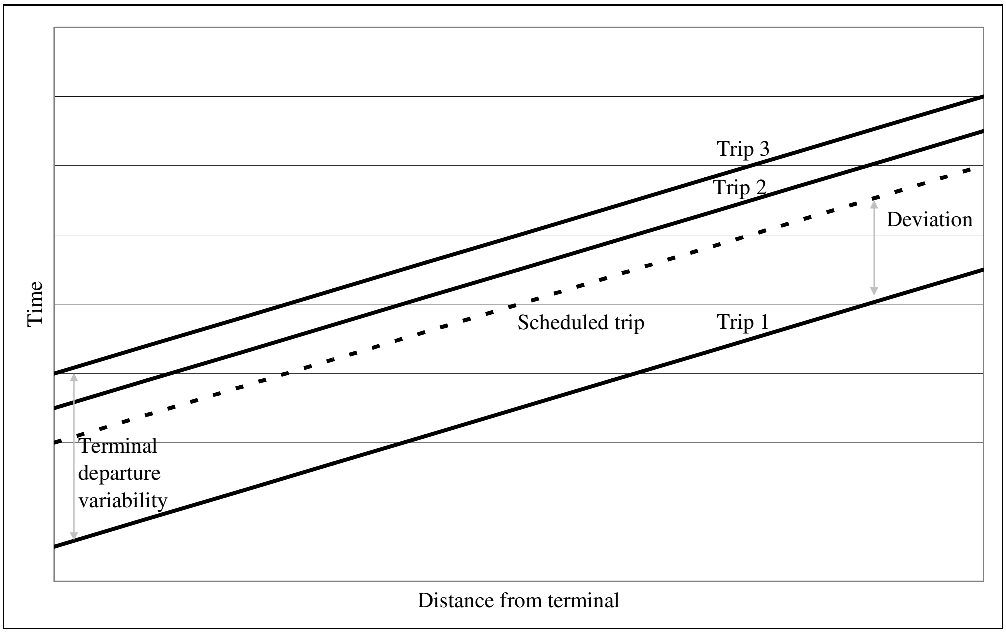
Looking at the supply side, a single vehicle trip is the basis of operations. Vehicle trips are scheduled in time and space resulting in departure and arrival times at all stops along the route from terminal to terminal. In addition to these exact departure times at a stop, the number of trips within a time frame is important. This frequency determines the number of possible departures for passengers per time frame and it determines the headways between successive vehicles.

In the schedule, every vehicle trip is planned in a deterministic way and no variation is accounted for. In most cases, schedules are designed for longer periods and trips in homogeneous periods per day are treated similarly. During operations however, actual vehicle trips suffer from disturbances and variations occur, both over the homogeneous periods per day as over longer periods.

In an ideal situation, vehicles depart on time from the terminal and drive perfectly according to the schedule. Therefore, deviations and variations of the supply side may be categorized into two source types:

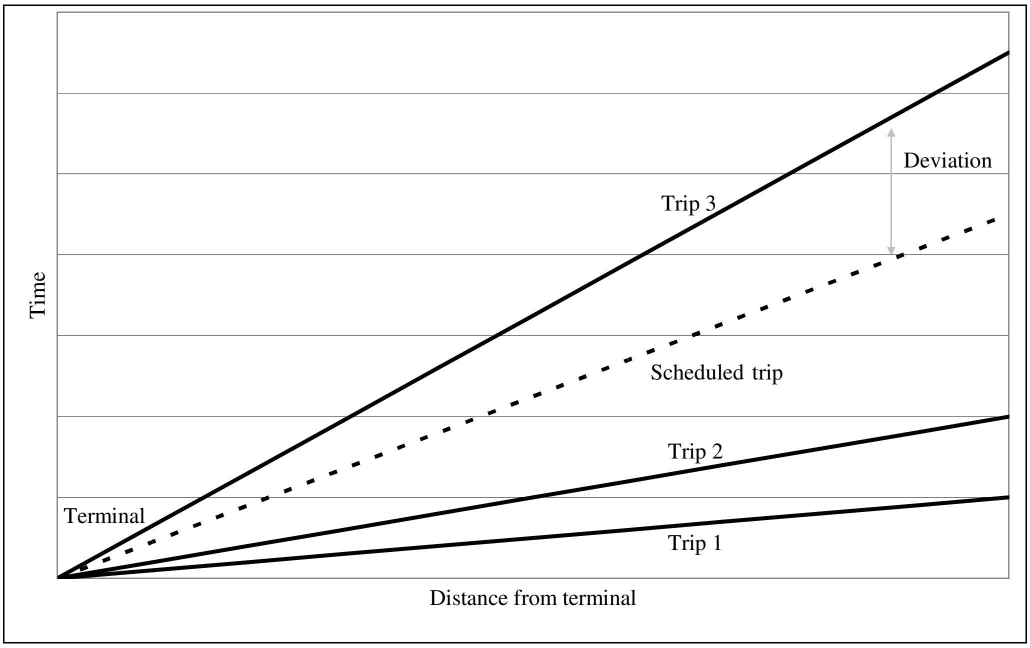
- *Terminal departure time variability;*
  This is the distribution of schedule deviations (early or late) of the vehicle trip departure at the terminal.
- *Vehicle trip time variability.*
  This is the distribution of the trip times along the route.

The deviation of the vehicle departure time at the terminal determines the offset of the deviation of the trip according to the schedule (as illustrated by Figure 2.3). In addition, vehicle trip time variability may arise along the route, as indicated by Figure 2.4. This variability arises due to for instance weather conditions, other traffic and human behaviour (both drivers and passengers). In general, this variability increases along the line due to a chain of stochastic events (Nelson and O'Neill 2000, Cham and Wilson 2006, Veisseth et al. 2007).



Dotted line is scheduled service, straight lines are fictitious examples of trips corresponding to the scheduled trip

Figure 2.3: Variability of service due to terminal departure time variability



Dotted line is scheduled service, straight lines are fictitious examples of trips corresponding to the scheduled trip

Figure 2.4: Variability of service due to trip time variability along the route

Concerning vehicle trip time, two sub elements may be distinguished:

- Driving times;
- Dwell times.

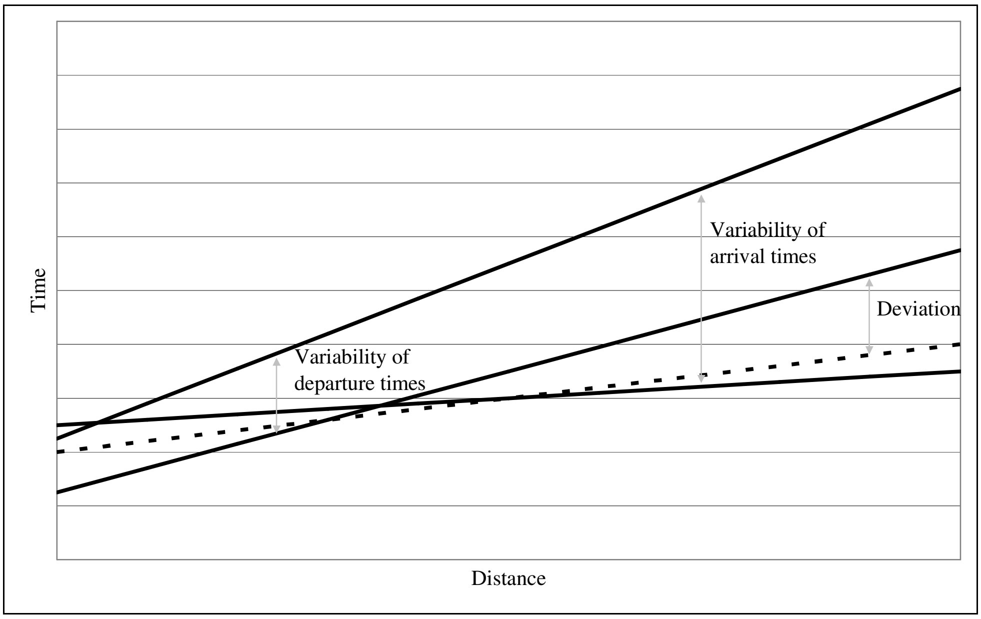
Driving times consist of actual driving times from stop to stop and unplanned stopping times between stops. All these time elements may be varying over time and these elements together affect the variability of total trip time, expressed in a trip time distribution. In general, the variability of driving times is proportional to the driving times themselves and thus depends on the line length (Levinson 1983, Van Oort and Van Nes 2009b).

Unplanned stopping is the stopping of vehicles at a location where no boarding and alighting is enabled, for instance at traffic lights. Eliminating this source completely is the best way to improve public transport reliability. Unfortunately, in urban public transport (bus, tram and light rail), unplanned stopping occurs and results in both delays and service variability. The main reason is other traffic. Unlike a metro system, which has exclusive right of way, these systems share parts of the infrastructure, lanes and junctions with car, bicycle and even pedestrian traffic. Besides, water traffic may create substantial stopping times as well, due to the openings of bridges.

In addition to other traffic, other public transport vehicles may cause slowing down or stopping as well. If traffic intensities are high at parts of infrastructure and/or capacity is low, vehicles may have to wait for each other at junctions. If signalling is applied (rail bound only), minimum possible headways increase, which may lead to slowing down or stopping due to predecessors as well.

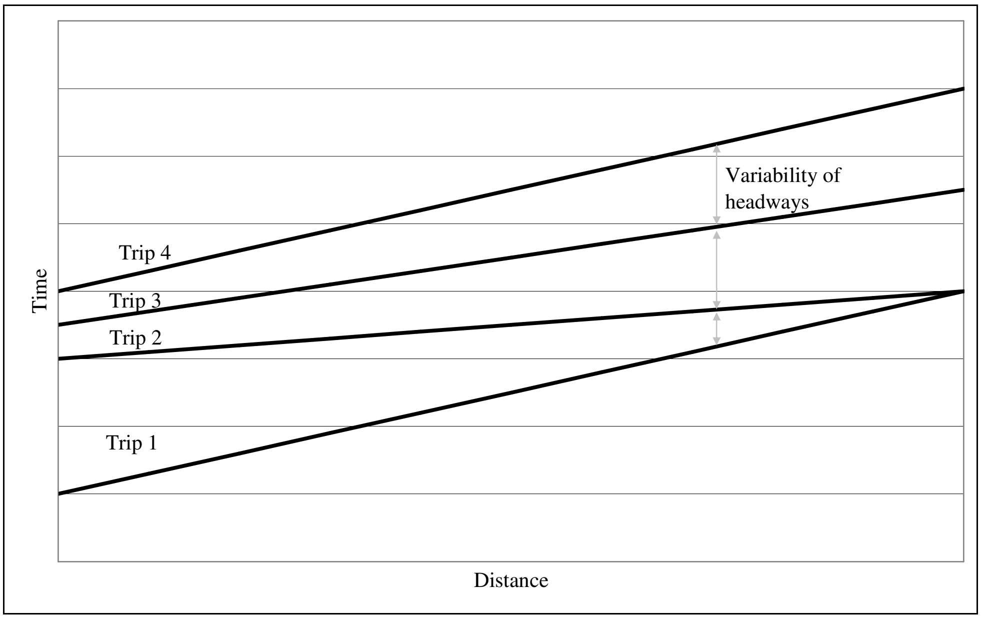
The other part of vehicle trip time is dwell time, which is the time used for boarding and alighting at a stop. In literature much attention is paid to analyzing and modelling dwell time considering causes and effects of dwell time variability (see e.g. Lin and Wilson 1992, Aashtiani and Irvani 2002, Rajbhandaru et al. 2003, Li et al. 2006 and Milkovits 2008). On an aggregate level, the number of stops per line is of importance regarding the variability of this element. In general, more stops lead to a higher level of variability.

As mentioned above, individual trip times may be distributed over time, due to a combination of terminal departure time and trip time variability. This distribution has two main effects with regard to the schedule. First of all, actual departure and arrival times of individual vehicle trips at stops will not match the scheduled times sufficiently, since schedules are deterministic. In addition, actual vehicle trip times are distributed as well. This phenomenon is illustrated in Figure 2.5. Second, if the focus is not on the variability of individual trips in time, but when successive trips are examined, headways between successive vehicles at stops are not constant due to these distributions. This implies a certain irregularity of vehicle departures at stops, as illustrated by Figure 2.6.



Dotted line is scheduled service, straight lines are fictitious examples of trips corresponding to the scheduled trip

Figure 2.5: Variability of service: example of variability of departure (at stop n) and arrival times (at stop n+x)



Presented lines are fictitious examples of successive trips on a route

Figure 2.6: Variability of headways between successive trips at stops along the route

Besides initial deviations, causing variability as shown above, deviation propagation is quite common in urban public transport. Deviation propagation may be considered in two ways. The first category is the knock-on of delays at the terminal. Arriving late at the terminal limits the possibilities of punctual departure of the next trip (mostly in the opposite direction). The second type of deviation propagation is on the line it self. In that case more than one vehicle is affected. This type of variability propagation is often referred to as bunching (of vehicles). The mechanism of bunching is illustrated in Figure 2.7 (based on Chapman 1978).

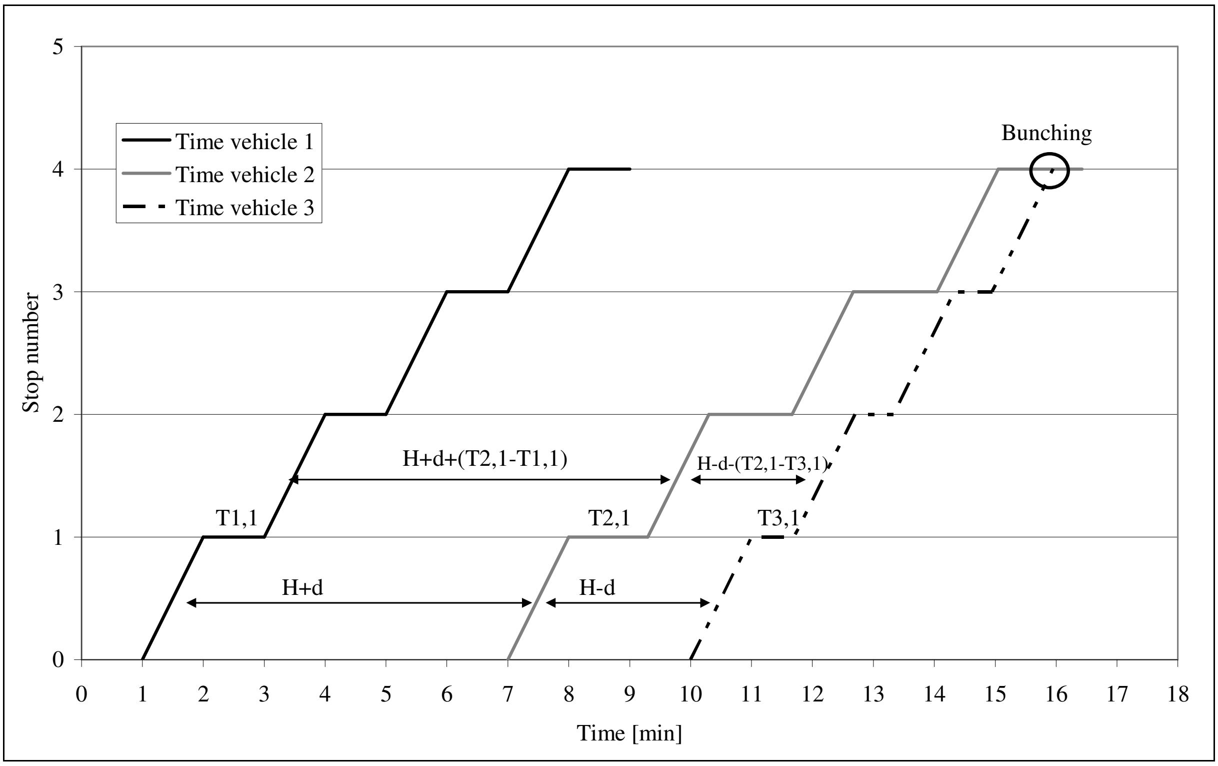


Figure 2.7: Bunching illustrated in a time-space diagram

If a vehicle suffers from an initial delay (d), the actual headway between this vehicle and its predecessor increases (and will equal the scheduled headway H plus initial deviation d). Due to this longer headway, the number of passenger at the stop, waiting for this vehicle will be increased. Due to this larger number of people, dwell time will be extended ($T_{2,1} > T_{1,1}$). The extended dwell time will create even more delay and thus the headway ahead will even more increase (H+d+($T_{2,1}$-$T_{1,1}$)). This process will enforce itself and will lead to larger delays.

When we look at the headway between a vehicle and his successor, this mechanism works the other way around. Due to the initial delay, the headway shrinks (H-d) and the number of passengers waiting for the successor will decrease. This enables shorter dwell times ($T_{3,1} < T_{1,1}$), which decreases the headway even more. This loop will enforce itself as well, resulting in bunched vehicles. The successor will reach the vehicle and they are bunched (at stop 4 in Figure 2.7). In Appendix D, more insights are provided concerning bunching of public transport vehicles.

2.3.3 Public transport demand

The supply side described in the previous subsection enables passengers to make a journey. The total journey from origin to destination consists of several parts, as shown in Figure 2.8.

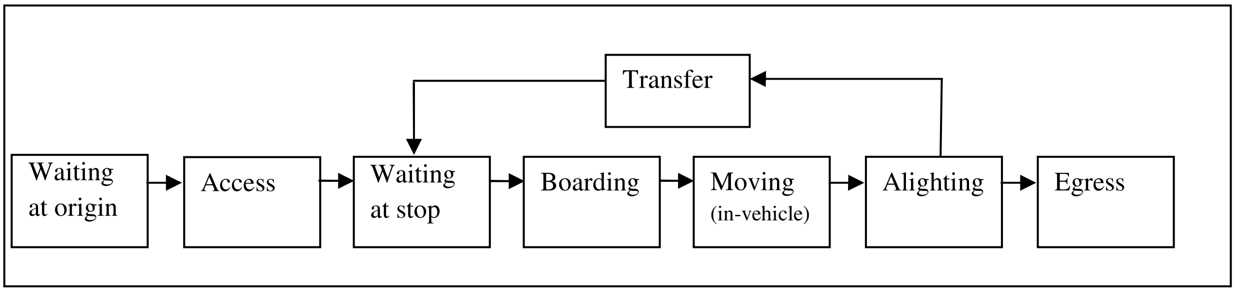


Figure 2.8: Passenger travel time components

The first part of passenger travel time (needed for the complete public transport journey) is the access time, which is the time needed between the origin and the departure stop. Often, this part of the journey is on foot and sometimes by bike. At the departure stop, waiting time will occur between arrival of the passenger and departure of the vehicle. Two arrival patterns may be distinguished. Passengers may arrive at random or they may plan their arrival according to the schedule. In the latter case, some waiting time at the origin may occur as well. This waiting time is referred to as hidden waiting time and arises due to a discrepancy between the preferred departure time and the available departure time.

Sometimes, the first vehicle is too crowded to enter, so passengers have to wait for the next one. After boarding the vehicle, the next element is moving (or "in-vehicle time") until the destination stop is reached. During public transport journeys, one or sometimes more transfers may be necessary. If so, the passenger needs to transfer to the stop of the next vehicle and wait there for the next departure. The final stop is seldom the destination of the passenger, so some egress time from stop to destination is unavoidable. In urban public transport, this is often walking. All the time elements related to the total journey are stochastic in real-life due to variability of different trips in a single period and variability of a single trip over different days. In our research we will focus on the part of the journey from the departure stop (j) to the arrival stop (k) of line l (i.e. passenger waiting and in-vehicle time). Transfers are considered to be the start of a new journey. The total journey time in case of a trip without transfers is expressed by Equation 2.1 (the ~ symbol indicates stochastic variables). Note that in case of transfers, waiting time and in-vehicle time occur for every service line used and that in addition transfer time may arise. Equation 2.2 shows the expectation of $\tilde{T}_{l,j-k}^{journey,tot}$, based on Equation 2.1.

$$\tilde{T}_{l,j-k}^{journey,tot} = \tilde{T}_{l,j}^{waiting\_origin} + \tilde{T}_{l,j}^{access} + \tilde{T}_{l,j}^{waiting} + \tilde{T}_{l,j-k}^{in-vehicle} + \tilde{T}_{l,k}^{egress} \tag{2.1}$$

$$E(\tilde{T}_{l,j-k}^{journey,tot}) = E(\tilde{T}_{l,j}^{waiting\_origin}) + E(\tilde{T}_{l,j}^{access}) + E(\tilde{T}_{l,j}^{waiting}) + E(\tilde{T}_{l,j-k}^{in-vehicle}) + E(\tilde{T}_{l,k}^{egress}) \tag{2.2}$$

where:

$\tilde{T}_{l,j-k}^{journey,tot}$ = *passenger travel time from origin to destination (on line l departing at stop j and arriving at stop k)*

$\tilde{T}_{l,j}^{X}$ = *stochastic duration of travel time element X (on line l departing at stop j)*

$E(\tilde{T}_{l,j}^{X})$ = *expected duration of travel time element X (on line l departing at stop j)*
j = *departure stop*
k = *arrival stop*

The expected value of passenger travel time ($E(\tilde{T}_{l,j-k}^{journey,tot})$) is an important input of choices made by travellers (for instance route, departure time and mode (Wallin and Wright 1974, Schmöcker and Bell 2002). In public transport practice, the timetable presents some of the elements of travel time $\tilde{T}_{l,j-k}^{journey,tot}$, affecting passenger choice behaviour. However, the schedule does not incorporate the variability of these elements. Some of these time components are related to the interaction of supply and demand elements of the demand side as well, which will be discussed in the next section.

These time components are perceived differently by passengers. Waiting (at the departure stop and during a transfer) is perceived longer than an equal amount of in-vehicle time for example. Research (Van Der Waard 1988 and Wardman 2001) found the perceived relative weights of all the components compared to in-vehicle time. These weights are shown in Table 2.1. Other references report that passengers attach a weight of 1.5 up to 2.3 to waiting times in urban public transport systems (Mishalani 2006, Dziekan and Vermeulen 2006), which makes waiting time an important component of the total journey time.

Table 2.1: Average relative weights of travel time components

Component	**Weight A (Van Der Waard 1988)**	**Weight B (Wardman 2001)**
Access time	2.2	1.8
Waiting time	1.5	1.5
In-vehicle time	1.0	1.0
Egress time	1.1	-

Equation 2.3 shows the incorporation of such weights into the generalized cost function of passengers for public transport (in case of no transfers). This function shows generalized travel time (consisting of the travel time components and their perceived weights) that enables to calculate the generalized travel time costs by the value of (VOT). To calculate the total generalized costs the ticket price (TP) and a mode specific constant (ϕ) are added as well. In their choice behaviour (between for instance destination, time or mode) travellers will tend to choose the alternative with the lowest value of C. Our objective is to reduce the average value of C per passenger by improving service reliability.

$$\tilde{C} = VOT * (\theta_1 * \tilde{T}_{l,j}^{waiting\_origin} + \theta_2 * \tilde{T}_{l,j}^{access} + \theta_3 * \tilde{T}_{l,j}^{waiting} + \theta_4 * \tilde{T}_{l,j-k}^{in-vehicle} + \theta_5 * \tilde{T}_{l,k}^{egress}) + TP + \phi \quad (2.3)$$

where:

$\tilde{C}$ = *generalized passenger costs for public transport*
VOT = *average value of time for public transport passengers*
$\tilde{T}_{l,j}^{X}$ = *stochastic duration of travel time element X (on line l departing at stop j)*
θ_X = *relative weights of travel time component x*

TP = *ticket price*
ϕ = *public transport mode preference constant*

2.3.4 Interaction between demand and supply sides

The variability of the supply side consists of deviations of actual headways, vehicle departure times, vehicle trip times and as a result the vehicle arrival times (over trips and days). Table 2.2 shows the different types of variability and which part of the passenger travel time is influenced.

Table 2.2: Types of service variability

Supply side (vehicle)	**Demand side (passenger)**
Types of service variability	*Main impacts on*
Variability of departure times	Waiting time
Variability of headways	Waiting time
Variability of trip times	In-vehicle time
Variability of arrival times	Arrival time

From an aggregated passenger perspective, the distribution of total passenger travel time (and as a result the distribution of passenger arrival time) is the most interesting one, since it covers the complete journey. This distribution is determined by the elements mentioned in Table 2.2.

From the perspective of the demand side, there is variation as well, i.e. the arrival pattern of individual passengers at their departure stop. This arrival pattern mainly consists of two types, as illustrated in Section 2.3.3, namely random arrivals and schedule-based arrivals. The combined result of the arrival pattern of passengers and the distribution of vehicle departure times and headways is a distribution of passenger waiting times.

Figure 2.9 illustrates the differences and relations between the demand and supply sides. Passenger waiting time is determined by actual headways and departure times next to passenger arrival time at the stop. In addition, passenger in-vehicle time is equal to the trip time of the vehicle and together with the departure time, the arrival time at the destination stop is set.

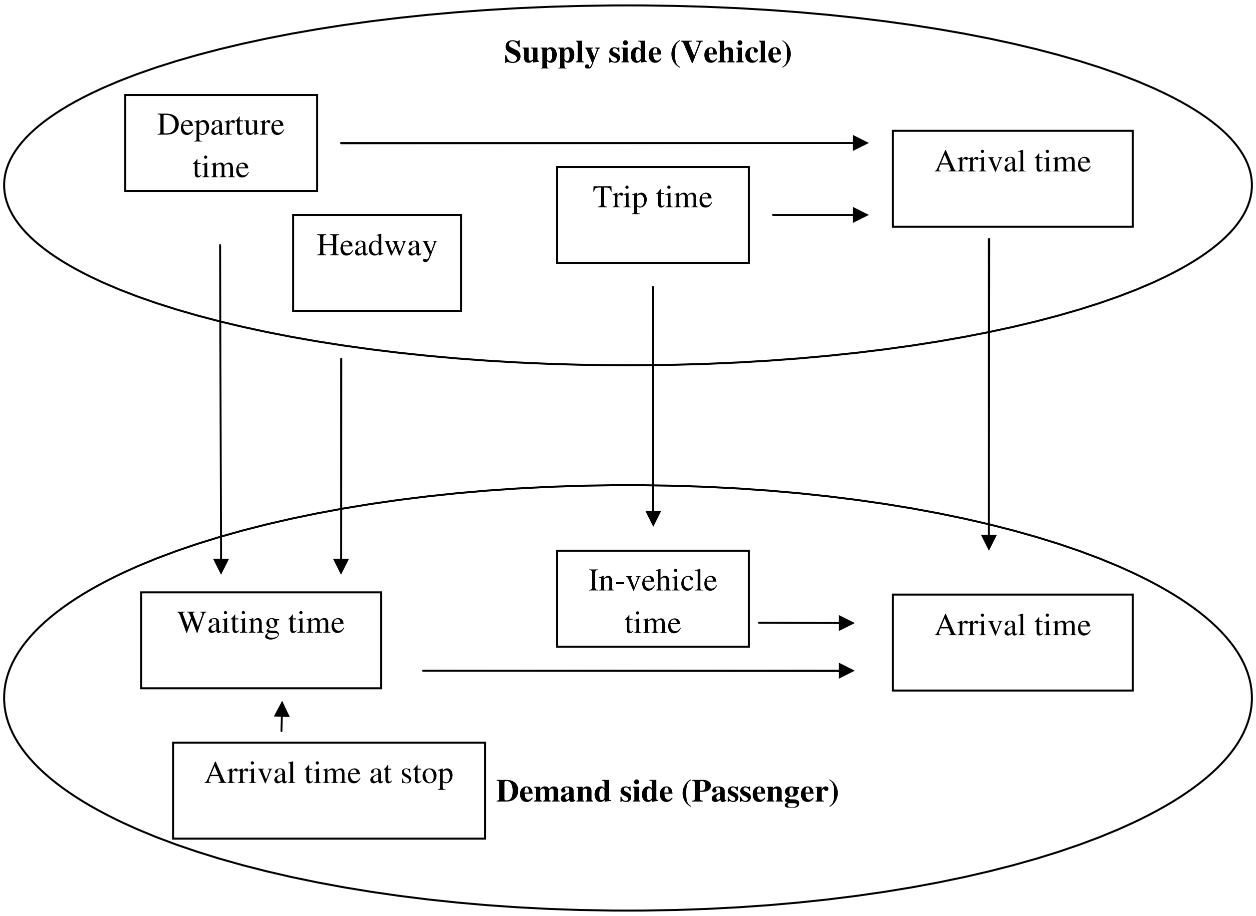


Figure 2.9: (Interaction of) Components on demand and supply sides

The previous analysis focused on vehicle trip time variability and the impacts on passenger travel time. We defined service reliability as the certainty of service aspects compared to the schedule (such as travel time (including waiting), arrival time and seat availability) as perceived by the user. Service variability is defined as the distribution of output values of the supply side of public transport, such as vehicle trip time, vehicle departure time and headways. In our research, we mainly focus on the travel time impacts. In literature many definitions of reliability may be found, some of them based on a different definition of the function of the system, especially connectivity, others focusing on specific components of public transport services. Table 2.3 gives an overview of the types of reliability in literature (Tahmasseby 2009). Some of them are closely related to travel time reliability and affect components shown in Figure 2.9.

Table 2.3: Types of reliability and references

Reliability	Reference
Connectivity	Berdica (2002), Chen et al. (2002), Bell (2000), Asakura et al. (2000), Kurauchi et al. (2004), Iida and Wakabayashi (1989), Bell and Iida (1997), Al Deek and Ben Emam (2006)
Travel time	Berdica (2002), Liu (2007), Chen et al. (2002)
Headways	Liu (2007)
Passenger waiting time	Liu (2007)
Schedule	Turnquist and Blume (1980), Carey (1999), Strathman et al. (1999), Kimpel (2001), Bell (2000), Al Deek and Ben Emam (2006), Rietveld et al.(2001)

Connectivity reliability is defined as the probability that network nodes are connected and may be reached (Iida and Wakabayashi 1989). Regarding the passengers' 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 be performed (Bell and Iida 1997, Al-Deek and Ben- Emam 2006). Connectivity reliability is also studied in the context of public transport supply. On the supply side (the service network), it may be measured as the probability that network nodes are connected (Bell 2000, Asakura et al. 2001 and Kurauchi et al. 2004). This perspective relates more to irregular conditions in which part of the services might not operate as planned. An elaborate study of urban public transport systems is irregular conditions may be found in Tahmasseby (2009). As stated in Chapter 1, we focus on situations in which the infrastructure is fully available.

In Liu (2007), three types of bus service reliability notions are discussed. These are travel time reliability, headway reliability and passenger waiting time reliability. They all are defined as to what extent the specific actual time matches the scheduled time. The first type refers to our focus, the latter two only express parts of the passenger effects of unreliability. Turnquist and Blume (1980), Carey (1999), Strathman et al. (1999), Kimpel (2001), Bell (2000), Al Deek and Ben Emam (2006) and Rietveld et al. (2001) also deal with schedule reliability. However, strictly focusing on schedule reliability may lead to a quality drop, due to low schedule speeds enabling reliable schedules.

Due to variability of several supply and demand components (over trips and days), passengers experience variability of the service affecting their travel time. The magnitude of this variation mainly determines whether passengers perceive the service as reliable or not.

2.3.5 Conclusions

Service reliability is the matching degree of the promised and actual public transport services and its impacts on passengers, which are mainly travel time related. Service reliability is the result of the interaction between supply and demand of public transport. This section described both sides. At the supply side, vehicle trips in time and space are provided. Due to terminal departure and vehicle trip time deviations, the operations do not match the schedule, resulting in departure time and headway variability (over trips and days). In addition, the variability may increase itself due to the bunching effect. At the demand side, the arrival of passengers at their departure stop is important when analyzing service reliability. Passenger may arrive at random or they may plan their arrival with the scheduled vehicle departure. The interaction between supply and demand affects the waiting and in-vehicle time of passengers. This will be further explored in the next section.

2.4 Impacts of service reliability on passengers

2.4.1 Introduction

In the previous sections, it was shown that the level of service reliability results from the interaction between the supply and demand sides. In literature several types of reliability have been distinguished to express the passenger effects of this interaction. In preparation of quantifying service reliability, this section demonstrates the impacts of service reliability on passengers, with a special focus on travel time reliability. The passenger mainly experiences the following three effects (Noland and Small 1995, Noland and Polak 2002, Van Oort and Van Nes 2004). Note that due to the stochastic nature, the impacts on individual passengers may differ from average values.

- Impacts on duration of travel time components, being in-vehicle time and waiting time, which lead to arriving early or late;
- Impacts on variability of travel time components, being departure time, arrival time, in-vehicle time and waiting time, which lead to uncertainty of the actual travel time;
- Impact on probability of finding a seat and crowding, which affects the level of comfort of the journey.

These aspects are described and analyzed in this section. The last part of this section presents the effects of the level of service reliability on choice behaviour of passengers.

2.4.2 Duration of travel time components

Travel time is a key component in all kinds of travellers' decisions. Irregular transport services influence in-vehicle times as well as waiting times, the latter both at the first stop and at transfer nodes. In this section we provide an analysis of the impacts of service variability on the magnitude of passenger in-vehicle and waiting times. Concerning waiting time, two scenarios are distinguished, that is waiting when passengers arrive at random and when they plan their arrival according to the schedule. In the case of transfers, waiting time depends on the arrival pattern of feeder vehicles.

2.4.2.1 In-vehicle time

Variability in vehicle trip times at the supply side will result in variability of the passenger in-vehicle time at the demand side. This may result in longer in-vehicle times for a part of the passengers as well as shorter in-vehicle times for other passengers. If in-vehicle time is compared to the schedule the effect is determined by the method of planning and publishing trip time in the schedule (e.g. a tight or loose schedule). If a public transport planner uses the average of actual or expected trip times to determine the scheduled trip time, the difference between scheduled and actual average in-vehicle time per passenger is minimized.

In the case of bunching (Section 2.3.2) the average in-vehicle time per passenger will be extended. More passengers will suffer from the delay than the number of passenger benefiting from the speeding up of the successive vehicle, because the slowest vehicle will collect more passengers. In addition, instruments affecting the actual vehicle trip time variability, such as vehicle holding, will also extend the average in-vehicle time per passenger.

2.4.2.2 Waiting time when passengers arrive at random at the departure stop

When passengers arrive uniformly distributed at their departure stop and services are regular, average waiting time per passenger will be equal to half the headway of the departing vehicles (Welding 1957, Osuna and Newell 1972, Heap and Thomas 1976). In theory, half of the passengers will have a shorter waiting time and half of them will encounter more. However, when headways are irregular, the average waiting time per passenger will increase. Headways will be both longer and shorter than scheduled, but the number of passengers benefiting from shorter headways will be smaller than the number of suffering from longer headways and longer waiting times (Welding 1957, Osuna and Newell 1972, Heap and Thomas 1976). Section 2.5.3.1 will discuss this mechanism in more detail.

2.4.2.3 Waiting time when passengers plan their arrival at the departure stop

Literature on the arrival rate of passengers and waiting times when passengers adjust their arrival to the scheduled departure is limited. In Vuchic (2005), a relationship is given showing the average waiting time as function of the headway (H), divided in random arrival and planned arrival of passengers and a mixed area in between (see Figure 2.10). The random arrivals lead to waiting times of half the headway as discussed above, while the case of planned arrivals yields an average waiting time of 5 minutes. In the areas in between, the value of the waiting time is highest.

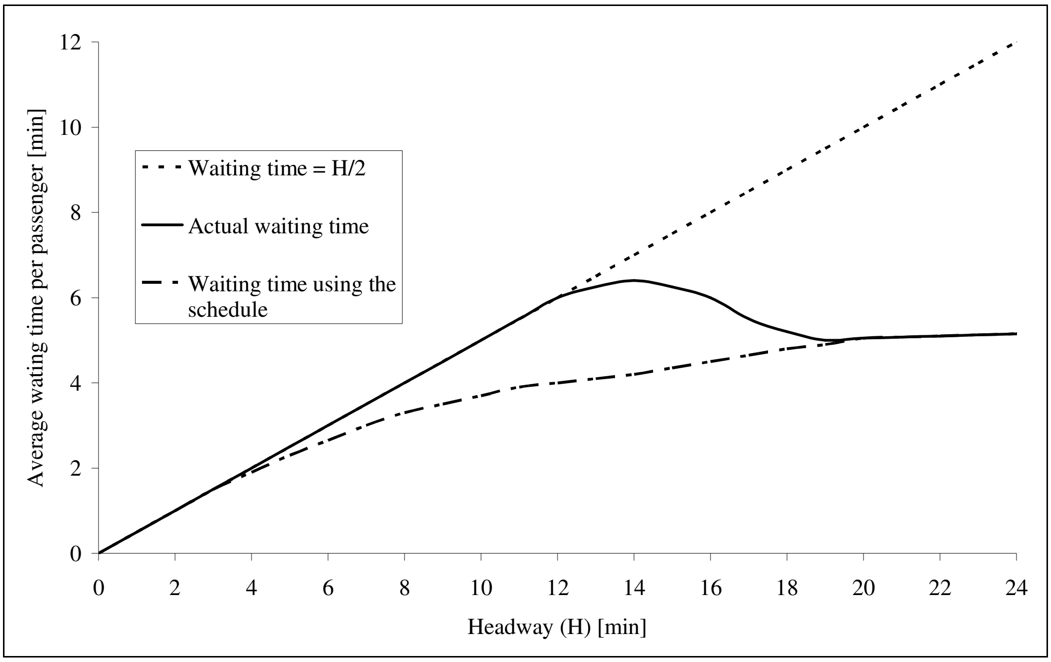


Figure 2.10: Average waiting time as a function of headway size (H) (Source: Vuchic 2005)

In the case of passengers planning their arrival at the departure stop, schedule adherence is important. For passengers, the difference between early and late departing vehicles is of great importance. Early vehicles might lead to waiting the full headway. Late vehicles only extend the waiting time by the amount of delay, which is, especially in long headway service, most of times much less. Variability of the supply side thus affects the waiting time of passengers in an asymmetrical way.

2.4.2.4 Conclusions

Since the average waiting time per passenger will increase due to service variability, the average travel time per passenger will increase as well. With regard to service variability, the average in-vehicle time only is extended due to bunching, a secondary effect of service variability, or instruments affecting actual trip time variability, such as vehicle holding. Since the schedule may be adjusted to regular trip time variability (by applying the average value in the schedule), this does not affect the average additional in-vehicle time compared to the schedule. However, this means that the additional in-vehicle time is accounted for in the schedule. This is not a matter of service reliability, but is still important in analyzing the impacts of instruments. Equations 2.4 and 2.5 show the expectation of waiting time and in-vehicle-time, both consisting of a scheduled component and a component expressing the additional time due to service variability. The ~ symbol indicates stochastic variables. The scheduled waiting time ($\tilde{T}_{l,j}^{sched,waiting}$) depends on the arrival pattern of passengers and is thus a stochastic variable. The scheduled in-vehicle time ($T_{l,j-k}^{sched,in-vehicle}$) is independent of stochastic processes and is thus a fixed variable. Equation 2.6 summarizes all the components of expected travel time, as shown by Equation 2.1, but explicitly distinguishes the components that arise due to service variability ($\tilde{T}_{l,j}^{add,waiting}$ and $\tilde{T}_{l,j-k}^{add,in-vehicle}$). This equation shows that passenger total travel time consists of the travel time according to the schedule (including the scheduled waiting (at the origin), access, in-vehicle and egress time) and in addition the extension of the waiting and in-vehicle time due to service variability. Equation 2.7 shows the schedule components. Considering our focus of the passenger journey, from stop to stop, as presented in Section 2.3.3, Equation 2.8 presents the expected travel time calculation ($E(\tilde{T}_{l,j-k}^{journey})$) that we will use in the remainder of this thesis.

$$E(\tilde{T}_{l,j}^{waiting}) = E(\tilde{T}_{l,j}^{sched,waiting}) + E(\tilde{T}_{l,j}^{add,waiting}) \tag{2.4}$$

$$E(\tilde{T}_{l,j-k}^{in-vehicle}) = T_{l,j-k}^{sched,in-vehicle} + E(\tilde{T}_{l,j-k}^{add,in-vehicle}) \tag{2.5}$$

$$\begin{aligned} E(\tilde{T}_{l,j-k}^{journey,tot}) = {} & E(\tilde{T}_{l,j}^{waiting\_origin}) + E(\tilde{T}_{l,j}^{access}) + E(\tilde{T}_{l,j}^{sched,waiting}) + E(\tilde{T}_{l,j}^{add,waiting}) + \\ & T_{l,j-k}^{sched,in-vehicle} + E(\tilde{T}_{l,j-k}^{add,in-vehicle}) + E(\tilde{T}_{l,k}^{egress}) \end{aligned} \tag{2.6}$$

$$E(\tilde{T}_{l,j-k}^{journey,sched}) = E(\tilde{T}_{l,j}^{sched,waiting}) + T_{l,j-k}^{sched,in-vehicle} \tag{2.7}$$

$$E(\tilde{T}_{l,j-k}^{journey}) = E(\tilde{T}_{l,j-k}^{journey,sched}) + E(\tilde{T}_{l,j}^{add,waiting}) + E(\tilde{T}_{l,j-k}^{add,in-vehicle}) \tag{2.8}$$

where:

$E(\tilde{T}_{l,j}^{X})$ = *expected duration of travel time element X (on line l at stop j)*

$\tilde{T}_{l,j-k}^{journey,tot}$ = *total passenger travel time from origin to destination (on line l departing at stop j and arriving at stop k)*

$\tilde{T}_{l,j-k}^{journey}$ = *passenger travel time from stop j to stop k on line l (including waiting)*

$\tilde{T}_{l,j}^{sched,waiting}$ = *waiting time according to the schedule per passenger at stop j on line l*

$\tilde{T}_{l,j}^{add,waiting}$ = *additional waiting time per passenger due to service variability at stop j on line l*

$T_{l,j-k}^{sched,in-vehicle}$ = *in-vehicle time (stop j-k) on line l per passenger according to the schedule*

$\tilde{T}_{l,j-k}^{add,in-vehicle}$ = *additional in-vehicle time due to service variability between stop j and k on line l*

$\tilde{T}_{l,j-k}^{journey,sched}$ = *total passenger travel time according to schedule (on line l departing at stop j and arriving at stop k)*

2.4.3 Variability of passenger travel time components

Above is shown that variability of the supply side may extend the average travel time per passenger due to an extension of average waiting time and to a lesser extent, due to the average in-vehicle time. In addition, the passenger travel time will become distributed as well due to variability of the supply side. Equation 2.1 already showed the stochastic elements of total travel time. Due to the combination of the passenger arrival pattern and the variability in departure time and headways, passenger waiting time will also be distributed. In addition, variability in vehicle trip time will create variability in passenger in-vehicle time and arrival time. Equations 2.9 and 2.10 show the variation of $\tilde{T}_{l,j-k}^{journey}$ in case of independency of waiting time and in-vehicle time. Since the expected correlation between these two, this equation may underestimate the variation.

$$Var(\tilde{T}_{l,j-k}^{journey}) = Var(\tilde{T}_{l,j}^{waiting}) + Var(\tilde{T}_{l,j-k}^{in-vehicle}) \quad (2.9)$$

$$Var(\tilde{T}_{l,j-k}^{journey}) = Var(\tilde{T}_{l,j}^{sched,waiting}) + Var(\tilde{T}_{l,j}^{add,waiting}) + Var(\tilde{T}_{l,j-k}^{add,in-vehicle}) \quad (2.10)$$

The variability in these three elements will lead to passenger uncertainty about the service and as a consequence, passengers may consider an extra time buffer when comparing travel alternatives due to this variability. Furth and Muller (2006) state that this time is a function of the perceived service variability. They propose as the value for this extra time buffer the difference between the 95-percentile value and the average of travel time to express this variability effect. In the passenger choices with regard for instance mode or route, passengers will consider the probability of an uncertain arrival time. Equation 2.11 shows this component (T^{budget}, which we assume to be a constant per passenger over all his trips, but different per individual passenger), added to the calculation of travel time per passenger of Equation 2.8, resulting in an expression for the experienced travel time ($\tilde{T}_{l,j-k}^{journey,\exp}$).

$$E(\tilde{T}_{l,j-k}^{journey,\exp}) = E(\tilde{T}_{l,j-k}^{journey,sched}) + E(\tilde{T}_{l,j}^{add,waiting}) + E(\tilde{T}_{l,j-k}^{add,in-vehicle}) + T^{budget} \quad (2.11)$$

where:

$\tilde{T}_{l,j-k}^{journey,\exp}$ = *experienced passenger travel time from stop j to stop k on line l*

T^{budget} = *travel time budget of passengers due to service variability*

2.4.4 Probability of finding a seat and crowding

Besides influence on travel time, variability will also decrease the level of comfort by decreasing the probability of securing a seat in the vehicle or creating overcrowding. This mechanism is illustrated by Figure 2.11. This effect of service variability is primarily relevant if passengers arrive at random at the departure stop. Due to bunching, vehicles will have shorter or longer headways than scheduled between their selves and their predecessor. When a vehicle is delayed and the headway is longer, the number of passengers will be larger than the expected average per vehicle. This additional number of passengers may lead to capacity problems in the vehicles. More people have to stand or are not even able to enter the vehicle at all. In the case passengers consult the schedule to arrive at their departure stop, crowding may occur if passengers miss a vehicle (due to early departure for instance) and board the next vehicle (which is not too early). This way, the second vehicle suffers from double loads at stops.

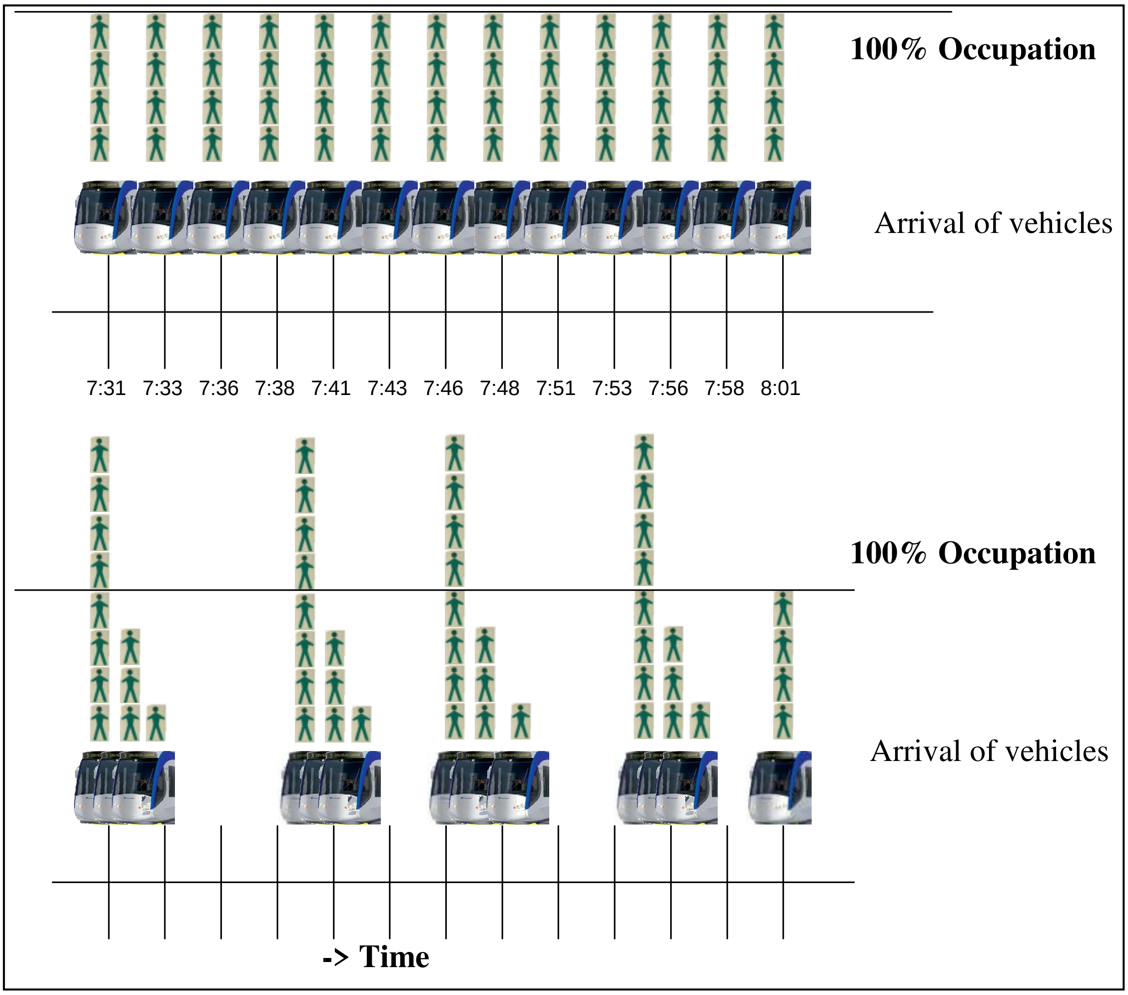


Figure 2.11: Distribution of passengers over vehicles in regular (upper part) and irregular (lower part) operations

In Wardman (2010), a study is presented, indicating the value of crowding, related to travel time. A meta-analysis of 135 valuation studies is reported, finding the travel time valuations to vary with load factor and journey purpose. The seating multiplier (as a relative weight compared to in-vehicle time) averages 1.15 for load factors between 60% and 100% and almost 1.5 for load factors in excess of 100%. The standing multiplier (as a relative weight compared to in-vehicle time) averages 2.4. These numbers indicate the substantial impact of crowding on passenger perception.

2.4.5 Passenger behaviour under service variability

The level of service variability affects passengers in different ways, as shown by the previous section. This is expressed in two ways. First of all the product attractiveness is affected by the level of service reliability. Especially the relative attractiveness compared to other travel options is important regarding the choices passengers make, both internal (within the public transport system) as external (options outside the public transport system). The internal factors concern the desired departure and arrival stop, the route or the time of travel. Externally seen, the modal split is affected by the relative level of service reliability compared to car of bike transport for instance.

While the (relative) attractiveness determines whether and which public transport line is used, passenger appreciation of public transport is affected by service reliability as well. This only concerns existing passengers and mainly affects the image of the public transport system, which may determine future use of public transport.

Passengers will either accept the conditions due to poor service reliability implying a loss of welfare, due to additional travel time, variability and less comfort, or they will adjust their behaviour due to their experiences and expectations concerning service reliability. The extension of average travel time, the variability of travel time and the decreased probability of finding a seat may all lead to the following changes in choice behaviour of passengers.

- Internal (within the public transport system)

  - Passengers change their departure time;
  - Passengers change their origin stop;
  - Passengers change their destination stop;
  - Passengers change their route (other line, less or additional transfers);

- External (options outside the public transport system)

  - Passengers change their mode;
  - Passengers change or cancel their journey.

In literature, much research is available with regard to the choices mentioned above. Bates et al. (2001) and Rietveld et al. (2001) state that service reliability of public transport systems has been considered critically important by most public transport users because passengers are adversely affected by the consequences associated with unreliability such as additional waiting time, late or early arrival at destinations and missed connections, which increases their anxiety and discomfort. Route choice might be affected by unreliability, as presented by Abdel-Aty (1994), Schmöcker and Bell (2002) and Liu and Sinha (2007). Service reliability has also been identified as important in determining the mode choice (Turnquist and Bowman 1980). Therefore, it may be stated that unreliability in public transport drives away existing and prospective passengers.

Reversely formulated, enhanced reliability will attract more public transport users, as stated in Chapter 1. Research (Vrije Universiteit 1998) shows that people are likely to change their mode of transport because of changes in the level of service reliability. Although the measures of this research are imprecise, the research demonstrates (as shown in Table 2.4) that service unreliability (expressed as standard deviation of travel time) has a great impact on the mode choice of travellers. People indicate that changes (without exact numbers) in service reliability are affecting their behaviour. Especially occasional travellers seem to be very sensitive to changes in unreliability.

Table 2.4: Effects of changes in unreliability (standard deviation of travel time) on mode choice

Travellers / Change of unreliability	Regular travellers	Occasional travellers	Non travellers
Decrease	9%[1]	22%[1]	9%[1]
Increase	17%[2]	44%[2]	-

[1] *part of travellers that will travel more often by public transport*
[2] *part of travellers that will travel less often by public transport*

2.4.6 Conclusions

This section showed three main impacts of service reliability on passengers, being the extension of travel time components in-vehicle time and waiting time, variability of travel time, and the probability of finding a seat in the vehicle. This section also showed the possible reaction of passengers when services are unreliable. They may for instance change their route or moment of their journey, they may change their mode or they may cancel their journey. All these effects lead to a loss of welfare and to a loss of patronage and thus revenues for public transport companies. Improving service reliability may thus lead to substantial benefits for operators and society. However, the selection of proper instruments to improve service reliability requires proper indicators to quantify the impacts of service unreliability. The next section will present current and new indicators for service reliability. We will show that the travel time effects on passengers are not properly expressed by traditional indicators. To deal with this shortcoming, we will propose new indicators, indicating the extension of travel time ($E(\tilde{T}_{l,j}^{add,waiting}) + E(\tilde{T}_{l,j-k}^{add,in-vehicle})$) and its variability ($Var(\tilde{T}_{l,j-k}^{journey})$). To a lesser extent, we will also show how to indicate the probability of finding a seat in the vehicle.

2.5 Indicators of service variability and reliability

2.5.1 Introduction

In order to improve service reliability it is essential to monitor and predict the level of service reliability of a public transport system. For this we need proper indicators. The commonly used indicators which are supposed to express reliability do not completely focus on service reliability concerning passenger impacts. In fact, they focus more on service variability of the system than on the actual impacts on passengers. However, Section 2.4 demonstrated the importance of taking the demand side into account while assessing service reliability. The impacts on passengers are mainly measured by customer surveys, which implies only a qualitative assessment. This section presents the traditionally used indicators and introduces new indicators enabling enhanced quantifying of service reliability. These new indicators will be used in our research in the next chapters.

2.5.2 Traditionally used indicators

Given the stochastic nature of public transport operations, statistical measures such as standard deviation or percentiles are logical indicators. A typical example is the coefficient of variation of headway, as shown by Equation 2.12 (Cham and Wilson 2006). This indicator may relate to an aggregate characteristic of a public transport line, or a branch served by a set of public transport lines. Equation 2.12 shows the coefficient of variation of actual headways per stop, but in practice expressing this indicator on line level is also common use, by calculating the average value over the stops. This way, the number of passengers per stop is neglected.

$$CoV(\tilde{H}_{l,j}^{act}) = \frac{StD(\tilde{H}_{l,j}^{act})}{E(\tilde{H}_{l,j}^{act})} \tag{2.12}$$

where:

$CoV(\tilde{H}_{l,j}^{act})$ = *coefficient of variation of actual headways of line l at stop j*

$\tilde{H}_{l,j}^{act}$ = *actual headway of line l at stop j*

$StD(\tilde{H}_{l,j}^{act})$ = *standard deviation of actual headways of line l at stop j*

$E(\tilde{H}_{l,j}^{act})$ = *expected headway of line l at stop j*

In practice, however, the use of purely statistical measures is limited. Commonly used indicators focus either on punctuality, the extent to which the scheduled departure times are met, or on regularity, the variation in the headways.

Taking the perspective of the production process (Section 2.2), the percentage of trips performed within a predefined bandwidth, are useful reliability indicators. Equation 2.13 expresses this type of indicator for average departure deviation for a complete line. Observed data is used to determine the relative frequency of deviations within a bandwidth. This indicator represents to which extent the production process requirements are met. Section 3.2.3 will present actual used values of $\delta^{\min}$ and $\delta^{\max}$. Obviously, these values are of great influence on the level of service reliability calculated.

$$P_l = \frac{\sum_{j=1}^{n_{l,j}} \sum_{i=1}^{n_{l,i}} P_{l,i,j}(\delta^{\min} < \tilde{D}_{l,i,j}^{act} - D_{l,i,j}^{sched} < \delta^{\max})}{n_{l,i} * n_{l,j}} \tag{2.13}$$

where:

P_l	= *relative frequency of vehicles on line l having a schedule deviation between* $\delta^{\min}$ *and* $\delta^{\max}$
$P_{l,i,,j}$	= *relative frequency of vehicle i on line l having a schedule deviation between* $\delta^{\min}$ *and* $\delta^{\max}$ *at stop j*
$\tilde{D}_{l,i,j}^{act}$	= *actual departure time of vehicle i on stop j on line l*
$D_{l,i,j}^{sched}$	= *scheduled departure time of vehicle i on stop j on line l*
$\delta^{\min}$	= *lower bound bandwidth schedule deviation*
$\delta^{\max}$	= *upper bound bandwidth schedule deviation*
$n_{l,i}$	= *number of trips of line l*
$n_{l,j}$	= *number of stops of line l*

Punctuality may also be defined as the (average) deviation from the timetable at a specific stop, a set of stops, or for all stops of a line. The latter is shown by Equation 2.14 (Hansen 1999).

$$p_l = \frac{\sum_{j}^{n_{l,j}} \sum_{i}^{n_{l,i}} \left| \tilde{D}_{l,i,j}^{act} - D_{l,i,j}^{sched} \right|}{n_{l,j} * n_{l,i}} \tag{2.14}$$

where:

p_l	= *average punctuality on line l*

Please note that this formulation has an important shortcoming. It does not indicate whether vehicles depart too early or too late, which has a large impact on passenger waiting time. If only a set of stops is considered, the location of the stops may be of influence. Chapter 3 will provide practical examples of measurement locations and implications of the chosen set of locations.

Irregularity is used to express headway deviations. Hakkesteegt and Muller (1981) introduced the PRDM (Percentage regularity deviation mean), which shows the average deviation from the scheduled headway as a percentage of the scheduled headway. The calculation of the PRDM is shown in Equation 2.15. This equation shows the calculation of the PRDM per stop. Taking into account all the stops, a calculation of the PRDM for the total line is also possible.

$$PRDM_{l,j} = \frac{\sum_i \left| \frac{H_{l,i}^{sched} - \tilde{H}_{l,i,j}^{act}}{H_{l,i}^{sched}} \right|}{n_{l,j}} \qquad (2.15)$$

where:

$PRDM_{l,j}$ = *relative regularity for line l at stop j*
$H_{l,i}^{sched}$ = *scheduled headway for vehicle i on line l*
$\tilde{H}_{l,i,j}^{act}$ = *actual headway for vehicle i on line l at stop j*
$n_{l,j}$ = *number of vehicles of line l departing at stop j*

All measures presented focus purely on characteristics for the supply side, although it should be noted that indicators for punctuality and regularity are linked with assumptions on the arrival pattern of travellers, i.e. arrivals based on the timetable and uniformly distributed arrivals respectively. More important is the fact that these measures make no distinction between stops having a high demand or a low demand. Punctuality and regularity have a strong influence on waiting time and are thus most important for stops having large numbers of passengers boarding the vehicles. Furthermore, these indicators do not quantify the impact the variability has on travellers, such as the extra travel time as discussed in Section 2.4. Mazloumi et al. (2008) support that focusing on on-time vehicles only is not sufficient. Therefore, the next section presents new indicators that are better suited to measure service reliability. In Chapter 3, we will use the presented indicators of punctuality (Equations 2.13 and 2.14) and the PRDM (Equation 2.15) to illustrate actual levels of service variability compared to passenger oriented indicators.

2.5.3 Passenger oriented service reliability indicators

Taking the perspective of the passenger would ideally require indicators for the door-to-door journey instead of punctuality or regularity at stops. Some researchers propose the standard deviation of the actual entire route travel times as an appropriate criterion for measuring travel time reliability of a particular route (Turnquist and Bowman 1980, Rietveld et al. 2001 and Tseng 2008). In addition to the standard deviation of route travel time, the following measures are proposed for describing travel time reliability (Turnquist and Bowman 1980, Tseng 2008 and Vincent and Hamilton 2008):

- Coefficient of variation of route travel time (CoV);
- Difference between the 90^{th} and 50^{th} percentile of travel time;
- Difference between the 80^{th} and 50^{th} percentile of travel time.

Tseng (2008) shows that these indicators are transformable into each other and transformation rates depend on travel time distribution as well. In literature, travel time reliability has also been defined as the inverse of the standard deviation of journey times (e.g. Polus, 1978 and Sterman and Schofer 1976) and the percentage of journeys on a bus route that takes no longer than the expected travel time plus an acceptable additional time (Strathman et al. 2001).

In order to use such journey oriented indicators would require detailed knowledge of the demand pattern in space and time. However, such information is usually not available for public transport operators and authorities. Information they do have is the number of boardings and alightings per stop and thus the occupancy along the line. As an example Figure 2.12 shows three different hypothetical functions of passenger occupancy along the line and the importance of service reliability on the complete line differs per function. Figure 2.12 A shows a high occupancy from the start to the end of the line (no exchange of passengers along the line is assumed). If we look at the impacts on passenger waiting time, the departure punctuality at stop 1 is very important, but departure deviations at other stops are not of any interest since nobody is boarding at those locations. In the case of Figure 2.12 B, in which only boardings in the first half of the line are assumed and only alightings in the second half, the first part of the line is of main interest. The assumption of the occupancy of Figure 2.12 C is also only boardings in the first half and alightings in the second part, but the number of boardings at the stop in the middle is substantial. In that case schedule adherence at this stop is most important.

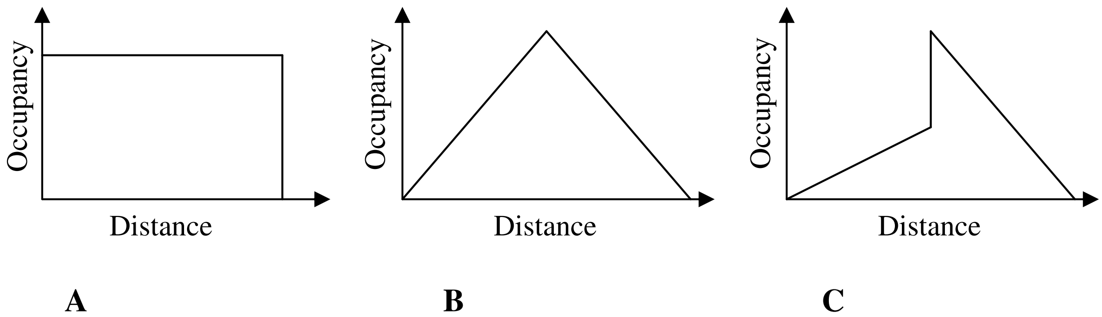


Figure 2.12: Common occupancy patterns on public transport lines

As we argued earlier, the use of punctuality as a reliability indicator using Equation 2.14 is not adequate, since the impacts of passengers of early and late vehicles is handled similarly (see also Camus et al. 2005). In practice, however, early vehicles cause more delay in general, since passengers that miss the vehicle have to wait a full headway. In this section, new indicators are introduced, namely additional travel time (Van Oort and Van Nes 2004 and 2006) and reliability buffer time (Furth and Muller 2006), enabling expressing unreliability in a way which better connects to the real impacts on passengers.

2.5.3.1 Additional travel time

Although the supply-side indicators often help to illustrate the level of service provided to the passenger, they do not completely match the customer perception. Driving ahead or being late for example are completely different phenomena for passengers. The arrival pattern of passengers at the stop where they depart is of importance to determine the impacts for the passenger. If passengers arrive at random, the deviation from the schedule is not relevant anymore. Passenger waiting time is then minimized if actual headways are constant (as explained in Section 2.4.2). If passengers use the schedule to plan their moment of arrival at their departure stop, the deviation from the timetable is important.

As shown in Section 2.4 service variability may lead to an extension of passenger average travel time, since average waiting time per passenger may be extended due to irregular, early or late vehicles. To express this effect of service variability on passengers more effectively than punctuality and regularity, we introduced a new indicator, called average additional travel time (Van Oort and Van Nes 2004 and 2006). This section describes this indicator and shows how to calculate it.

Figure 2.13 illustrates the phenomenon of additional travel time from an example of a single passenger journey. In a situation without service variability (Figure 2.13A), the travel time consists of access time, waiting time, in-vehicle and egress time. Next to regularity and schedule adherence, passenger waiting time depends on the arrival pattern of passengers. In-vehicle time is determined by the scheduled vehicle trip time and access and egress times are a result of line and stop spacing.

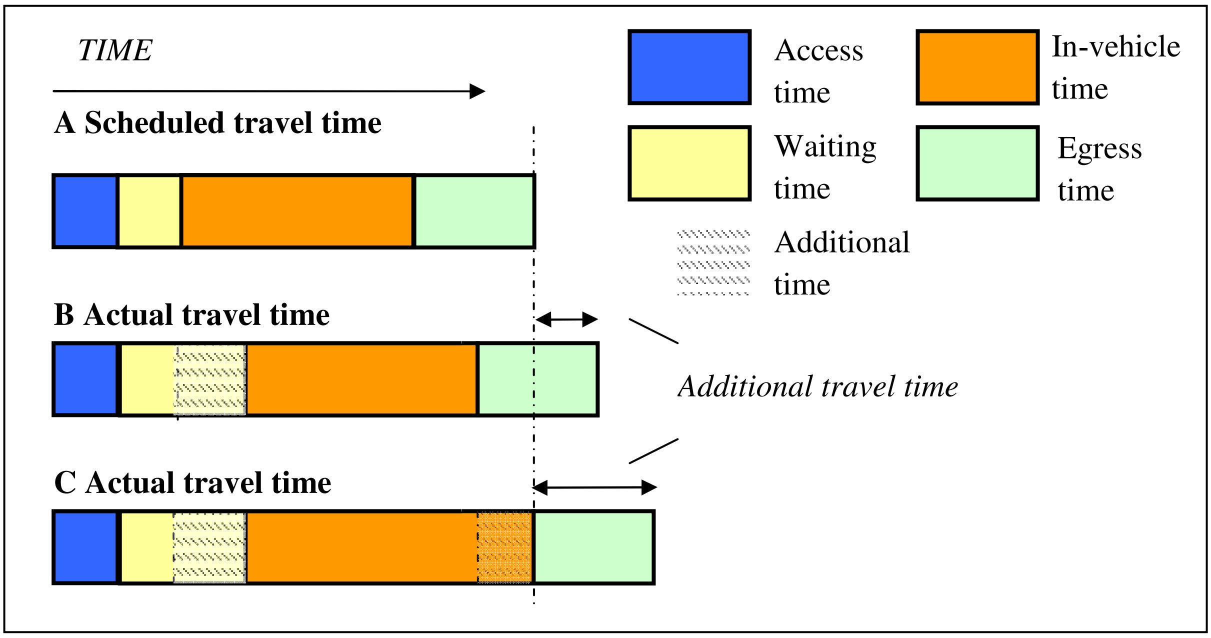


Figure 2.13: Scheduled travel time and additional travel time (illustrated for an example of an individual passenger journey)

Due to variability in actual vehicle trip times, and corresponding deviations of scheduled vehicle departure times and headways, waiting times at stops will increase on average per passenger (as explained in Section 2.4), leading to longer travel times than the planned travel time. An example of this extended travel time is shown by Figure 2.13 B. Access and egress times are not directly affected by variability in operations. In-vehicle time is affected by this variability as well, but this may result in an extension of travel time for some passengers (as shown by Figure 2.13 C) and a decrease for others. The net effect depends on the scheduled trip time (tight or loose schedule). So, the reference (the scheduled trip time) is of importance whether a delay will occur (or earliness). If vehicle trip time variability is fixed, no additional average in-vehicle time per passenger will arise. Only when instruments or design choices affect this distribution (e.g. vehicle holding), the additional in-vehicle time is relevant, as demonstrated in Section 2.4.2. After calculating all individual additional travel times, the final indicator, the average additional travel time per passenger may be calculated.

Using the average additional travel time per passenger as an unreliability impact indicator, the focus on quantifying service reliability shifts from the supply side (variability) to the impacts on the demand side. Using this indicator, increase or decrease of average total travel time due to changes in service variability may be properly expressed, enabling analyses of introducing new instruments and comparing several network designs and timetable proposals in for instance cost-benefit analyses. At this moment, proper expressing of passenger reliability benefits is hardly possible (Snelder and Tavasszy 2010). The additional travel time indicator also enables to deal properly with the trade-off between speed and service reliability (as also discussed by Furth and Muller 2009). Using supply oriented indicators would lead to a focus on the match between schedule and operations which might lead to suboptimal timetables. For instance, the timetable is the reference indicating the match and decreasing the speed in the timetable might improve this match. As schedules (and operations) might become slow, it is obvious that this will not necessarily lead to an increase in overall service quality.

Additional travel time is not commonly used in both theory and practice. Our international survey (see Section 3.2.3) showed that only London seems to use a comparable indicator: excess journey time (Frumin et al. 2009 and Uniman 2009). This indicator also expresses the additional travel time due to unreliability, but it compares actual and free-flow travel times instead of actual and scheduled travel times.

When calculating the additional travel time, two situations have to be distinguished, namely planned or random arrivals of passengers at the stop. If passengers arrive at random, exact departure times are not relevant anymore. In general, passengers do not use any schedule anymore. Sometimes, operators do not even provide departure times, but just show the headway during different time periods. Section 3.3.3 will elaborate on the values of short and long headways. This section continues describing additional travel time regarding these two types of arrival patterns. Main assumptions in the calculations are:

- The examined period is homogeneous concerning scheduled departure times, trip times and headways (for instance rush-hour on working days in a month);
- The passenger pattern on the line is assumed to be fixed;
- All passengers are able to board to the first arriving vehicle.

If passengers arrive at the stop at random, the additional travel time is calculated using the coefficient of variation (CoV) of the actual headways ($\tilde{H}_{l,j}^{act}$). A generic formulation for the expected waiting time per passenger is given by Equation 2.16 (Welding 1957, Osuna and Newell 1972, Heap and Thomas 1976), given the assumptions mentioned above.

$$E(\tilde{T}_{l,j}^{waiting}) = \frac{E(\tilde{H}_{l,j}^{act})}{2} * (1 + CoV^2(\tilde{H}_{l,j}^{act})) \tag{2.16}$$

where:

$\tilde{T}_{l,j}^{waiting}$ = *passenger waiting time at stop j on line l*

If the service is regular, the covariance equals zero and the average waiting time will be equal to half the headway. In the case of irregular service, the additional waiting time may then be calculated using Equation 2.17. It should be noted that the additional waiting time may be calculated in a similar way using the PRDM (Equation 2.15, Hakkesteegt and Muller 1981). Assuming no change in the actual vehicle trip times, the total average additional travel time per passenger will be equal to the average additional waiting time per passenger.

$$E(\tilde{T}_{l,j}^{Add,waiting}) = \frac{E(\tilde{H}_{l,j}^{act})}{2} * (CoV^2(\tilde{H}_{l,j}^{act})) \tag{2.17}$$

where:

$E(\tilde{T}_{l,j}^{Add,waiting})$ = *average additional waiting time per passenger due to unreliability of line l at stop j*

Based on the average additional travel time per passenger per stop of a line, we may calculate the average additional travel time per passenger on the complete line. To do this, the proportion or percentage of boarding passengers per stop is used ($\alpha_{l,j}$), as shown by Equation 2.18. Please note that using the proportion of passengers makes the indicator independent of the actual number of passengers.

$$E(\tilde{T}_{l}^{Add,waiting}) = \sum_j (\alpha_{l,j} * E(\tilde{T}_{l,j}^{Add,waiting})) \qquad with \quad \sum_j \alpha_{l,j} = 1 \tag{2.18}$$

where:

$\alpha_{l,j}$ = *proportion of passengers of line l boarding at stop j*

If passengers plan their arrival at the stop according to the schedule, another method of calculating additional travel time is necessary. Equations 2.19-2.21 show this method. Passengers are assumed to arrive randomly between the scheduled departure time minus τ_{early} and plus τ_{late} and it is assumed that in that case they do not experience any additional waiting time if the vehicle departs within this time window. Chapter 3 presents empirical research of these values. It is important to note that there is a difference between driving ahead of schedule and driving late. Driving ahead (i.e. departing before the scheduled departure time minus τ_{early}) leads to a waiting time equal to the headway (H_l^{sched}*; assuming punctual* departure of the successive vehicle). Especially in the case of low frequencies, this leads to a substantial increase in passenger waiting time. Driving late creates an additional waiting time equal to the delay ($\tilde{d}_{l,i,j}^{departure}$).

Just as before, the additional waiting time is first calculated per stop (Equations 2.19 and 2.20) and next it is computed as a weighted average for all passengers on the line (Equation 2.21), depending on the number of boardings per stops.

$$\begin{cases} \tilde{T}_{l,i,j}^{Add,waiting} = H_l^{sched} & if \quad \tilde{d}_{l,i,j}^{departure} \leq -\tau_{early} \\ \tilde{T}_{l,i,j}^{Add,waiting} = 0 & if \quad -\tau_{early} < \tilde{d}_{l,i,j}^{departure} < \tau_{late} \\ \tilde{T}_{l,i,j}^{Add,waiting} = \tilde{d}_{l,i,j}^{departure} & if \quad \tilde{d}_{l,i,j}^{departure} \geq \tau_{late} \end{cases} \tag{2.19}$$

$$E(\tilde{T}_{l,j}^{Add,waiting}) = \frac{\sum_i E(\tilde{T}_{l,i,j}^{Add,waiting})}{n_{l,i}} \tag{2.20}$$

$$E(\tilde{T}_{l}^{Add,waiting}) = \sum_j (\alpha_{l,j} * E(\tilde{T}_{l,j}^{Add,waiting})) \qquad with \quad \sum_j \alpha_{l,j} = 1 \tag{2.21}$$

where:

$E(\tilde{T}_{l,i,j}^{Add,waiting})$ = *average additional waiting time per passenger due to unreliability of vehicle i of line l at stop j*
H_l^{sched} = *scheduled headway at line l*
$\tilde{d}_{l,i,j}^{departure}$ = *departure deviation of vehicle i at stop j on line l*
τ_{early} = *lower bound of arrival bandwidth of passengers at departure stop*
τ_{late} = *upper bound of arrival bandwidth of passengers at departure stop*
$n_{l,i}$ = *number of trips on line l*

2.5.3.2 Reliability buffer time

The average additional travel time per passenger is a proper indicator for the impacts of service variability on passengers. However, it only addresses the average extension of travel time and does not express the variability itself, which is a decrease in quality as well. To incorporate this effect, research of Furth and Muller (2006) and Uniman (2009) is used, see also Section 2.4.3. They state that besides the average travel time, the 95th percentile value of travel time should be taken into account, as passengers have to budget extra time for the variability in actual travel time. Intuitively stated; they experience this occasionally large travel time about, let's say once per month and if they do not want to be late at their destination, they have to account for this extra travel time in their planning, or, formulated otherwise, include it in their travel time budget. This additional time is called reliability buffer time (RBT) and may be used to express T^{budget}, as shown by Equation 2.11.

Ideally, the RBT should be calculated for the whole journey. However, based on the data available for operators and authorities, it is possible to determine the RBT only for the 2 main components of a journey as discussed in Section 2.4.3, namely waiting time and in-vehicle time. The weighted sum of these two RBT-indicators might be used as an approximation of the actual RBT used by passengers. We consider the RBT as a time component in total travel time for passengers, to take the variability explicitly into account when comparing different instruments. We do not consider RBT affecting the passenger departure behaviour at home. More research is required on this topic.

Above we showed how to calculate the waiting times of passengers at their departure stop. Using this data, Equation 2.22 enables calculating the RBT due to variability in waiting times and Equation 2.23 is used to calculate the average RBT per passenger on the line, where the relative number of boardings per stop ($\alpha_{l,j}$) is taken into account to achieve a weighted total. Similarly, Equations 2.24 and 2.25 show the calculation of reliability buffer time with regard to in-vehicle times, now using the proportion of through passengers ($\beta_{l,j}$).

$$RBT_{l,j}^{waiting} = T_{l,j}^{waiting,95\%} - E(\tilde{T}_{l,j}^{waiting}) \qquad (2.22)$$

$$RBT_{l}^{waiting} = \sum_{j=1}^{n_{l,j}} (\alpha_{l,j} * RBT_{l,j}^{waiting}) \qquad with \qquad \sum_j \alpha_{l,j} = 1 \qquad (2.23)$$

$$RBT_{l,j}^{in-vehicle} = T_{l,j}^{in-vehicle,95\%} - E(\tilde{T}_{l,j}^{in-vehicle}) \qquad (2.24)$$

$$RBT_l^{in-vehicle} = \sum_{j=1}^{n_{l,j-1}} (\beta_{l,j} * RBT_{l,j}^{in-vehicle}) \qquad with \quad \sum_j \beta_{l,j} = 1 \qquad (2.25)$$

where:

$RBT_{l,j}^{waiting}$ = *Reliability Buffer Time at stop j on line l due to variability in waiting time*

$T_{l,j}^{waiting,95\%}$ = *95th percentile value of waiting time due to vehicle i at stop j on line l*

$\alpha_{l,j}$ = *proportion of passengers of line l boarding at stop j*

$T_{l,j}^{in-vehicle,95\%}$ = *95th percentile value of in-vehicle time due to vehicle i between stop j and j+1 on line l*

$RBT_{l,j}^{in-vehicle}$ = *Reliability Buffer Time at stop j on line l due to variability in in-vehicle time*

$\beta_{l,j}$ = *proportion of passengers of line l travelling between stop j and j+1*

2.5.3.3 Level of crowding

In addition to the extension of travel time and the reliability buffer time, variability may also result in a loss of comfort due to overcrowding (Fernandez 2010, Wardman 2010). It is important to note that this topic is mainly relevant in short-headway services. In that scenario, ridership is high and small deviations already lead to large deviations of vehicle occupancy. Overcrowding occurs due to unequal headways since they result in uneven loads of vehicles. In the case of headway deviations, overcrowding always occurs parallel to “undercrowding” that is when vehicles are (much) less occupied than planned. Similar to the calculation of waiting time, only a few passengers benefit of this, while most passengers experience overcrowding. Given the correlation between headways and overcrowding, indicators of headway deviations are good indicators for assessing the level of overcrowding as well (e.g. PRDM, as calculated by Equation 2.15).

2.5.4 Conclusions

In this section we stated that indicators regularly used in practice do not indicate the impacts on passengers in a proper way. The focus is mainly on vehicles instead of passengers. For instance, the passenger pattern along the line is not considered and the different impacts of early and late vehicles are often neglected. This section introduced a new indicator, namely additional travel time. This is the additional travel time due to unreliable services that mainly consists of additional waiting time. Next to this indicator, the reliability buffer time (RBT) is presented, as introduced by Furth and Muller (2006). This indicator enables to demonstrate the impact of travel time variability. Figure 2.14 illustrates the average additional travel time per passenger (T^{add}) and the variability of actual travel time relative to the scheduled travel time. RBT is presented in this figure as well. It is important to note that $T^{journey,\ sched}$ consists of the scheduled waiting time and the scheduled in-vehicle time (see Equation 2.7). The latter is directly related to the scheduled vehicle trip time and is thus controllable being a function of schedule design (e.g. tight or loose schedule). As stated in this section and in Section 2.4.2, we will focus on the average passenger in-vehicle time in our calculations and only account for additional in-vehicle time if the variability is adjusted during the operations (e.g. by vehicle holding).

AVV (2004) presented a figure concerning travel time extension and variability for car traffic. Although it looks very similar, the main difference between public transport and car traffic is the existence of a timetable, introducing two relevant distributions in the transport process. Both the variability of the supply side (vehicle) and demand side (passenger) are of interest (shown by Figure 2.9). In addition, the time in the schedule is controllable since it is the result of the schedule design process enabling direct influence of schedulers on the level of reliability.

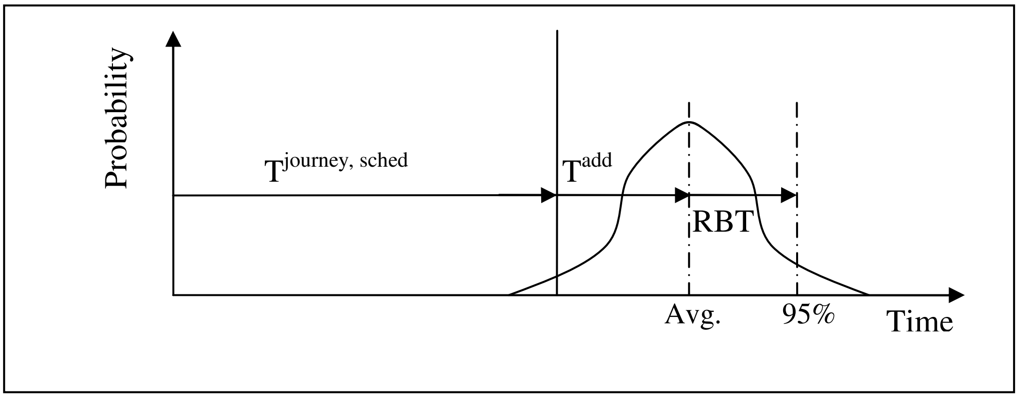


Figure 2.14: Scheduled passenger time ($T^{journey, sched}$), average additional travel time per passenger (T^{add}) and reliability buffer time (RBT).

In addition to travel time impacts we also discussed crowding in this section. We showed that the level of crowding may be indicated by the level of headway deviations expressed as PRDM (Equation 2.15). These indicators will be used in our research described in the following section and next chapters, with a special focus on our indicator being the average additional travel time per passenger. We will use them to express service reliability effects on passengers in the case of a planning process with or without applying planning instruments.

2.6 Improving service reliability

2.6.1 Introduction

When improving service reliability, we should maximize the match between operations and planning as shown by Figure 2.15. Given the production process analogy presented in Section 2.2, control is a suitable means to achieve this. In this section various control types are analyzed with special attention for options to improve service reliability already in the planning process. This analysis leads to the research framework applied in this thesis.

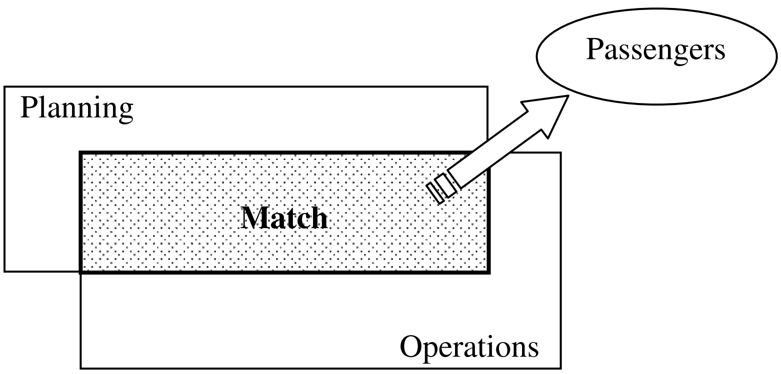


Figure 2.15: (Mis)match between operations and planning affects passengers

2.6.2 General control methods

In Section 2.2, a general description of production processes was given. It was shown that variability and unreliability may arise due to both internal and external factors. To deal with this variability, controlling is a method which may reduce or remove the variability and thus the unreliability. In Van den Top (2010) a description is given of systems and reliability using cybernetics to describe reliability of systems. Cybernetics is the general science of controlling systems. It focuses on functions and information flows rather than on what the system consists of and it may therefore be applied to a broad diversity of systems, such as business, technical and biological systems (Heylighen and Joslyn 2001). The cybernetic principles are compatible with those of process control theory, of which the objective is "to maximize production while maintaining a desired level of product quality and safety and making the process more economical" (Hahn and Edgar 2002). Cybernetics makes use of basic notions, as introduced below. They are illustrated in Figures 2.16-2.18.

- *The desired output;*
  This is the required result of the process.
- *Disturbances;*
  These are influences apart from the input and from outside the process that affect the process and output.
- *The regulator;*
  This is a control system or instrument that may adjust the process.
- *The buffer.*
  A buffer is an addition of resources (for instance time, crew or production measures) enabling producing the required output even when disturbances occur.

In Figures 2.16-2.18, the main control methods of a system are illustrated (Ashby 1956). The goal of the control is to achieve the desired values of the output under disturbance(s). Three types of control are shown:

- *Using a buffer*
  A buffer is often determined during the design of a system. The buffer absorbs (a number of) disturbances. This method is passive, since no adjustments may be made after the design and the buffer is available independent of the actual disturbances.
- *Feedback*
  This is a reactive mode. The regulator measures how much the output deviates from its desired value and then acts afterwards. Instruments affecting the process and thereby reducing the impacts of disturbances are applied.
- *Feedforward*
  This mode is anticipatory; the regulator predicts the disturbances and then assesses the impacts on the output. Measures are chosen that influence the process such that no or a minimized effect of the expected disturbances on the output will be noticeable.

All three types have their own specific advantages and disadvantages and in practice, they are used in combination as well.

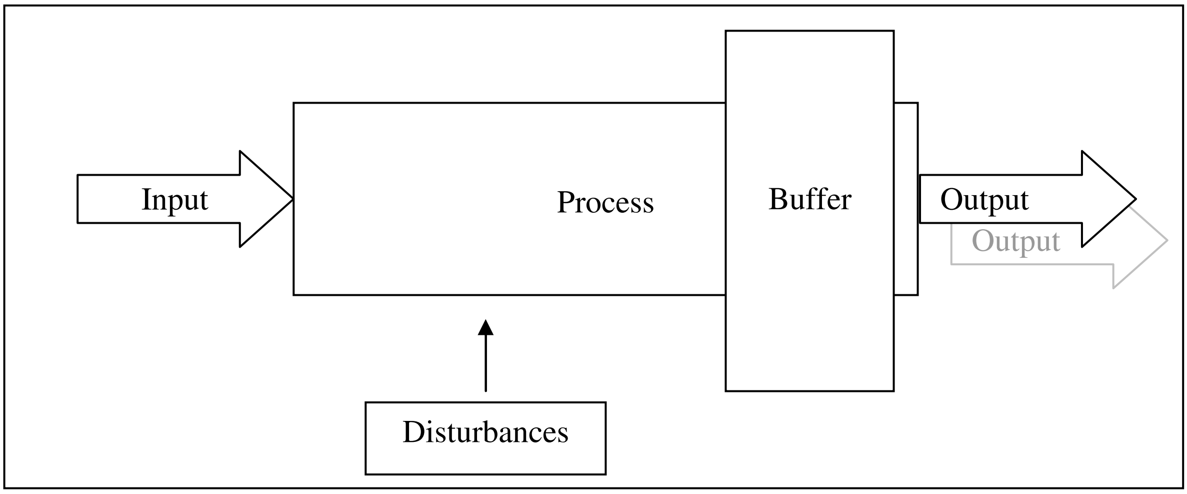


Figure 2.16: Control methods: buffer

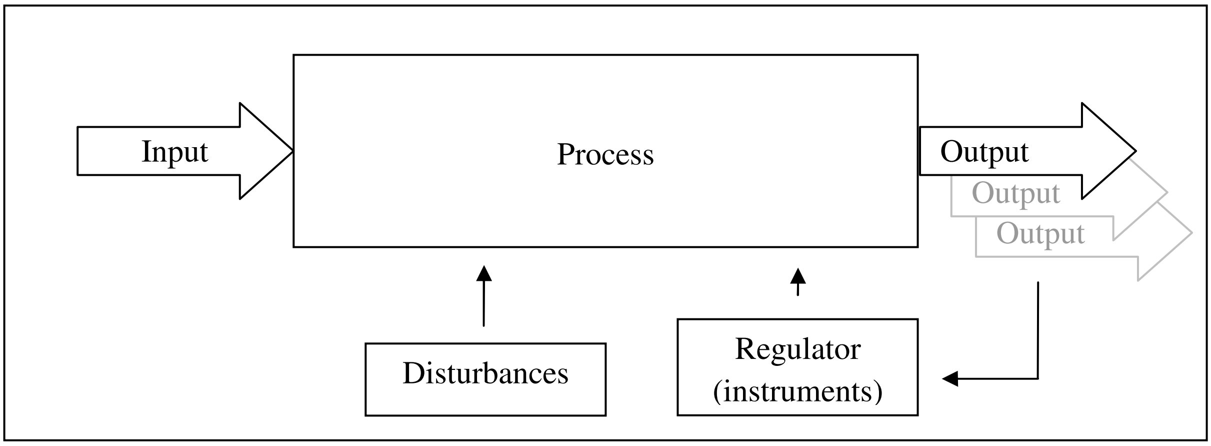


Figure 2.17: Control methods: feedback

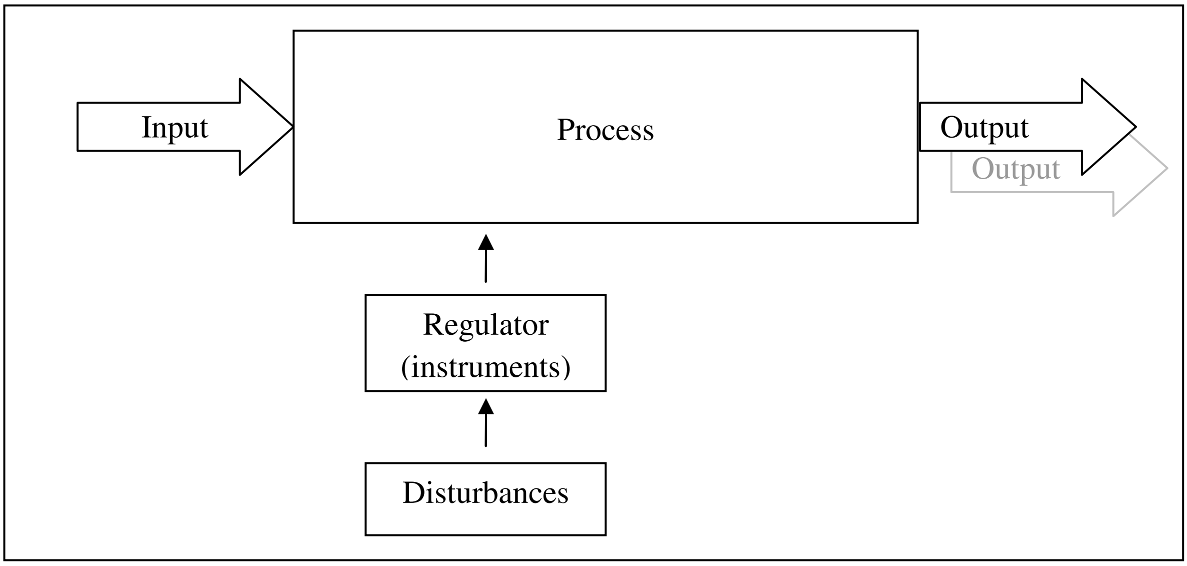


Figure 2.18: Control methods: feedforward

The control types mentioned above are applicable to public transport as well. As mentioned in the beginning of this chapter, public transport consists of two processes: operation and planning (the latter consists of network and timetable design). Regarding the improvement of reliability most attention is paid to the operations nowadays. Feedback is used to check the actual performance and to adjust the operations accordingly. Feedforward is applied as well, using historical experiences enabling predictions of the output and if necessary adjustment of the process. Interestingly, the input of the operations process, that is the network and the timetable itself, is rarely taken into account, when considering the level of reliability. It appears that the network and timetable are used as a fixed input. Question thus is to what extent it is possible to include instruments in the planning process which would improve service reliability as well. This is exactly the topic of this thesis. In our research we will investigate this input, i.e. the network and schedule, and look for solutions to improve the level of service reliability already during the design stages. A feedforward loop is applied, as shown in Figure 2.19. The process of design is adjusted (taking operational disturbances explicitly into consideration), resulting in an adjusted input for the operational process. Note that compared with Figure 2.17 it is not possible to use actual disturbances in the planning stages. Therefore a prediction of disturbances is used. This will reduce the impacts of external factors on the output of the operational process (without affecting the external factors themselves) and will often simplify the operation process as well. Together with instruments applied at the operational level this will enable a higher level of service reliability than we have today. Chapter 4 will elaborate on instruments on all levels of public transport planning, representing the regulators of both strategic and tactical level. This analysis will yield promising instruments for the planning stage, which will be analyzed in detail in Chapters 5 and 6.

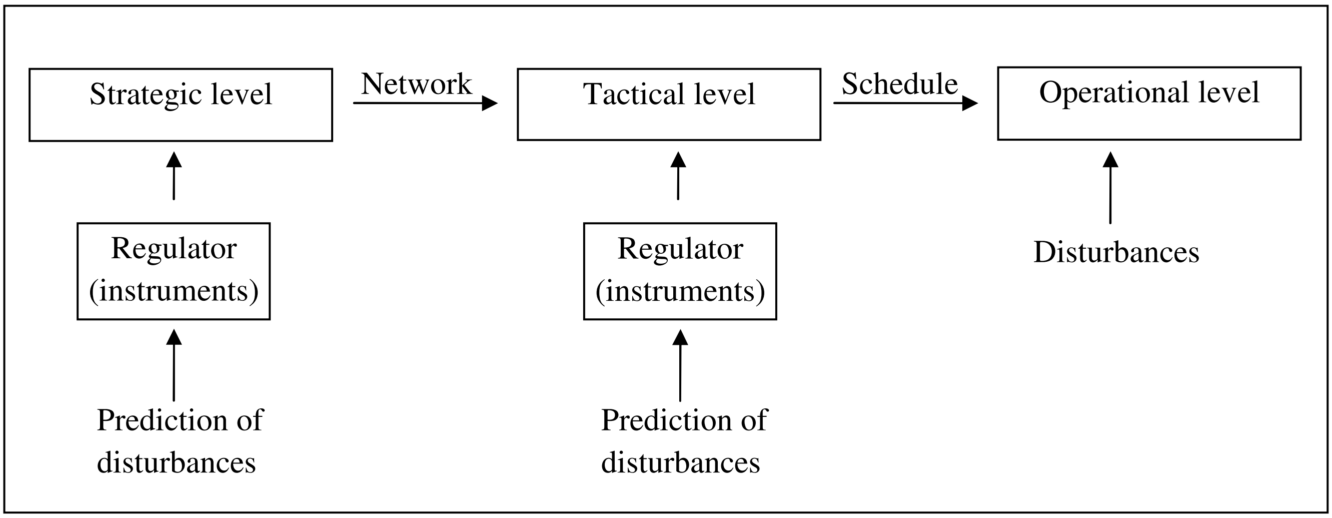


Figure 2.19 Feedforward loop in PT planning and operation

2.6.3 Research framework

In this chapter, the interaction of the demand and supply side of public transport has been demonstrated, next to the impacts of this on passengers. Understanding this interaction is necessary to improve the level of service reliability. To support our research concerning enhanced service reliability, we apply the framework shown in Figure 2.20. It consists of three main blocks:

- Traditional indicators or supply indicators;
- Passenger related indicators;
- Impacts of reliability on passenger behaviour.

The traditional indicators for punctuality and regularity focus on variability of supply in relation to the schedule, with respect to departure times and headways respectively. These indicators are dominantly used in practice; however, they do not quantify the actual impacts on passengers. Therefore, these indicators are used in this thesis for illustrative purposes (Chapter 3). In addition, service variability is used as a base for calculating the passenger oriented indicators.

By including the passenger arrival pattern and the demand pattern along the line new indicators may be defined which do quantify important impacts of service reliability on passengers. These are additional travel time and reliability buffer time which illustrate the extension and variability of travel times due to service variability. A third impact on passengers, the probability of having a seat in the vehicle, may be accounted for by indicators related to regularity. Our new indicator, the additional travel time per passenger will be used in this thesis to demonstrate the importance of improving service reliability (Chapter 3) and to assess various instruments at the strategic and tactical level to improve service reliability (Chapters 5 and 6). The reliability buffer time will be used, although to a lesser extent, to illustrate the effects of travel time variability.

The third block relates to the actual impacts on traveller behaviour consisting of all possible kinds of changes in travel choice making. Passengers make choices based on the impacts on their travel time indicated by the second block (i.e. optimizing their nuts function). These choices affect the way the network is used as well as the number of passengers using the public transport system. The impacts of service reliability improving instruments on these choices will be discussed in a quantitative way in the synthesis of the assessment of the individual instruments (Chapter 7).

The analysis of levels of current service variability and reliability as well as the assessment of promising instruments for improving service reliability at the strategic and tactical level will be performed from the perspective of an operator who is explicitly considering the passenger interests. The latter implies that passenger related indicators for service reliability are used. The consequence of the operator’s perspective is that the unit of analysis is the public transport line, branch of lines or network. In general, operators will not have detailed information on the passengers travel pattern in space and time; however, they do have detailed data on boardings, alightings and vehicle occupancy. Thus, the description of the passenger journey is limited to waiting time and in-vehicle time only. In our analysis the expected total travel time will thus be split up in five components, as illustrated by Equation 2.26, showing the perceived passenger travel time from stop to stop. In this equation, the relative weights of the travel time components are also incorporated. Since we mainly focus on the additional time and variability effects in our research, the weighting of the scheduled components is not indicated.

$$E(\tilde{T}_{l,j-k}^{journey,perc}) = E(\tilde{T}_{l,j-k}^{journey,sched}) + \theta_{waiting} * E(\tilde{T}_{l,j}^{add,waiting}) + \theta_{in-vehicle} * E(\tilde{T}_{l,j-k}^{add,in-vehicle}) + \theta_{waiting,RBT} * RBT_{l,j}^{waiting} + \theta_{in-vehicle,RBT} * RBT_{l,j-k}^{in-vehicle} \quad (2.26)$$

where:

$\widetilde{T}_{l,j-k}^{journey,perc}$ = *perceived passenger travel time from stop j to stop k on line l*

$\theta_{waiting}$ = *relative weight of additional waiting time*

$\theta_{in-vehicle}$ = *relative weight of additional in-vehicle time*

$\theta_{waiting,RBT}$ = *relative weight of RBT of waiting time*

$\theta_{in-vehicle,RBT}$ = *relative weight of RBT of in-vehicle time*

This equation is our full description of the travel time to be used in subsequent chapters. It should be noted that weights are not always being used. The total travel time is thus expressed in plain minutes, enabling a comparison with timetables and regular travel times. In the analysis of the various instruments, a relevant selection of components will be made for clarity sake, e.g. if the measure primarily focuses on reducing additional waiting time while the other components will not be affected, the assessment criterion will be limited to additional waiting time only.

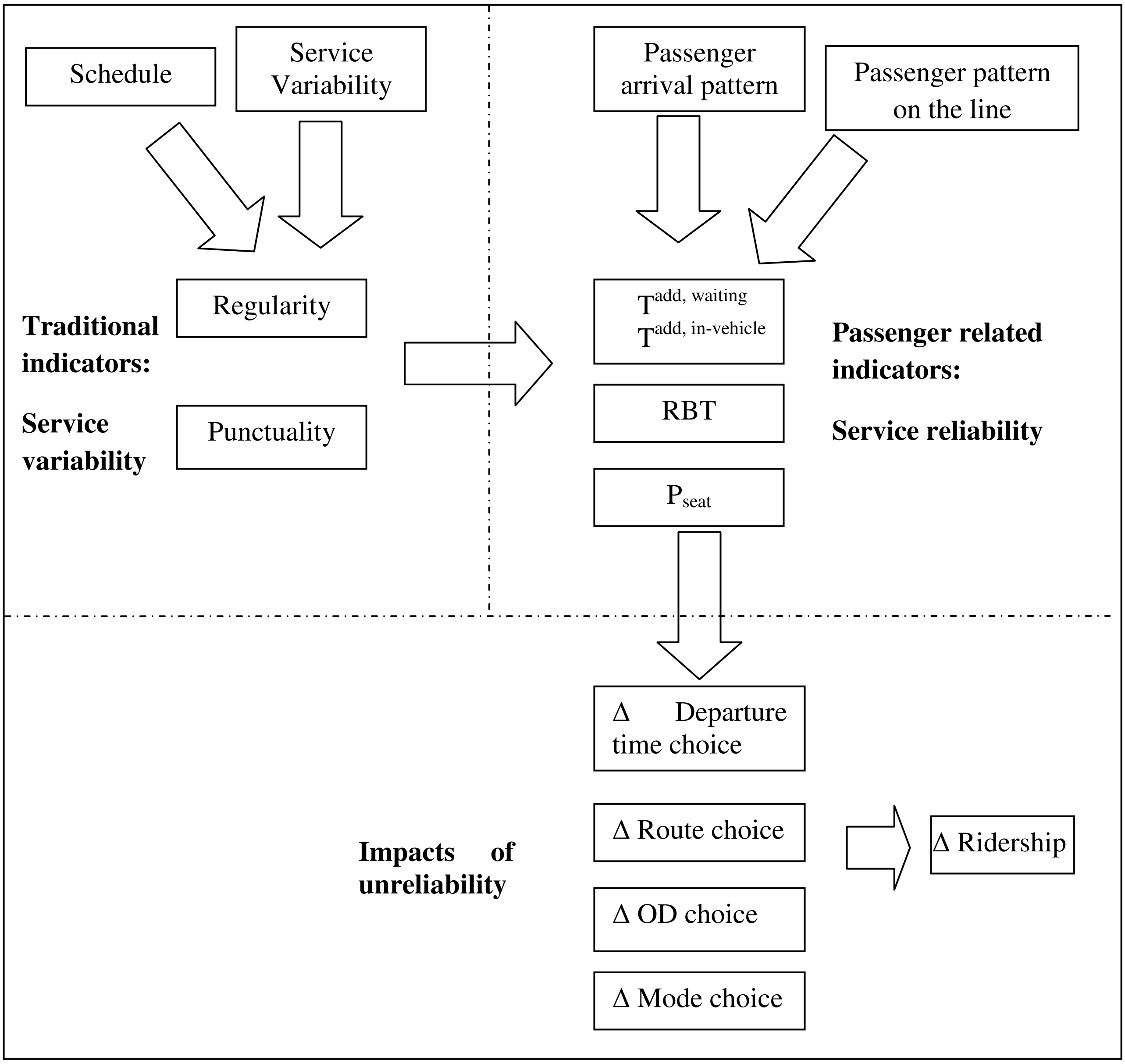


Figure 2.20: Research framework for service variability and service reliability in urban public transport

2.7 Summary and conclusions

Service reliability is an important quality aspect of public transport. In this section, we provided a theoretical view on service reliability. To gain insights into methods to improve service reliability, we presented the mechanisms between service variability and reliability in this section, with special attention to passenger effects.

Studying output variability is the start of an analysis of reliability of public transport. Variability appears if the output of a process does not meet a constant value. Variability leads to decreased reliability. We defined service reliability as the certainty of service aspects compared to the schedule (such as travel time (including waiting), arrival time and seat availability) as perceived by the user. In this chapter, an overview is given of different types of reliability: e.g. travel time reliability and connectivity reliability. The focus of our research is on travel time reliability, or put otherwise, the match between the schedule and the operations. We focus especially on its impacts for passengers, since passengers take service reliability into account in their choice process, in terms of mode, departure time and route choice.

Although service reliability is a main factor in the passenger experience of provided service, the quantification of this phenomenon is still very supply side focused. The main indicators used in assessing the level of service reliability are punctuality and regularity. In order to gain more insights into the impacts on passengers, we introduced a new indicator, namely additional travel time. This indicator demonstrates the extra travel time, compared to the travel time according to the schedule, which passengers on average experience in practice when making a journey. The main factor of this extra travel time is the waiting time at the departure stop. Due to the variability of the service provided, average waiting time per passenger will increase.

In addition to the extension of average travel time per passenger, unreliability also leads to unsecure arrival times. Previous research introduced the reliability buffer time (RBT) to deal with this issue. Passengers budget additional time for their journey to deal with unsecure arrival times. The larger the variety in travel times, the more buffer time is added when planning the journey. The last presented impact of unreliability on passengers is the probability of overcrowding. In short-headway services, headway deviations lead to an uneven distribution of passengers over the vehicles which may result in overcrowding. Since overcrowding thus is correlated with regularity, we will use the presented indicator for headway deviations (PRDM, see Equation 2.15) for indicating the level of crowding in the remainder of this thesis.

To improve service reliability, principles from control in production processes are adopted. We presented the principle of feedforward, which will be used in our research. By adjusting the input of the operational process of public transport (i.e. the network and schedule), negative impacts of external factors may be reduced, thus improving the level of service reliability. In Chapter 5 and 6 we will present and assess instruments showing these adjustments of network and timetable using the indicators for additional travel time and the reliability buffer time.

In the next chapter we will present a practical perspective on service reliability. Our international survey is presented showing how operators and authorities deal with service reliability nowadays. Extensive empirical data is provided to illustrate the mechanisms described in this chapter and besides, this quantitative analysis clearly shows the size of the actual effects with regard to unreliability. In Chapter 4 we will analyze causes of service variability and we will explore possibilities of improving the level of service reliability, focusing on the planning stages.

3. Service reliability in practical perspective

3.1 Introduction

The previous chapter presented the mechanisms of service variability and reliability, with a special and new focus on the impacts on passengers. This chapter provides a practical and quantitative perspective of service reliability. Questions to be answered are: what is the magnitude of service variability and reliability today? What are the important components? What are possible effects of using the newly proposed indicators and are there patterns that might be of interest if one wants to improve service reliability?

We will quantify service variability and reliability using two empirical data sources. We use detailed data of the operations of the public transport system in The Hague to understand patterns and relations of service variability and reliability. The importance of improving service reliability is shown by the actual level of service reliability and the impacts on passengers in The Hague using our new indicator, additional travel time. Second, an international survey is performed to gain insights into the methods of quantifying and dealing with service reliability in several cities in the world.

Both data sources play an important role in the remainder of this thesis as well, as our research is data-driven. Empirical data is used to analyze service variability and reliability. Through the use of the extensive data sets of the public transport system of The Hague, combined with theory, new insights are developed. These insights concern the actual impacts of service reliability on passengers and improved methods to quantify service reliability. For the calculation of the additional travel time, an empirical analysis of the passenger arrival process at the stop is included. This chapter demonstrates that the new indicator, additional travel time, yields a better and more understandable representation of the impacts of service reliability on travellers than indicators that are currently used in practice.

The set up of this chapter is as follows. First, in Section 3.2 a brief description is given of The Hague and its public transport network, consisting of bus, tram and light rail, followed by a summary of the main characteristics of the international survey on ways of dealing with service reliability of urban public transport in several cities in the world. In Section 3.3, the variability of vehicle trip time and its elements, as introduced in Chapter 2, is analyzed in detail using actual data of The Hague. Results of our survey on passenger arrival patterns are given, enabling a proper analysis of the impacts of service variability on passengers. Finally, we present in Section 3.3 an analysis of actual service reliability, using both supply-focused and demand-focused indicators, as were introduced in Chapter 2. We will demonstrate different results of supply-side and demand-side indicators. In Section 3.3 we also present several methods applied in practice to quantify service variability. After this chapter, Chapter 4 will continue on possibilities for improving service reliability, combining the theoretical perspective of Chapter 2 and the practical analysis of this chapter.

3.2 Empirical data

3.2.1 Introduction

In our research, we combine both theory and practice to address service reliability properly. Empirical data of public transport is used to gain insights into mechanisms and design choices concerning service reliability and in addition, empirical data is used to test strategic and tactical instruments. In this section, the city and public transport of The Hague is introduced. Detailed data of this public transport system is used in our research. The international survey that we performed is presented as well. This survey has yielded insights into how other cities deal with service reliability.

3.2.2 Case study The Hague

According to population numbers, The Hague is ranked the third city of the Netherlands, with a population of approximately 500,000 inhabitants. The region, called Haaglanden, has a total population of almost 1 million people. The urban public transport system in The Hague and in parts of the Haaglanden Region is operated by HTM Company. Table 3.1 shows the main transport characteristics of HTM Company for the year 2008 (HTM 2009).

Table 3.1: Main characteristics HTM Company for the year 2008 (source: HTM 2009)

Total number of passengers	159,800,000
Total number of passenger kilometres	480,900,000
Revenues	€ 255,300,000
Fleet size - Number of trams - Number of light rail vehicles - Number of buses	 157 54 142
Number of employees	2100

The public transport system of HTM consists of three network types: light rail, tram and bus. Figure 3.1 shows the combined public transport service network of The Hague while Table 3.2 shows the main characteristics of these systems (HTM 2009).

Table 3.2 Characteristics of the urban public transport of The Hague in 2008 (source: HTM 2009)

	Number of lines	Total line length[1]	Headway, peak hour	Average operational speed
Light Rail	2	60 km	5 min	29 km/h
Tram	10	130 km	5-10 min	20 km/h
Bus	10	140 km	7-15 min	19 km/h

[1] in one direction

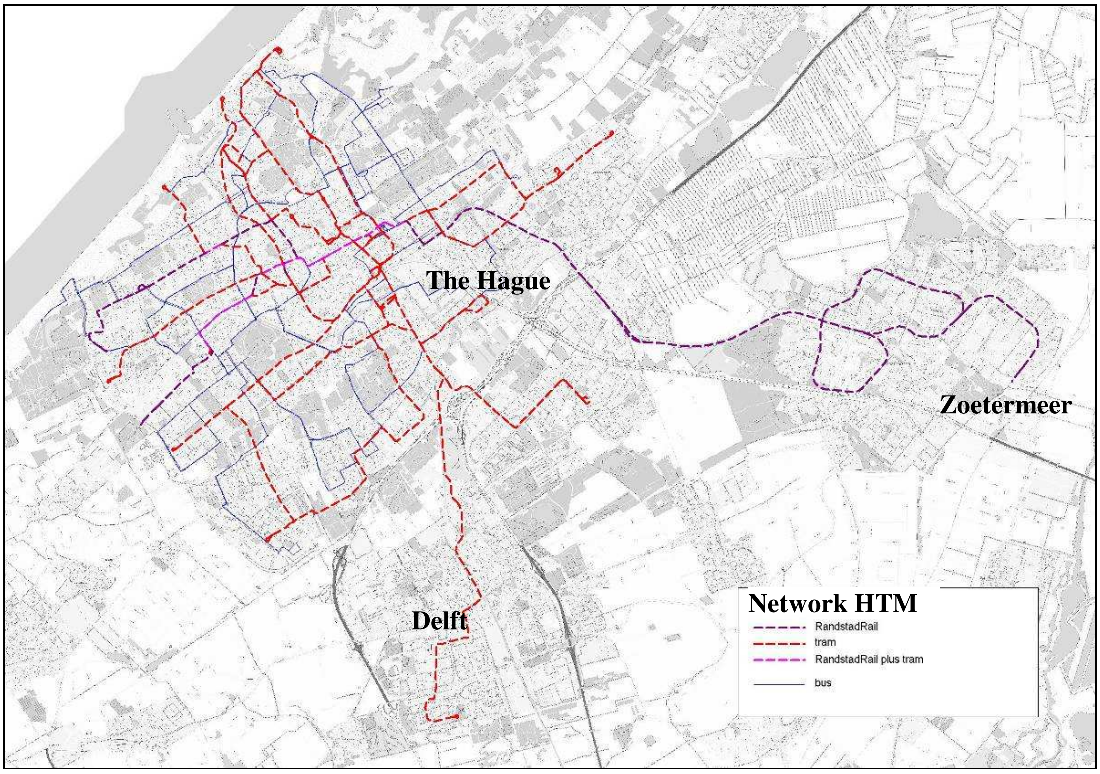


Figure 3.1: The public transport network of The Hague in 2009

Light rail

The light rail network in the The Hague area, called RandstadRail, consists of two lines (lines 3 and 4), partly operating on the same route. The light rail service opened in 2007 and connects the suburb of Zoetermeer with The Hague. The line consists of a former heavy rail that is connected to 2 former tram lines in The Hague. New vehicles have been introduced, average stopping distances were increased and frequency was improved as well.

Tram

The second layer in the public transport of The Hague is the tram system. Ten tram lines, of which 2 lines operate only during peak hours, provide mainly diametric services. The tram lines have a large share of exclusive lanes and at many intersections priority is applied. In 2008, tram and light rail facilitated 366 million passenger kilometres (HTM 2009).

Bus

The third layer is the bus network. The bus services mainly complement the tram and light rail network, ensuring accessibility of all main locations in the Hague area. Most lines are less busy than the rail lines, but some exceptions exist. 167 million passenger kilometres were facilitated in 2008 (HTM 2009).

Our research is using data of the urban public transport company of The Hague, as described in the previous section. To generate and process the required service data, the vehicle trip monitoring system Tritapt was used (Muller and Knoppers 2005). Appendix B shows the characteristics of all mentioned lines. The data used corresponds to lines and periods in which only structural delays appeared and the infrastructure was fully available, enabling research on recurrent delays.

3.2.3 An international survey on public transport service reliability

3.2.3.1 Introduction

In Van Oort (2009), the results of an international survey of service reliability we performed are presented. The objective of the international survey is to learn about reliability and planning topics in other cities in several countries. The survey demonstrates how public transport operators quantify service reliability in practice and provides insights into design guidelines that might affect service reliability too. This section focuses on the survey and the quantification of service reliability. The design guidelines will be discussed in Chapters 5 and 6.

The survey consisted of a questionnaire, which is shown in Appendix C. This questionnaire was sent all over the world and almost 30 authorities and operators responded. Table 3.3 shows the respondents and in Figure 3.2 they are shown on the map.

Table 3.3: Participating cities and systems in international reliability survey (Source: Van Oort 2009)

City	PT Type	City	PT Type	City	PT Type
Amsterdam	Metro, tram, bus	Gothenburg	Tram	Rouen	Tram, bus
Barcelona	Metro, bus	Halle	Tram, bus	Salt Lake City	Light Rail
Berlin	S-Bahn, tram	Hong Kong	Light rail	Stockholm	Metro, bus
Brussels	Tram	Lolland	Bus	Stuttgart	Rail
Chicago	Metro, bus	London	Tram, bus	Santa Cruz de Tenerife	Tram
The Hague	Light rail, tram, bus	Milano	Bus, tram	Vienna	Metro, tram, bus
Dresden	S-Bahn, tram	Minneapolis	Bus	Zurich	S-Bahn
Dublin	Tram	Rotterdam	Metro, tram, bus		

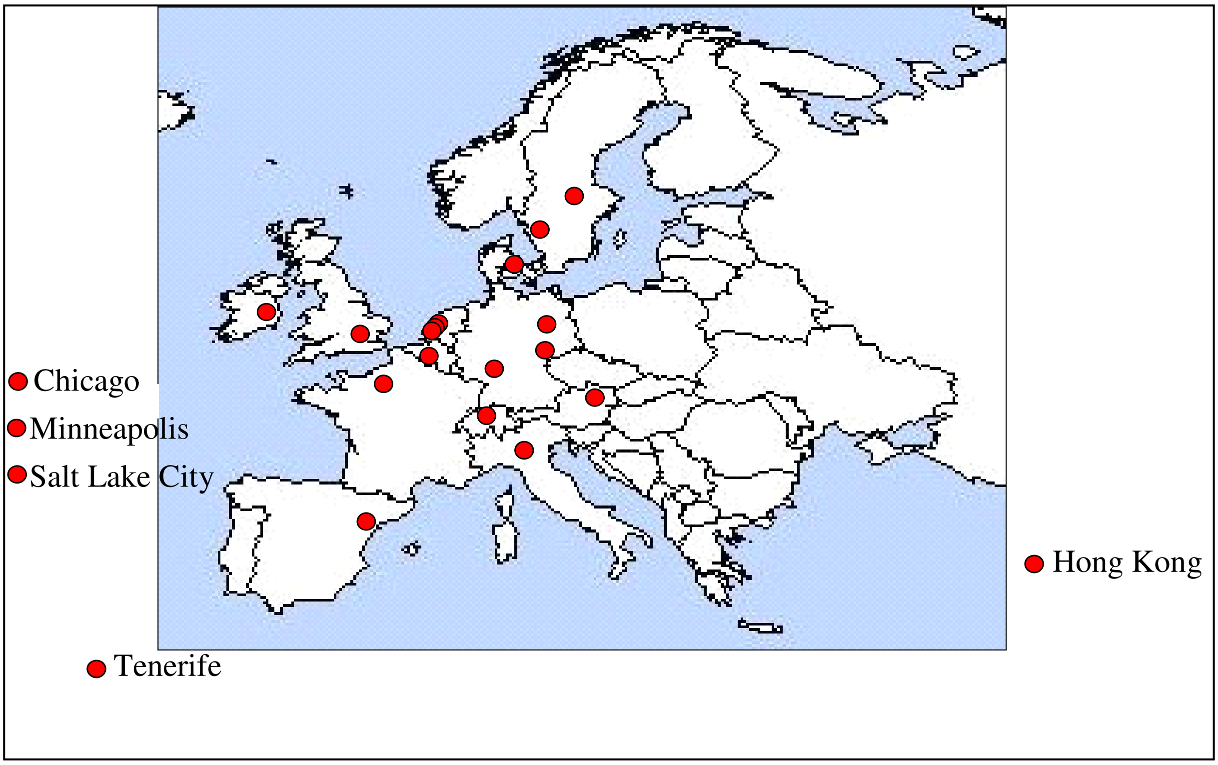


Figure 3.2: Participating cities in international reliability survey (Source: Van Oort 2009)

3.2.3.2 Service reliability measurement in the sample

Section 2.5 dealt with quantifying service reliability. More than one method/indicator is used in practice to present the level of service reliability. Both in theory and practice, analysts tend to focus on supply-side indicators which do not illustrate the actual service reliability, but rather show the output variability of the system. Most applied measures focus on departure time deviations. Mostly, no differentiation between early and late vehicles is made. The departure time deviations may be calculated per line or network, including all or only a few stops.

Another way to express schedule adherence is the percentage of vehicles' schedule deviations within a certain bandwidth. Section 2.2 already introduced excess variability, the variability which is larger than the variability which is acceptable. Equation 2.13 in Section 2.5 showed how to calculate this indicator (in which δ^{min} and δ^{max} represent the lower and upper bound respectively). This method is very common in heavy railways. The Dutch Railways, for instance, used to periodically present the number of trains departed not later than 3 minutes from 32 main stations in the Netherlands until 2010 (i.e. δ^{max} = 3 min.). Most heavy railway companies in Europe use 5 minutes as a maximum (Landex and Kaas 2009, Schittenhelm and Landex 2009). In the U.S., even 30 minutes delay is considered being on time (Bush 2007). Among the urban public transport industry, sometimes the bandwidth has a lower boundary value as well (i.e. δ^{min}), which means that driving ahead of schedule is considered explicitly. Vehicles are for example considered punctual when they depart between 0 and +5 minutes compared to the schedule (Nakanishi 1997). Besides different indicators (average punctuality, bandwidth punctuality and regularity) the boundaries of the bandwidth are not uniform (see Figure 3.3). Of the participating cities, 74% use a bandwidth to quantify and analyze schedule adherence, while 21% use the average punctuality. The results of the survey showed that only London has another way of measuring the difference between schedule and operations, being excess journey time (Van Oort 2009).

If the bandwidth is used, different boundary values are applied. Figure 3.3 shows the different values used where every line corresponds to the boundaries of one city or system. It is shown that three cities do not even use a lower boundary value (indicated as -5 minutes). The maximum boundary value ranges from +1 to +6 minutes. These differences in bandwidth obviously have a large impact on the percentage of on-time vehicles. Setting the requirement for excess variability thus determines the quality of operations. If a broad bandwidth is set, excess variability will be small for instance.

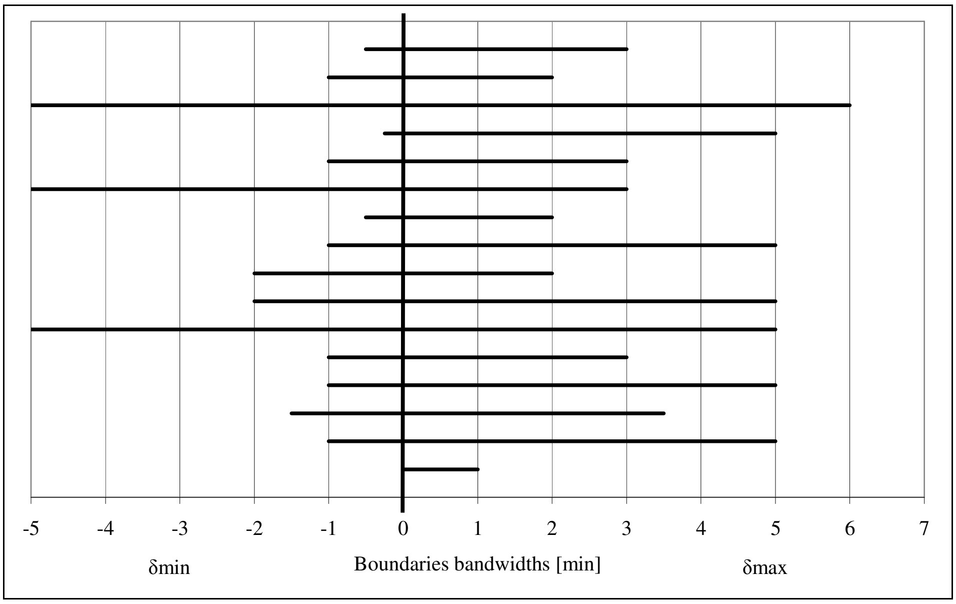


Figure 3.3: Boundaries of bandwidths applied in sample cities, to measure departure reliability at stops

Besides differences in indicators and boundaries, locations of measuring service reliability differ among the participating cities as well. Sometimes, only departure at the terminal is considered or just the main stops. Figure 3.4 shows the response on the question of where to measure service reliability (i.e. departure time deviations).

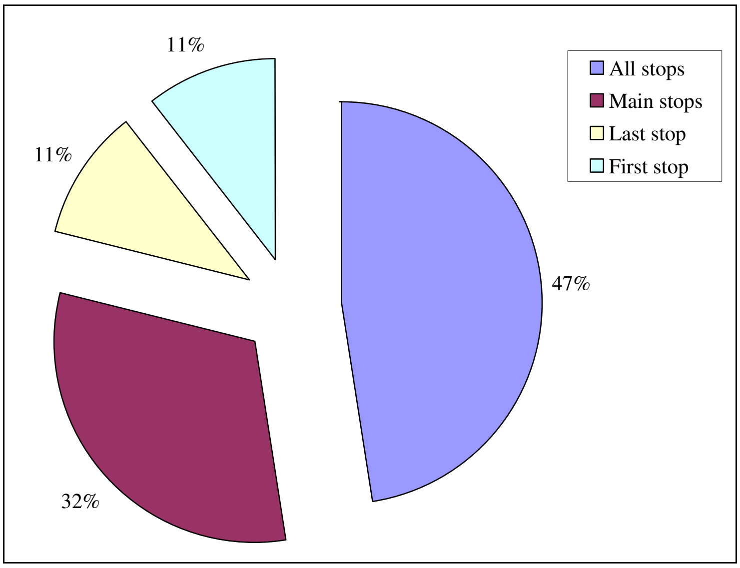


Figure 3.4: Locations used to measure service reliability (i.e. departure time deviations)

These results show that there is no uniform method applied in practice to measure service reliability, although this quality aspect is considered very important. Besides, the focus in practice is mainly on the supply side of public transport. Only Transport for London uses indicators showing the effects of unreliability for passengers, being excess journey time. These survey results support the statement of Chapter 2 to introduce a new indicator for reliability namely the average additional travel time per passenger. In literature, the need for a more passenger-focused indicator is recognized as well (e.g. Landex and Nielsen 2006, Mazloumi et al. 2008, Frumin 2009 and Savelberg and Bakker 2010).

3.2.4 Conclusions

This section showed the main characteristics of The Hague and its public transport. The public transport operator HTM operates trams, buses and light rail in The Hague and the region. Empirical data of this public transport system will be in the next section used to study service reliability with special attention to the impacts on passengers. Besides, an international survey on service reliability that we performed has been introduced. Almost 30 public transport systems in the world have been investigated concerning service reliability with regard to measuring, quantifying and planning. This section demonstrated that several types of indicators are used and several measuring methods are applied (for instance the investigated locations). The boundary values of what is considered as reliable strongly differ as well. In addition to these results, the survey yielded more information concerning service reliability and planning. These results will be used and presented in Chapters 5 and 6.

3.3 Service reliability of urban public transport in The Hague

3.3.1 Introduction

This section presents the results of a quantitative analysis of service reliability of the urban public transport in The Hague in 2008. Following our analysis of Chapter 2, we will show a first analysis of service variability (indicating vehicle trip time variability). Analyzing service variability, the examined time window is an important factor. In this section we show different examples of variability of vehicle trip time depending on the examined period. To gain insights into factors affecting service variability, the magnitude of variability of components of vehicle trip time is investigated. It is demonstrated that variability occurs in all components of vehicle trip time, being driving, stopping and dwelling times. In addition, the level of service reliability (with concern to passenger effects) is expressed in indicators for vehicle departure punctuality and regularity, using both the frequently used supply oriented indicators as well our new indicator, the average additional travel time per passenger. For the latter we conducted a survey to gain insights into the arrival pattern of passengers.

The results of the international survey are used to perform a case study with data of tram lines in The Hague, demonstrating the impacts of different indicators used in practice (Section 3.2). The case of the tram lines in The Hague presents the impacts of these different measurement and quantifying methods, demonstrating the value of our new indicator additional travel time. Using this indicator, consistent and reliable insights into the level of service reliability are yielded.

3.3.2 Service variability

3.3.2.1 Vehicle trip time variability over different time periods

Vehicle trip times are not deterministic, but stochastic. Obviously, the time windows used affect this variability (Lehner 1953). This section will elaborate on the distribution of vehicle trip times over different periods. First, vehicle trip times differ over the year. The autumn tend to be more crowded as more people use public transport since biking is less popular due to the weather. Besides, these weather conditions create less preferable circumstances at the roads/tracks decreasing speeds and increasing service variability. Figure 3.5 shows an example of vehicle trip time distribution (tram line 1, working days, 7-9 A.M., 2008) over the year. This figure illustrates that during summer (especially August), the vehicle trip time distribution is tighter, compared to autumn (especially the difference between the minimum and maximum value) and the average value is lower.

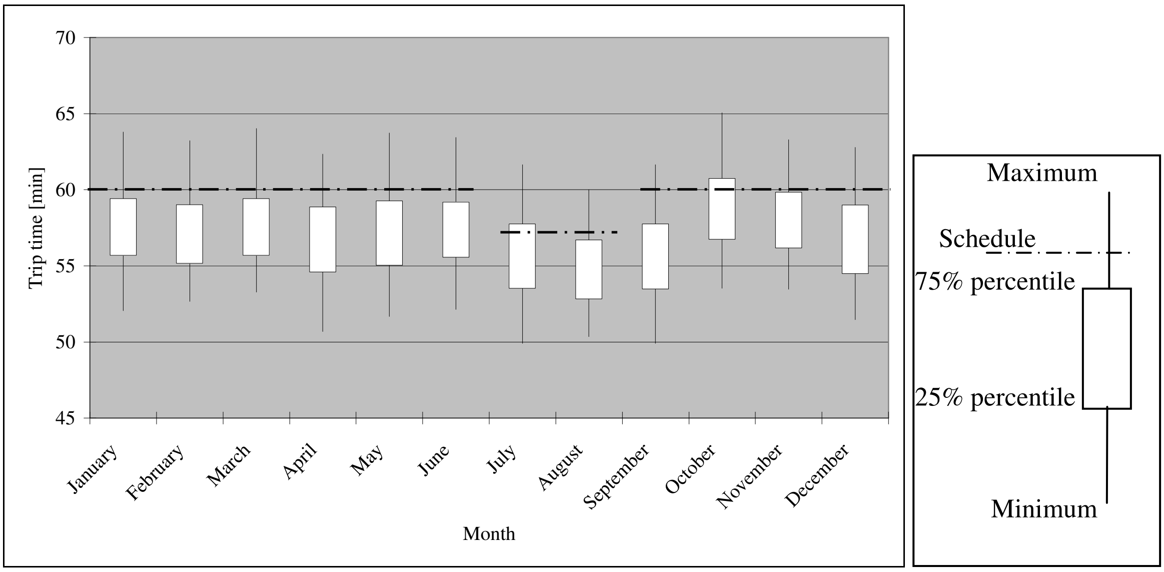


Figure 3.5: Vehicle trip time distribution tram line 1 over the year 2008 (minimum, 25 and 75-percentile and maximum values) (year 2008, N=2500)

Most public transport companies deal with these variations by applying different schedules over the year, for example summer and winter timetables.

Besides over the year, trip times differ over the week as well. Sunday is generally least busy and Saturdays differ in peak hours from working days, due to shopping activities. Because of part-time jobs, Fridays are less crowded, in terms of traffic and passengers for instance. Figure 3.6 shows actual trip times of line 1 over the week (one week in October 2008, 7-9 A.M.). Monday, Tuesday and Saturday have the widest distribution.

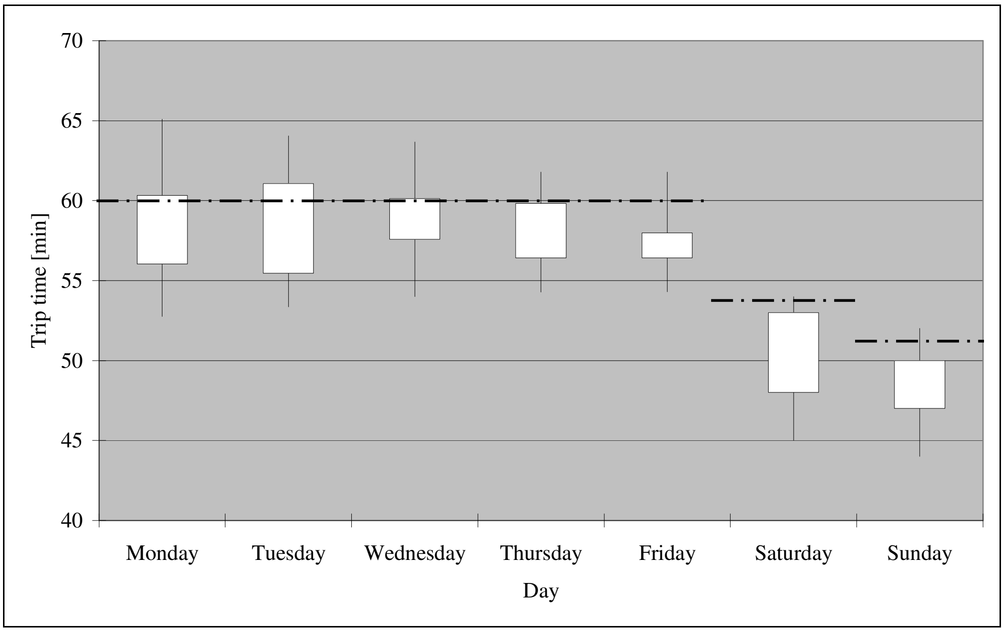


Figure 3.6: Vehicle trip time distribution tram line 1 over the week (minimum, 25 and 75-percentile and maximum values) (year 2008, N=60)

Although sometimes special timetables exist (for instance enabling evening shopping), usually only differentiation between working days (Monday-Friday), Saturday and Sunday is applied in timetables.

The last structural distribution of trip times is over the day. The main example of this is peak hour vs. evening hours. To deal with this, most urban public transport planners define different time frames in their schedule. Figure 3.7 shows the distribution of trip times of line 1 over the day (Mondays in October 2008). A wide distribution is visible in the morning peak. The distribution in the evening is wide due to a small share of fast trips in the late evening.

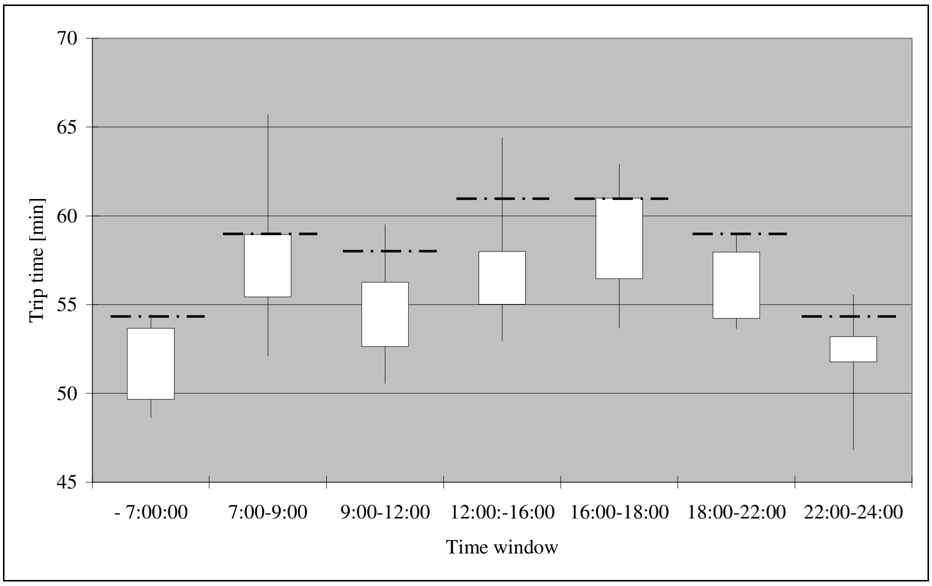


Figure 3.7: Vehicle trip time distribution tram line 1 over the day (minimum, 25 and 75-percentile and maximum values) (year 2008, N=100)

Most schedules take such distributions mentioned above into account by setting different trip times per homogeneous period. However, in these homogeneous periods (e.g. peak hours) still variability arises. All distributions show that scheduled trip time, with only a few exceptions, is above the 75 percentile value of actual trip time.

Figure 3.8 shows an example of such a distributed trip time. This graph represents data of line 1 in a rush-hour (7-9 A.M.) of a working day of one week in October 2008. It is shown that even with filtering of the above mentioned issues, trip time is still distributed. The variability of trip times in homogeneous periods per day (e.g. peak hour) in homogeneous periods per year (e.g. weekdays in May) is the main focus of our research. In the next section, this variability is examined, investigating the aspects terminal departure variability and trip time variability, as introduced in Section 2.3.2.

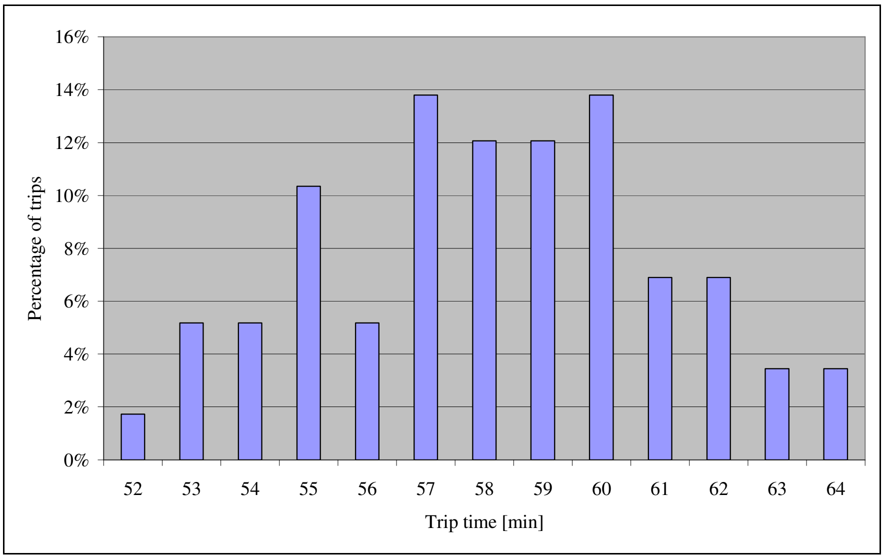


Figure 3.8: Vehicle trip time distribution (99%) tram line 1 during rush-hour on a working day (year 2008, N=60, scheduled trip time = 60 min.)

3.3.2.2 Terminal departure variability

Terminal departure variability is a part of total service variability, as presented in Chapter 2. Figure 3.9 presents two examples of terminal departure variability in The Hague in terms of schedule deviation. Examples are shown of tram line 1 in terminal Scheveningen and tram line 15 in Nootdorp. This example shows for line 1 a punctual departure where about 10% of the vehicles depart later than 90 s late. The variability of terminal departure for line 15 is larger, even showing substantial early departures. Although the deviations are relatively small compared to the variability of trip time shown in the previous section, this variability is of importance. First of all, all passengers on the line are affected, since the variability already occurs at the first stop and secondly, these deviations may be the initiator of bunching, as described in Section 2.3. Chapter 4 will elaborate more on this topic, showing possibilities to reduce terminal departure variability.

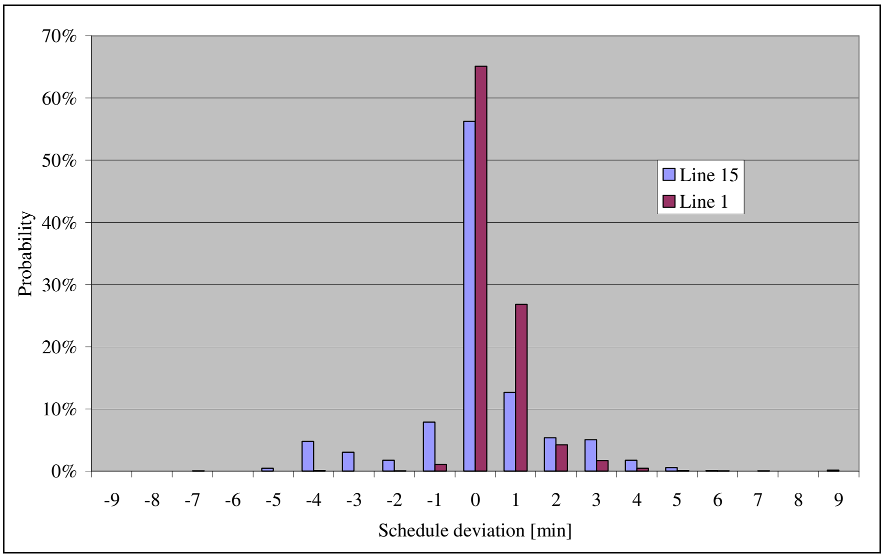


Figure 3.9: Terminal departure time variability, tram line 1 in Scheveningen and line 15 in Nootdorp (year 2008, N=1600)

3.3.2.3 Total trip time variability

Although only one trip time is scheduled for trips in a homogeneous period over several days (considering different day types and periods per year), in the operations different actual trip times occur. Figure 3.8 already showed an example of the distribution of total trip time. Figure 3.10 shows an example of such a distribution along the route, illustrating the increase in variability per stop. The focus is just on trip time, so departure time variability is not taken into account. The figure shows trips of tram line 1 (Scheveningen to Delft) during peak hour on working days in March 2006. The average total trip time (from begin to end terminal) is 60 minutes and its standard deviation is 3.7 minutes. The difference between the maximum and minimum actual trip time is almost 20 minutes, which is over one third of the average trip time. This will result in substantial schedule deviations along the route of this line.

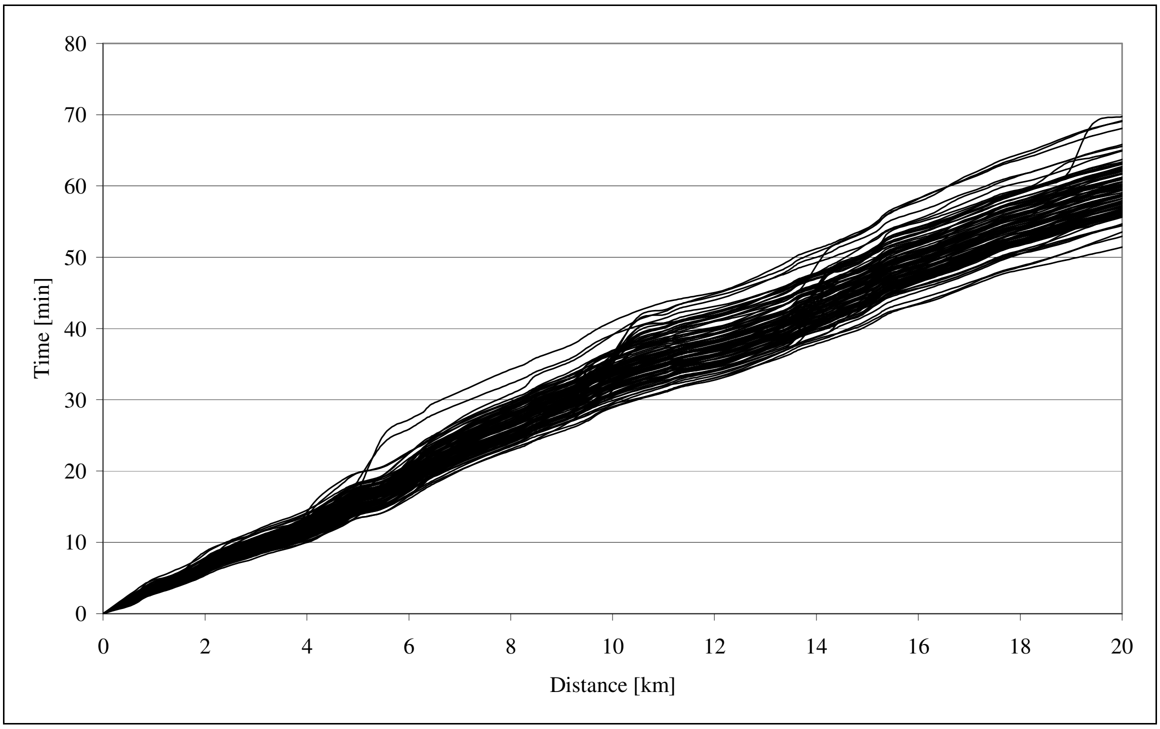
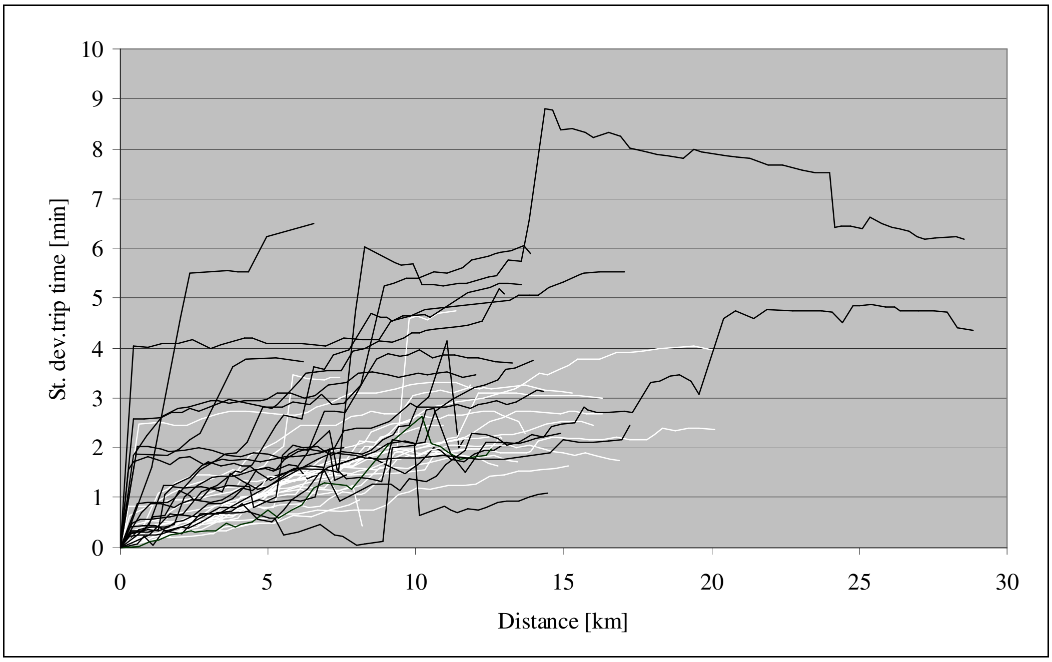


Figure 3.10: Pattern of individual trip times over days by distance from terminal (line 1 in the direction of Delft; working days, one month, 7.30-8.30 A.M.) (year 2006, N=100)

In addition to the examples of line 1, a time spreading analysis is performed of all HTM lines in The Hague. Figure 3.11 shows for each line the standard deviation of travel time as a function of the distance from the departure terminal. Morning peak-hour trips are analyzed during one month (March 2006). As is to be expected, the time variance increases with the distance from the departure terminal and with the length of the line. The increase per kilometre is larger for the bus lines than for the tram lines. Contrary to tram lines, the variance of trip times of bus lines sometimes decreases with distance, because of operational instruments like holding vehicles that are ahead of schedule at a stop. Despite these control instruments, the variance of trip times of bus lines is still larger than that of tram lines, probably because of a lower proportion of buses having their own right of way and priority at intersections. For the tram lines the average increase of the standard deviation over the distance is 11.1 s/km. For bus lines this increase is even larger, namely 17.6 s/km. Because the standard deviation increases every kilometre by these numbers, the 99%-bandwidth values of vehicle trip time increase by values about 6 times higher, namely 66 s/km for tram and 105 s/km for bus.



White= tram lines; black= bus lines

Figure 3.11: Standard deviation of trip times of all lines as a function of distance from departure terminal (year 2006)

The presented distributions of trip times imply a difference between the scheduled times and the actual operations. This difference might be expressed in two ways. First of all the departure times at stops differ. Chapter 2 already presented theoretical approaches to quantify this type of unpunctuality. Secondly, successive trips suffer from different deviations from the schedule and if these trips are scheduled with even headways, this will lead to irregularity. In that case, the headways between vehicles are not constant any more, as planned. Figure 3.12 shows the trip times of a sample of successive trips given in Figure 3.10, but now presented in a time-distance diagram, showing the uneven headways. The larger the distance from the terminal is, the less even the headways are. The bunching effect, described in Section 2.3, is also visible. Towards the end of the line, vehicles are slowed down (and sped up) in such a way that they almost have reached each other.

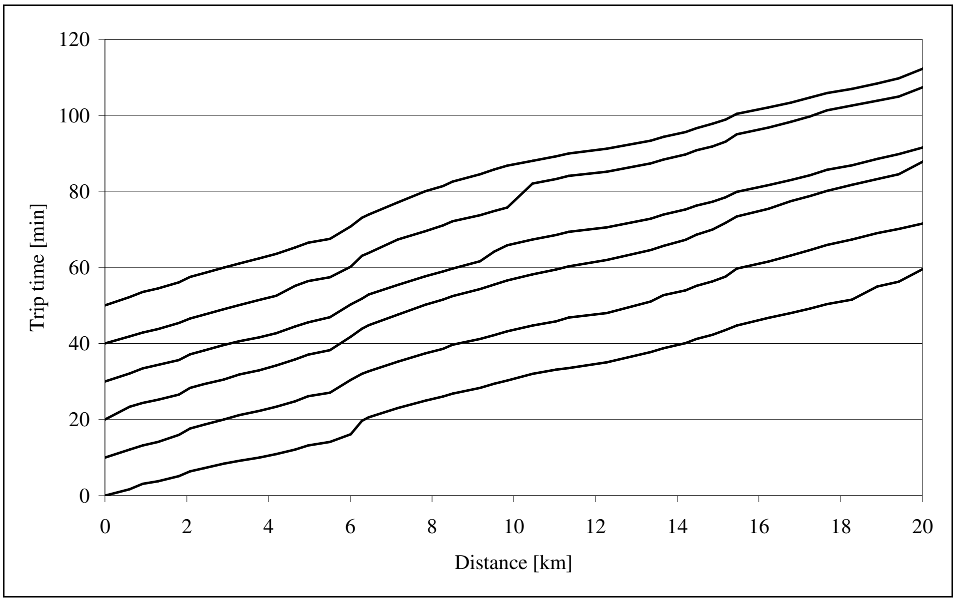


Figure 3.12: Time distance diagram of successive trips of tram line 1 during a day (year 2006)

3.3.2.4 Variability of vehicle trip time components

In Chapter 2, it was already stated that variability of components of vehicle trip time are together responsible for the variability of total trip time. To illustrate this variability in practice, actual data of tram lines in The Hague is presented in this subsection.

Figure 3.13 shows for all tram lines in The Hague what the part of each aspect in total vehicle trip time is. The main part is the actual driving of the vehicle. Dwelling is about a quarter of total trip time and the stopping time is 6%. The proportion of these elements differs substantially per line, per system and per city. It mainly depends on instruments and facilities applied for public transport. In this example, 90 % of the tracks are own right of way and traffic light priority is applied at most important intersections. Levinson (1983) presents a similar research in U.S. cities, showing ratios of stopping time of 12-26%.

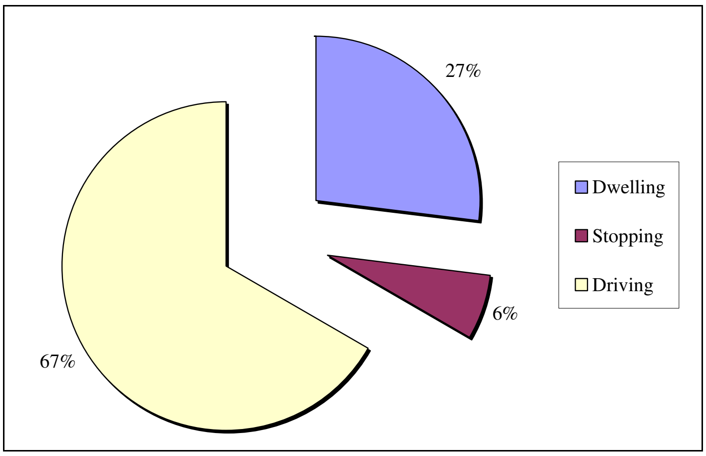


Figure 3.13: Components of trip time: example of ratio of all tram lines in The Hague (year 2008)

The first element is the driving time. This is the time when the vehicle is actually moving. Figure 3.14 shows an example of this time, for which data of tram line 1 in The Hague is used (7-9 A.M., January-March 2005). It is demonstrated that much differences arise in the actual driving part of the trip. In this case, the difference between the fastest and slowest vehicle is almost 20 minutes.

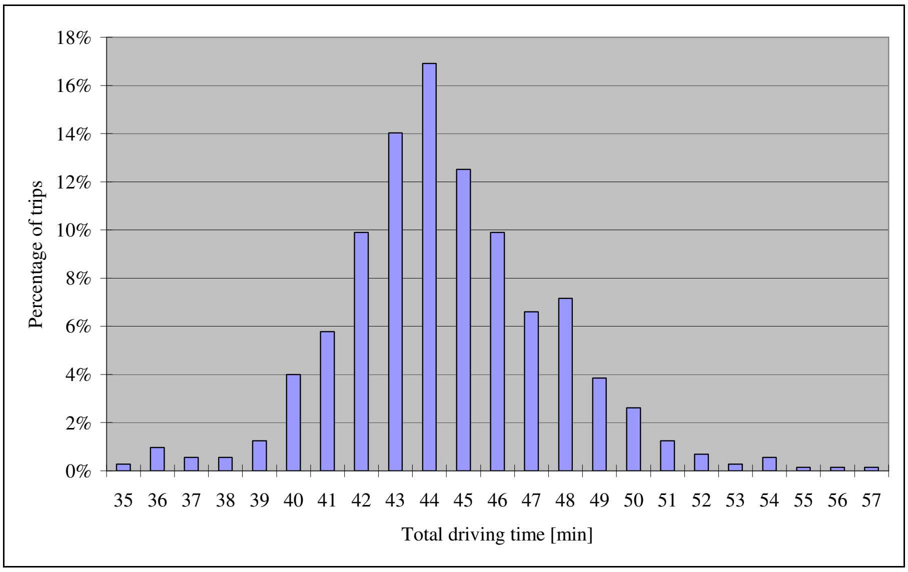


Figure 3.14: Distribution of total driving times, tram line 1 (year 2005, N=750)

Section 2.3 presented that stopping time is closely related to driving time. Interaction with other traffic may cause the public transport vehicle to stop, without boarding and alighting. Figure 3.15 shows the distribution of the total stopping time of line 1 (7-9 A.M., January-March 2005). The larger part of the vehicles experiences 2 minutes of stopping times or more. Although this delay decreases the level of quality (by decreasing travel speed), service reliability may not be affected as long as all vehicles suffer this delay and it will be accounted for in the schedule. However, the stopping time is not constant per trip and introduces variability as well.

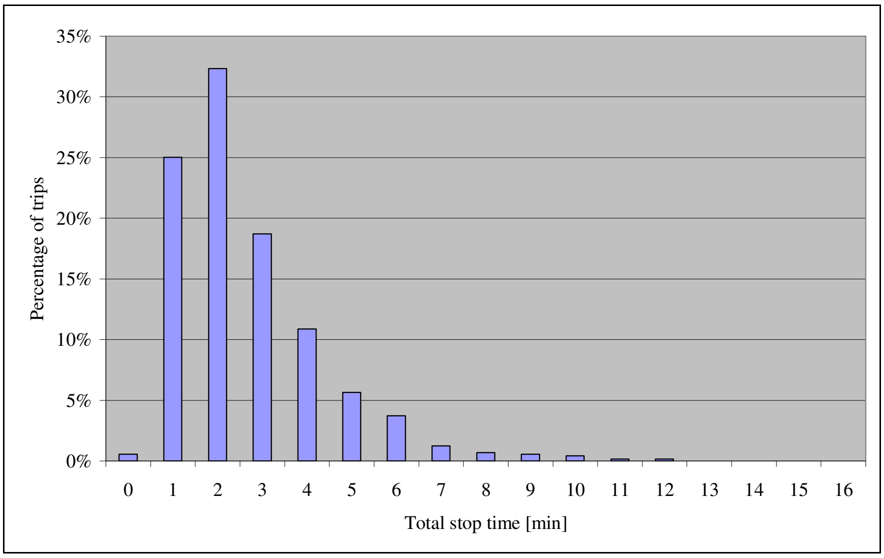


Figure 3.15: Distribution of total stopping times, tram line 1 (year 2005, N=750)

Another important part of vehicle trip time is dwell time. In Figure 3.16, we show the distribution of total dwell time of line 1 (7-9 A.M., January-March 2005). This figure shows that the variability in dwell time is substantial. The difference between the minimum and maximum dwell time is over 10 minutes, while total trip time is on average about 60 minutes.

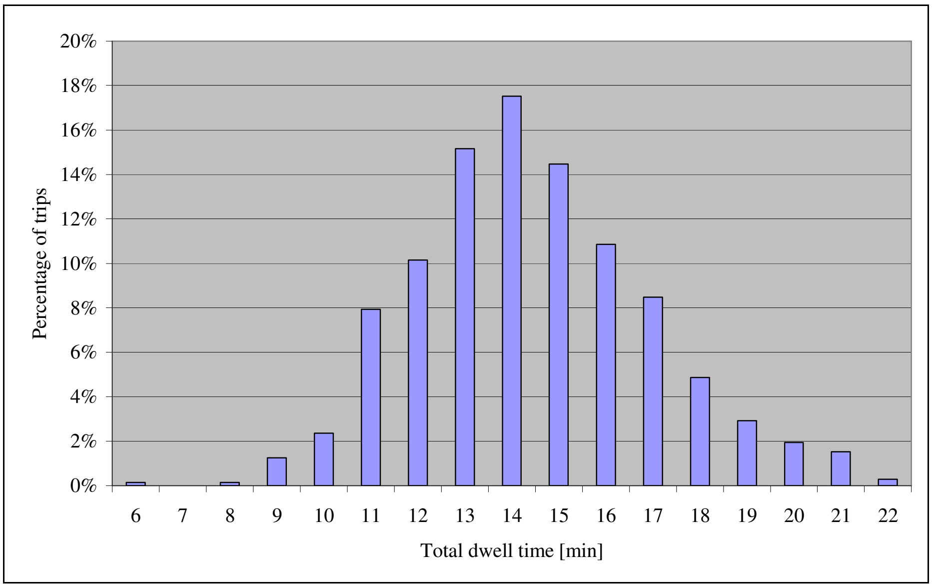


Figure 3.16: Distribution of total dwell times, tram line 1 (year 2005, N=750)

Above, three components of vehicle trip time are described and actual data of line 1 in The Hague illustrated the variability in the individual elements. This individual variability leads to variability in total vehicle trip time, as shown in Figure 3.8. Local characteristics always create other ratios of driving, dwelling and stopping and the variability in these elements will differ per line and period as well. However, the analysis of the components of trip time showed that all three elements are distributed. Especially dwell times and driving times show a wide distribution. This variability depends at least on the length of the line and the number of stops.

3.3.3 Arrival pattern of passengers

In the following section, the impact of variability on punctuality and regularity will be determined, both for traditional supply oriented indicators and the new passenger oriented indicator. For the latter the passenger arrival is of importance too. To calculate the impacts of service variability on passengers, it is necessary to know the arrival pattern of passengers at the departure stop, as demonstrated in Section 2.3. Although this is of major influence, little attention is paid in literature to this phenomenon. Section 2.3 presented some available references. Many researchers assume passenger arrival to be at random, since in urban public transport systems headways are usually short and waiting time is on average half the headway (if actual headways are constant in time). An assumption of planned passenger arrival in case of long headways is found in Furth and Muller (2006) who assume that all passengers arrive at the stop at the moment equal to the 2nd percentile value of the actual vehicle departure time distribution. O'Flaherty and Mangan (1970) and Seddon and Day (1974) state that passengers arrive at random if scheduled headways are shorter than 10 to 12 minutes. Longer headways lead to planned arrivals, but more information of this scheduling of passengers is lacking. Csikos and Currie (2007) found that passenger arrive more at random off peak than during peak hours. No support for the general expectation of a higher degree of early passenger arrivals in relation to unreliable services was found. Fan and Machemehl (2009) found that headways of 11 minutes mark the transition point from practically random to less-random passenger arrivals and they show a case where all arrivals may be regarded as coordinated arrivals after headways of 38 minutes. We performed additional research to gain more empirical insights into the type of arrival pattern and passenger behaviour in case of planned arrivals.

We conducted a customer survey in The Hague asking passengers about their arrival behaviour. About 3000 passengers (distributed over all lines and periods) participated in this research, which was part of the regular quality survey of HTM. The passengers were asked whether they plan their arrival at the departure stop using the schedule or arrive at random. If they planned their arrival using the schedule, they were asked how many minutes before the scheduled departure time they arrived at the stop. The survey yielded results for all tram and bus lines during different time periods on a day. Figure 3.17 shows for both peak periods (7-9 A.M. and 4-6 P.M.) and the off peak period the proportion of passengers arriving at random at the departure stop, compared to passengers using the schedule (which they know, either because of frequent use or which they checked before departure at home). The difference between peak and off-peak is the number of people that already knew the schedule. During the peak more people know their departure time by heart, probably because of frequent use. Although the number of provided trips is lower during the off-peak and thus the provided headways are longer, there surprisingly is no substantial difference between peak and off-peak in the ratio of passenger arriving at random and passengers using the schedule.

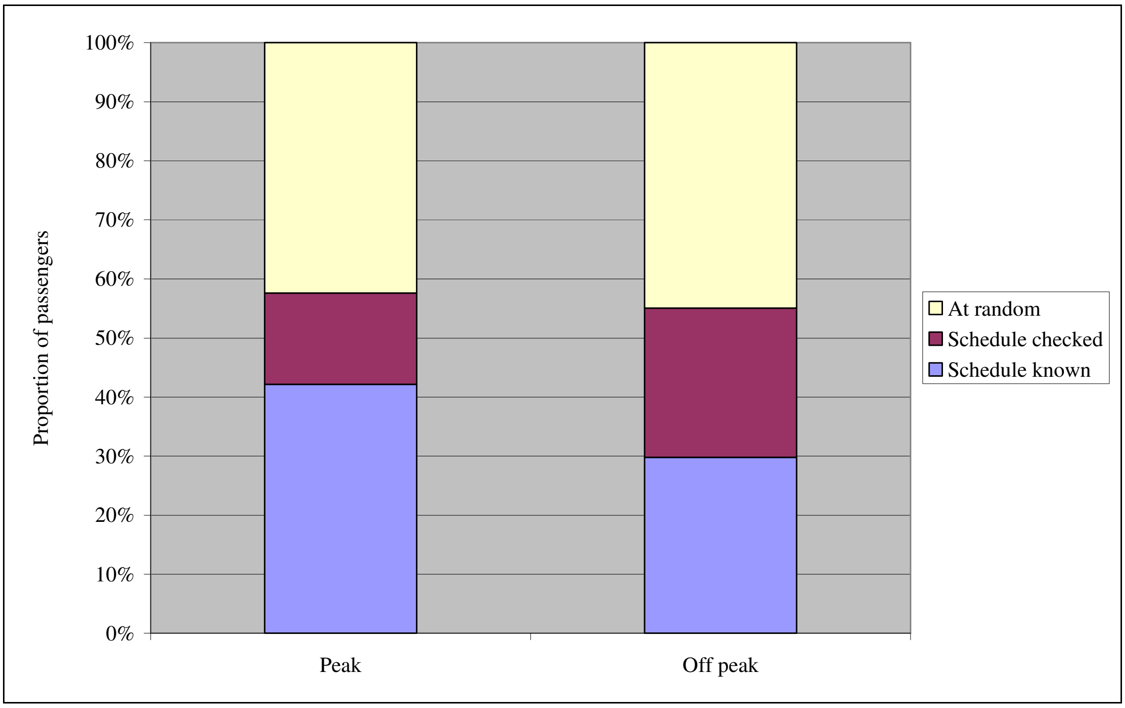


Figure 3.17: Passenger behaviour concerning arrival pattern at departure stop

From this data two important inputs for the analysis may be derived. The difference between random arrival and coordinated arrival probably arise due to differences in passenger types, headways and actual service variability. Based on our survey, the relationship between headways and arrival pattern has been assessed as well. In general, passengers on average tend to arrive at random if headways are 10 minutes or less. This matches the results of O'Flaherty and Mangan (1970) and Seddon and Day (1974). Therefore we use headways of 10 minutes as the criterion to distinguish between random arrival of passengers and scheduled arrivals. However, it is important to note, based on the results above, that headways alone do not completely explain the arrival pattern and differences in arrival behaviour among individual passengers may be large. We recommend more research on this topic.

Looking at planned arrivals, we would like to determine the interval around the scheduled departure time. Figure 3.18 indicates how early passengers of our survey arrive at the stop by showing the proportion of passengers arriving a certain amount of minutes before scheduled departure. In this case, they knew or checked the schedule before going to the stop. It appears that about 70% arrive within 2 minutes before the scheduled departure time. For our analysis, we propose to use a value of 2 minutes for τ_{early}. This value represents the distribution of the arrival pattern of all passengers (consisting of arrival times of more and less than 2 minutes early) in a proper way.

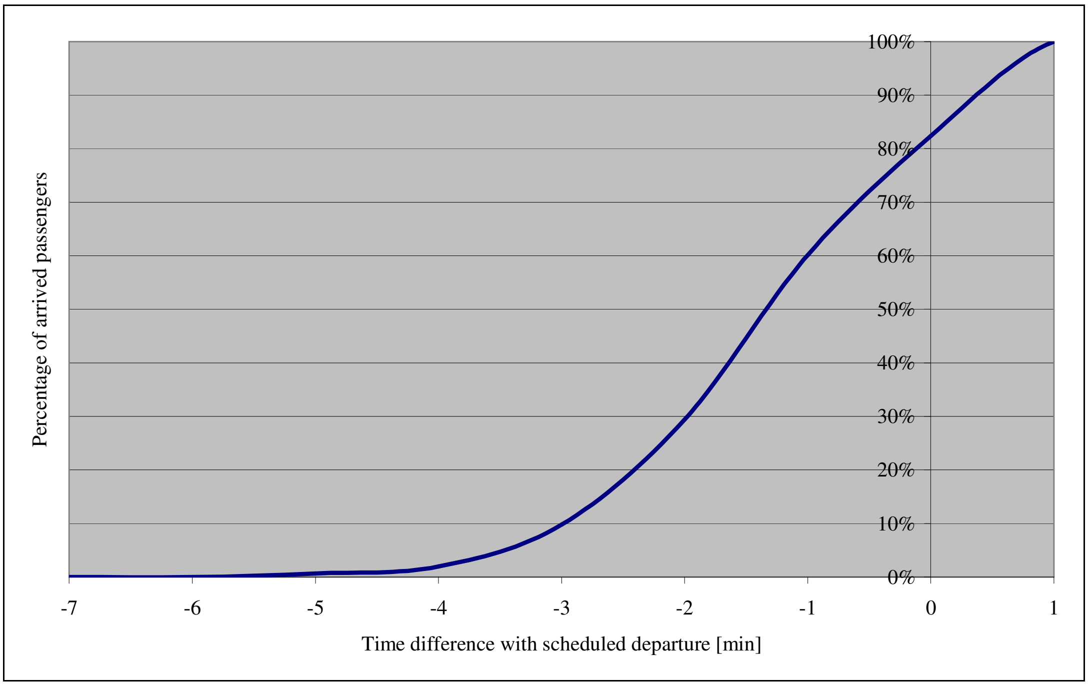


Figure 3.18: Percentage of passengers arrived as function of time difference with scheduled departure time (if schedule is known)

The value of τ_{late} is set to 1, because it is considered possible that passengers may speed up a little while approaching the stop in combination with drivers waiting for arriving passengers.

3.3.4 Supply and passenger oriented indicators

The following subsection will present an analysis of empirical data of public transport in The Hague by calculating both supply and passenger oriented indicators. It is demonstrated that the new indicator, the average additional travel time per passenger, presents the impact of passengers in an improved way. We performed the analysis on all lines in The Hague and a detailed example of both a high and low frequent line is provided.

3.3.4.1 Vehicle departure punctuality and passenger additional travel time

If the frequencies of the services are low (i.e. headways longer than 10 minutes), passengers tend to arrive at their departure stop according to the schedule. As mentioned before, in such a case punctual operations are needed. The worst scenario in this case is driving ahead of schedule because people who miss the vehicle then have to wait the full (long) headway before a new vehicle arrives.

Using a traditional supply side indicator, we calculated that the average punctuality of all relevant lines during relevant periods (in which scheduled headways are longer than 10 minutes) in The Hague (i.e. absolute schedule deviation of actual vehicle departure at a stop, averaged over all trips and stops (Equation 2.14)) was 2.1 minutes during working days in March 2006. This means the average delay at every stop is plus or minus 2.1 minutes. Figure 3.19 shows the distribution of the punctuality of all lines.

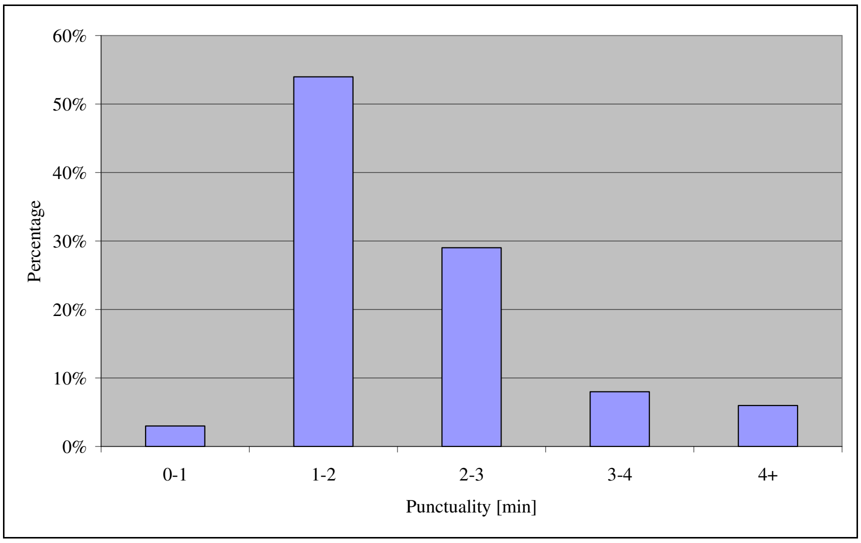
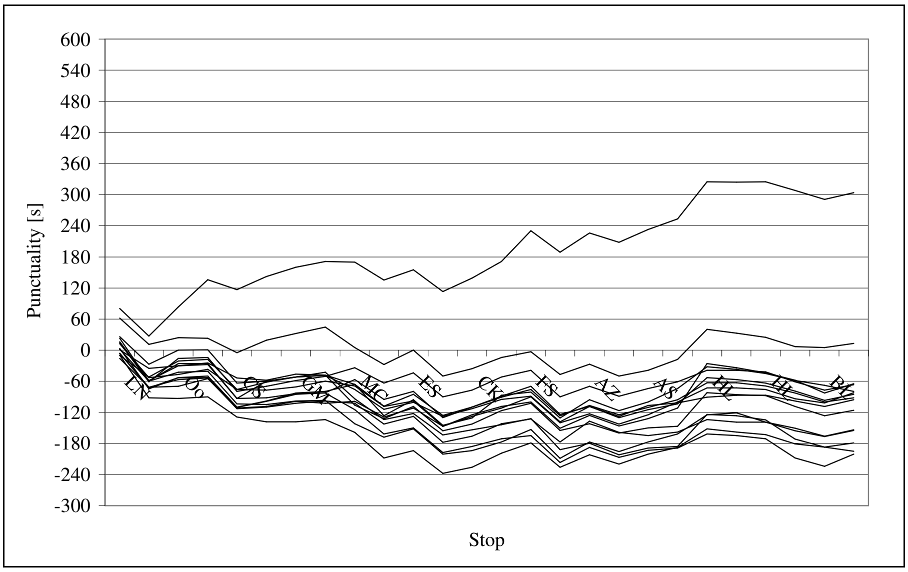


Figure 3.19: Distribution of absolute vehicle departure punctuality of all lines (with headways longer than 10 minutes) in The Hague (year 2006)

However, if we use the new indicator we find that these mere 2.1 minutes still yield substantial consequences for passengers. Figure 3.20 shows a sample of the measured stop punctualities along tram line 3 of trips in the evening on working days during March 2006. (the scheduled headway was 15 minutes; see Appendix B for more characteristics of this line). It is clear that a majority of the runs are ahead of schedule, which increases passenger waiting times enormously, given the scheduled headway of 15 minutes. However, the absolute punctuality is 2 minutes which seems to be good. Figure 3.21 illustrates the average additional waiting time for the passengers at every stop (calculated using Equations 2.19-2.21 in Chapter 2), due to the lack of punctuality. This additional waiting time is calculated by determining the delay (in case of late vehicles) and the headway (in case of early vehicles). This graph clearly indicates the effect of driving ahead of schedule, since at the stops where this occurs, passengers waiting times increase. Taking the pattern of passengers along the line explicitly into account as well yields the average additional waiting time for a passenger of 2.5 minutes.

Given the average in-vehicle time on this line of about 10 minutes, the unreliability thus leads to an average increase in passenger total travel time of about 20%. Besides, it is an average, so some passengers will even experience much more additional travel time, as shown by Figure 3.21. Due to the passenger pattern on the line (i.e. much boardings at the first part of the line where the additional travel time is limited), the average value is low compared to the values at some stops. At some stops, the average additional travel time is about 12 minutes per passenger.



+ (late) and - (early)

Figure 3.20: Measured vehicle departure punctuality per stop on tram line 3 (year 2006)

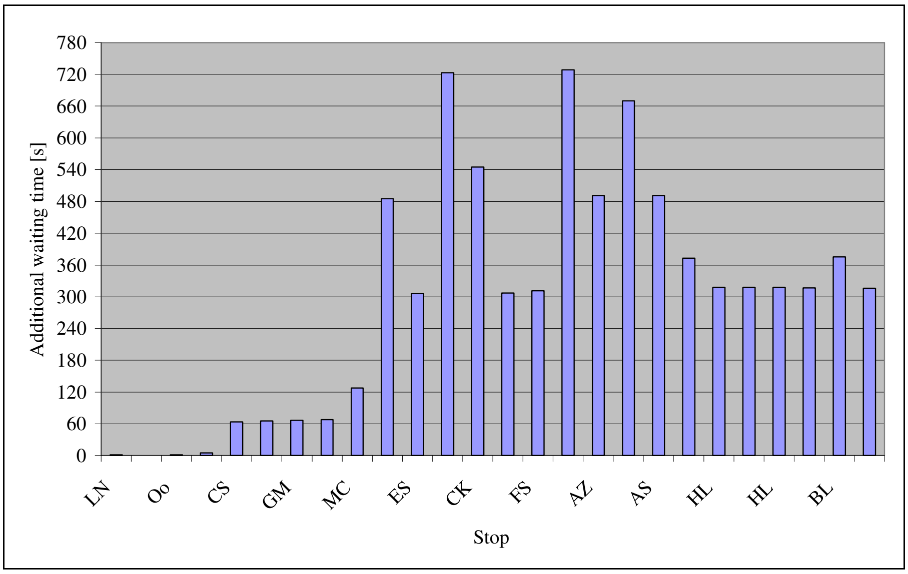


Figure 3.21: Calculated average additional waiting time per passenger per stop on tram line 3 (year 2006)

3.3.4.2 Service regularity at stops and passenger additional travel time

If public transport operates with high frequencies (i.e. headways of 10 minutes or less), passengers tend to randomly arrive at their departure stop. In this case service regularity is very important meaning that headways should be equal between successive vehicles, since exact vehicle departure times are less important. Note however, that punctual departures also imply regular departures in case of regular schedules. In case of equal headways the average passenger waiting time is minimized and the distribution of passengers among vehicles is optimal, which prevents overcrowding (i.e. under the assumption of a uniformly distributed arrival pattern). Section 2.4 already elaborated on that aspect.

We analyzed and expressed the average vehicle regularity of the lines in The Hague (with headways of 10 minutes or less) using the traditional indicator Percentage regularity deviation mean (PRDM, see Equation 2.15). This indicator expresses the average deviation of actual headways compared to the scheduled ones. The average PRDM was 27% during the morning rush-hour on working days in March 2006. This means that on average over all relevant lines and stops, the headway deviation is 27% of the scheduled ones. If scheduled headways are 10 minutes for example, average headways will be about 7 and 13 minutes. This number is the average of all stops on a line. Usually the regularity at the beginning of the line is better while it decreases with every added stop. At the end of the line, regularity is much worse than the average value (due to increasing vehicle trip time variability as shown by Figure 3.10). Figure 3.22 shows the distribution of the irregularity of all lines.

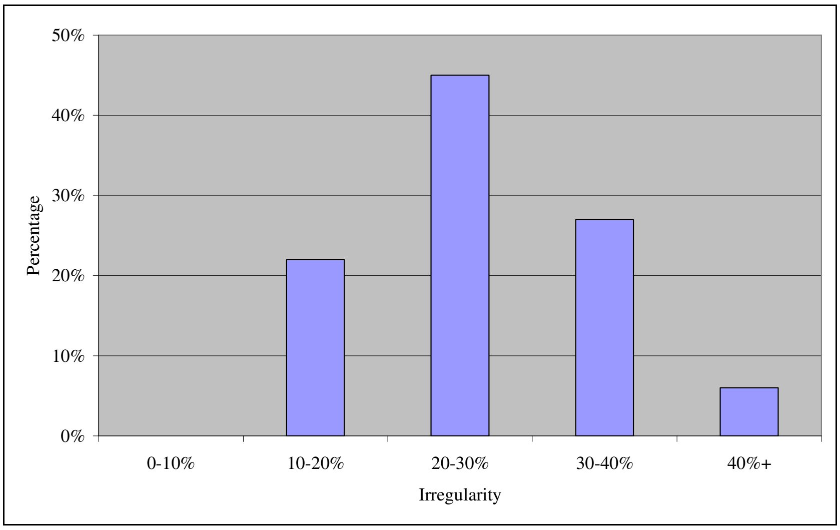


Figure 3.22: Distribution of irregularity of all lines (with a headway of 10 minutes or less) in The Hague (PRDM), averaged over all stops (year 2006)

In Chapter 2 we claimed that the supply side indicators do not properly express the impacts of service variability on passengers and we introduced additional travel time. The following analysis shows the translation of vehicle regularity into passenger additional travel time indicating passenger impacts. This additional travel time arises by the extension of waiting time, which is substantial at many stops. Figure 3.23 shows the regularity of some morning rush-hour vehicle trips of tram line 9, having a scheduled headway of 5 minutes (see Appendix B for more characteristics of this line). Their irregularities are quite high, especially at the end of the line. Values of PRDM over 60-70% correspond to vehicles that are bunching. Figure 3.24 illustrates the impacts on passenger average additional waiting time at the stops of the line (calculated by using Equations 2.17 and 2.18 from Chapter 2). This also indicates that passengers departing at the end of the line are most affected by the irregularity. Taking into account the boarding pattern along the line, passenger waiting time has been increased by 1 minute, which is about 20% on average in relation to the 100% regular situation. Considering the average in-vehicle time of 10 minutes, this means an increase of 5-10% in total passenger travel time. In addition, the irregular headways lead to an uneven load of passengers over the vehicles implying a lower probability of finding a seat in the vehicle and even overcrowding.

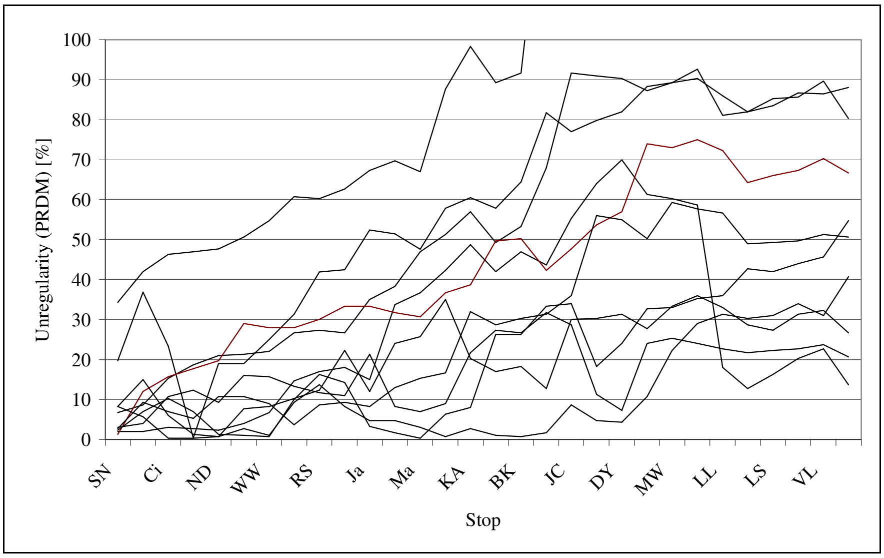


Figure 3.23: Measured vehicle irregularity (PRDM) per stop on tram line 9 for a selection of runs (year 2006)

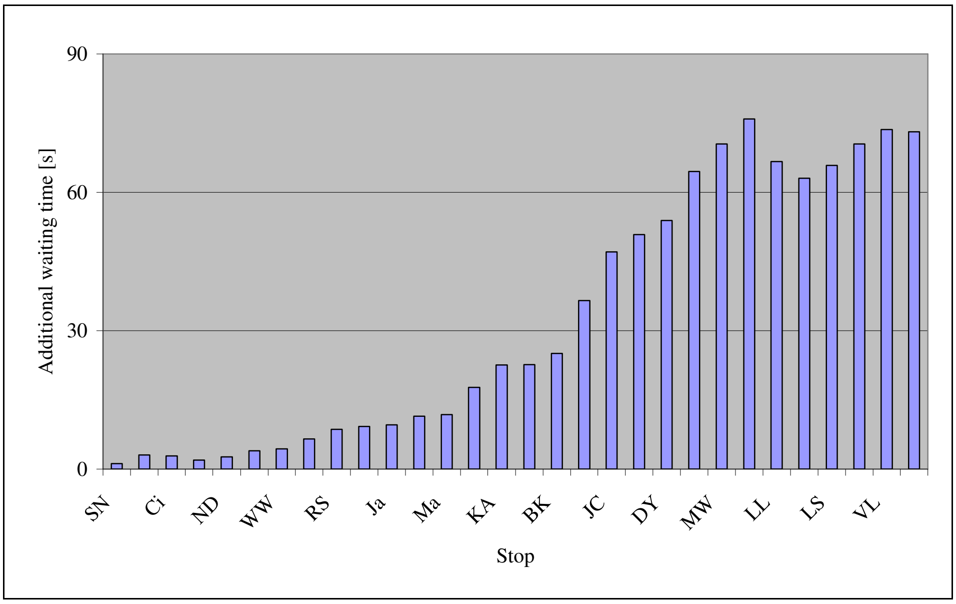


Figure 3.24: Calculated average additional waiting time per passenger per stop on tram line 9 (year 2006)

3.3.4.3 Impact of service reliability on passengers for all lines

The previous sections presented results of a study on a sample of lines considering service reliability using the indicator which considers both the supply and demand sides of public transport. The examples showed that unreliability causes negative impacts on passengers in the form of extended travel time. We calculated average additional travel time for all lines and directions in The Hague, using Equations 2.17-2.21 from Chapter 2, similar to the shown examples above. In addition, the relative extension of the average total travel time per passenger has been calculated, shown by Figure 3.25. This figure shows that on some lines, the level of service reliability may lead to 20% to over 30% of additional travel time. Figure 3.25 also shows that on some lines the extension is limited. The extension of total travel time depends of on service variability, but also on passenger patterns. For instance, line 11 SH and

12 DD have a small amount of additional travel time, since most passengers board at the first stop of these lines, where service variability is still relatively low. The example of line 3 already showed that the difference of departing too late or too early plays an important role as well. If the value of the travel time extensions is roughly calculated, using a value of time of € 5.97 (as presented by the Dutch Ministry of Transport and Ministry of Economics 2004), the value of the extended travel time due to unreliability would be about € 12 million per year (2004) for the tram and bus lines of HTM in The Hague. We expect this number to be twice as high if also the value of the variability of the (additional) travel time extension due to service variability is considered.

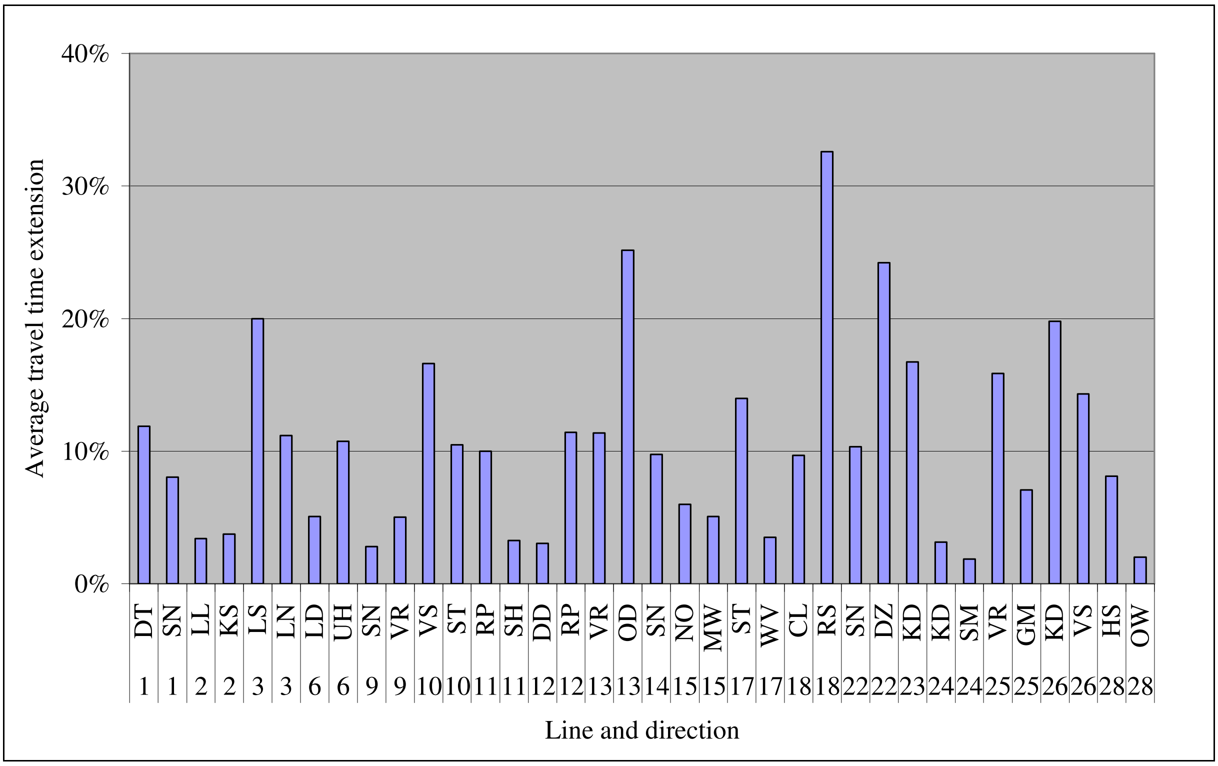


Figure 3.25: Average total travel time extension per passenger per line in The Hague

3.3.5 Limitations of service reliability definitions used in practice

Section 2.5 showed that there are many methods to illustrate service reliability and Section 3.2 demonstrated that these methods are applied differently in practice. In this section the impacts of the measurement location and the definition of punctuality are analyzed. To show the effects of using these different methods, a case study is conducted using empirical data of tram lines in The Hague. All tram lines are analyzed and data of rush-hours on working days in April 2007 are used. Figure 3.26 shows the impact of different measurement locations on service reliability. This figure illustrates the difference between measuring only at the first stop, at a central stop or at all stops. Figure 3.4 already showed that all of these methods are regularly applied in practice. To express service reliability, a bandwidth of timetable deviation of -1 and +2 minutes is used. The figure shows per tram line the percentage of vehicles departing on the specific stop(s) between these boundary values. It is shown that the different methods do not yield consistent results. The punctual trip percentage per tram depends on the measurement method and the order of tram lines differs per measurement method as well. Line 2 in the direction of KS and line 11 SH prove for example to be the most reliable lines using the first stop measurement, but if only a central stop is investigated, line 2 LL and line 1

SN are more reliable. If all stops are inserted in the calculation, line 11 HS is the most reliable line. This case proves that different methods do not yield comparable results and thus a consistent method is recommendable. In our research, all stops are taken into account, using the number of passengers as weights. This method is expressed in Equations 2.18 and 2.21 in Chapter 2.

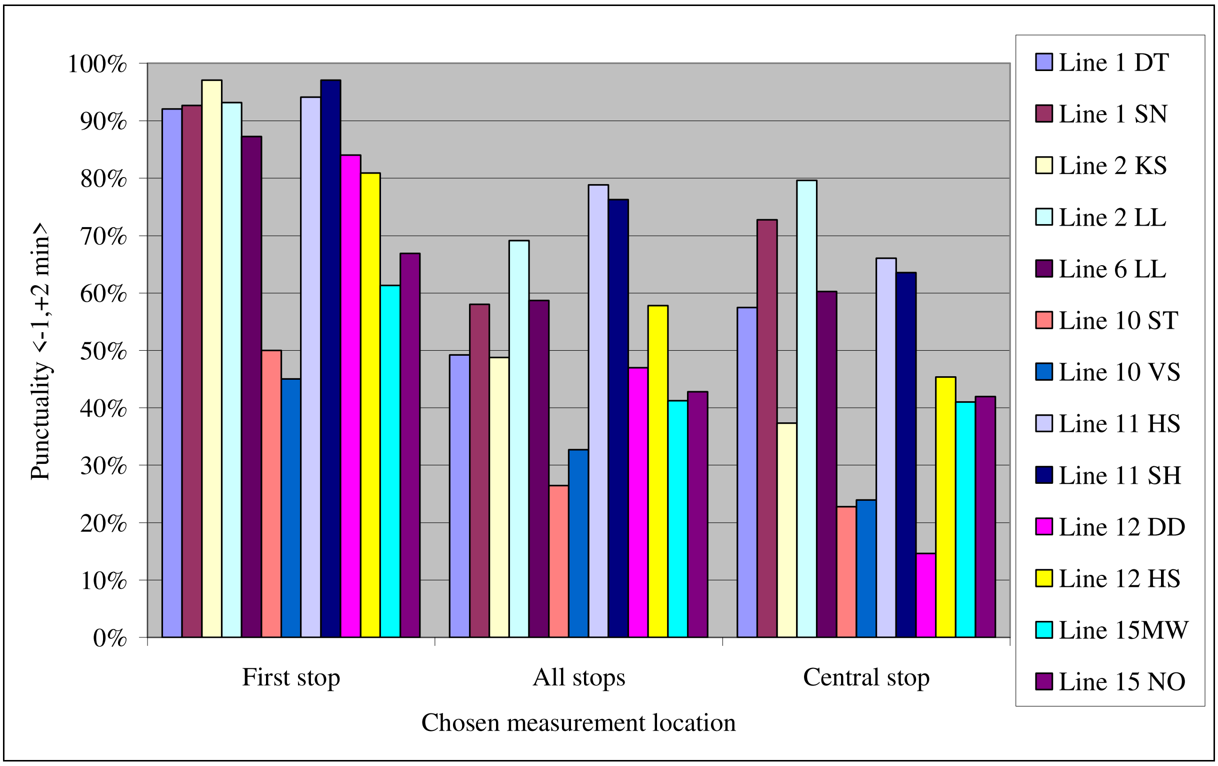


Figure 3.26: Punctuality <-1,+2> of tram lines in The Hague using different measurement locations

Besides the location of measurement, the indicator used is of great importance and influence as well. As stated in Section 2.5, punctuality is a supply-focused indicator which is commonly used in urban public transport. The definition of punctuality differs among cities and countries as well, as mentioned in the previous section. In Chapter 2, a new indicator was introduced, additional travel time. This indicator enables an improved illustration of the level of service reliability; the focus is on the passenger, there is only one definition and it is comparable to travel time.

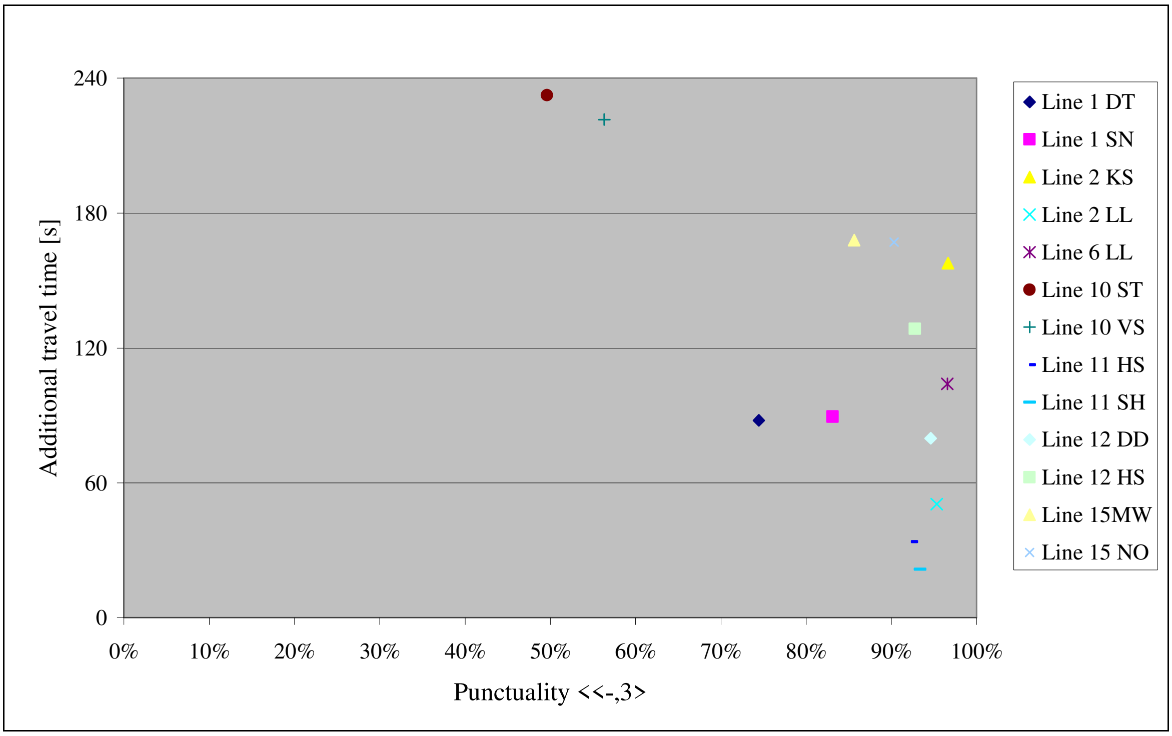
Figures 3.27 A, B and C show a comparison between three definitions of departure punctuality found in the international survey and additional travel time for actual tram lines in The Hague. The used definitions of punctuality are (calculated for all trips at all stops):

- A The percentage of schedule deviations that is less than 3 minutes late;
- B The percentage of schedule deviations which is both less than 2 minutes late and more than 1 minute early;
- C The absolute average of the deviation.

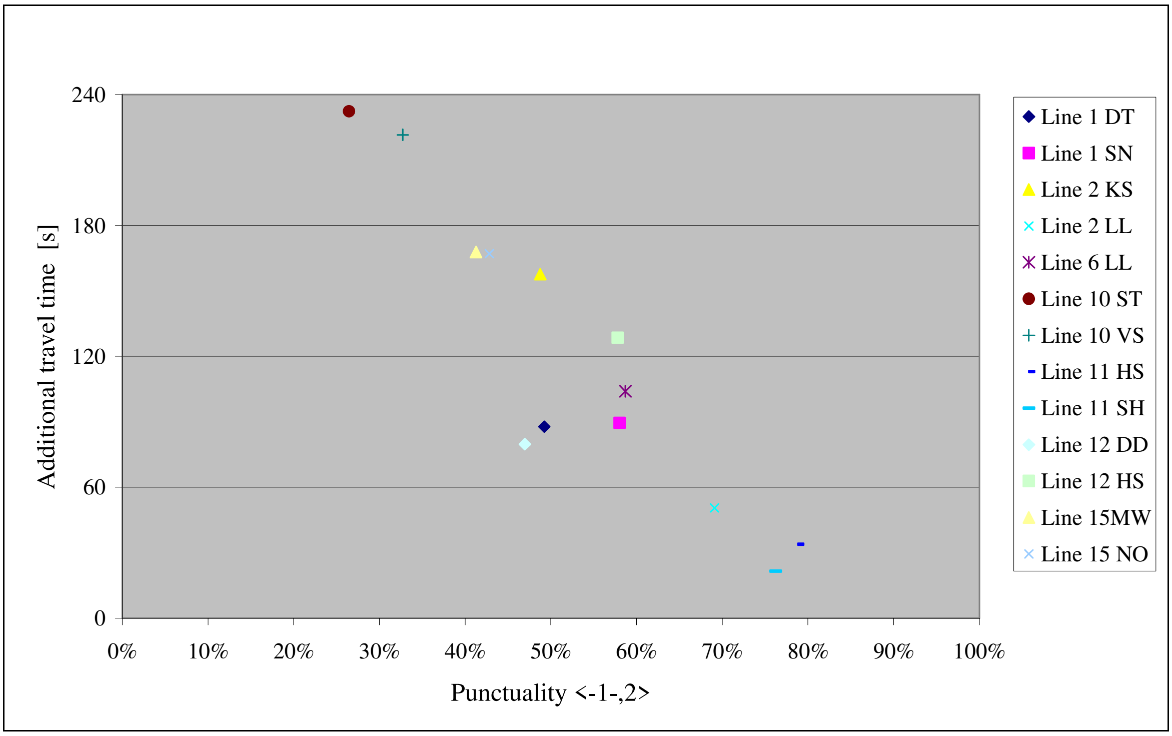
Although these figures roughly show a linear relationship between these indicators and the additional travel time, the order of tram lines regarding the highest reliability differs per indicator. For example, line 15 MW has a low reliability using category B (<-1,+2>; only

40%), but a high reliability in category A (<<-,+3>; 85%).Tram lines with many early departures score better on reliability when no lower boundary is used.

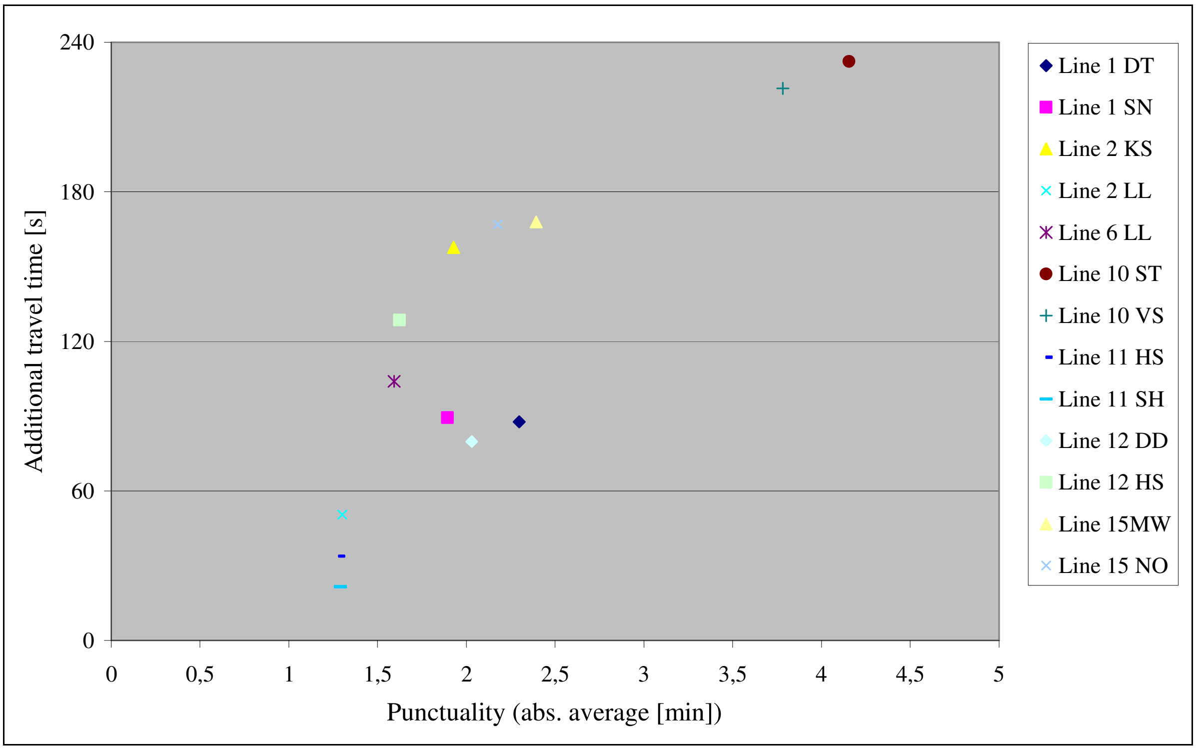
Another example of inconsistency is line 2 KS, which has a better reliability than line 1 SN if category B is used. However, the additional travel time per passenger is higher in the first line, so passenger will have another experience than what the common indicators illustrate. Looking at Figure 3.27 C, it is illustrated that line 12 DD and 2KS have about the same value of punctuality, but the average additional travel time per passenger of the latter is about two times higher. The level of service reliability thus depends on the chosen definition. The additional travel time only has one definition and is better suited to addressing the level of service reliability of a specific line or network. This indicator really shows the impact on passengers.



3.27A: Punctuality as a percentage of vehicles experiencing a departure deviation smaller than +3 minutes (no lower boundary)



3.27B: Punctuality as percentage of vehicles experiencing a departure deviation between -1 and +2 minutes



3.27C: Punctuality as absolute average of departure deviation

Figure 3.27: Calculated additional travel compared to three types of punctuality measurement

3.3.6 Conclusions

This section presented empirical data of service variability and reliability. Although variability of supply is handled by providing different timetables for different homogenous periods (e.g. peak hours of working days), it was demonstrated that in these homogeneous periods service variability still occurs. The linear progression of service variability by increasing distance from the terminal was shown, being 17.6 s/km on average for bus lines and 11.1 s/km for tram lines in The Hague. Terminal departure and trip time variability were illustrated as well in this section. It was demonstrated that both factors are responsible for service variability. Trip time variability was analyzed by investigating variability of trip time elements being driving, stopping and dwelling time. All elements proved to be substantially distributed.

A passenger survey showed when people use the schedule to arrive at their departure stop and when they arrive at random. On average, people start to arrive at random if headways are 10 minutes or less. Besides, this survey showed that in case passengers consult the schedule, about 70% of them are present at the stop within 2 minutes prior to the scheduled departure.

This section demonstrated that the newly introduced indicator, that is additional travel time, represents the level of service reliability in a good way, considering factors that are neglected by traditional indicators, e.g. driving too early and passenger boardings patterns. A case study in The Hague showed that due to unreliability, about € 12 million is lost per year, roughly calculated based on the value of time.

In addition, the additional travel time was calculated for tram lines in The Hague and compared to the indicators found in the international survey (presented in the previous section). It was demonstrated that no consistent result is possible, since different kinds of indicators are used. The location of measuring, that differed over the cities as well, proved to be important too. This inconsistency may lead to wrong conclusions. Our indicator of additional travel time incorporates the mentioned factors enabling a more complete and consistent quantification of service reliability.

3.4 Summary and conclusions

In this chapter, we presented a practical and quantitative perspective on public transport service reliability, using detailed data on public transport operations in The Hague and results of our international survey on service reliability indicators and planning topics in cities around the world.

We described the urban public transport system of The Hague, consisting of bus, tram and light rail service lines and we analyzed their respective levels of service reliability in depth. The theoretical approach to service reliability given in Chapter 2 is applied. An analysis of service variability over different periods demonstrated that even after incorporating effects of variability over the year, week and day, still service variability occurs over homogeneous periods. The variability of terminal departure time and trip time, split up in driving, stopping and dwelling, is substantial. Empirical analysis showed that terminal departure variability, dwell time variability and line length might require extra attention in the planning process.

In order to gain insights into the arrival pattern of passengers, which is necessary to calculate the additional travel time, this chapter presented results of a passenger survey we performed. On average, people start to arrive at random if headways are 10 minutes or less. If headways are higher, people use the schedule to plan their arrival accordingly. In addition, this survey showed that in case passengers consult the schedule, about 70% of them are present at the stop within 2 minutes prior to the scheduled departure.

To show the level of service reliability in The Hague, we calculated supply side indicators for punctuality and regularity next to the indicator additional travel time, the new demand-oriented indicator for service reliability used in our research. By changing the focus from supply to demand side, a better indicator has been developed presenting the impacts of design choices on passengers. This chapter demonstrated this added value. It is shown that service reliability affects the travel time substantially (by extending the waiting time). A rough estimate showed that about € 12 million is lost per year in The Hague, due to unreliability of buses and trams. This estimate has been calculated based on the value of time and the extended travel time and we expect this value to be at least twice as high, if the variability of the extended travel time variability is considered as well.

Our international survey confirmed the statement from Chapter 2 that in practice there is a strong focus on supply-oriented indicators. There appears to be a wide variation in definitions and proposed measurement locations. Our analysis for the tram lines in The Hague using the indicator additional travel time, showed that indicators used in practice might lead to inconsistent conclusions, while additional travel time proved to be a more complete and consistent indicator.

In the next chapter we will combine the theoretical analysis of Chapter 2 and the empirical data of this chapter, to determine planning instruments that improve service reliability. We will perform an analysis of causes of unreliability and an overview of instruments improving service reliability at all planning levels will be given. Next, we will make a selection of promising strategic and tactical instruments, which we will analyze and assess in Chapters 5 and 6.

4. Planning instruments improving service reliability

4.1 Introduction

After our theoretical analysis of service variability and reliability in Chapter 2 and the actual impacts in practice we illustrated in Chapter 3, we will present in this chapter a number of planning instruments that facilitate enhanced service reliability. The first part of this chapter presents our research on causes of service variability and unreliability, being the first step toward service reliability improvements. Based on these causes, the second part of this chapter deals with our main research objective to be addressed, namely possibilities of improving service reliability.

In Chapter 1 we introduced the hypothesis of our research that during all planning stages of urban public transport, significant opportunities exist to improve service reliability. The main focus nowadays in practice is however restricted to instruments applied mainly at the operational level. Planning instruments applied in practice mostly are limited to traffic light priority and exclusive lanes. Although impressive results may be achieved in this way, as will be demonstrated in this chapter by a case study of a new light rail network in western Netherlands, we will also show that service variability is not eliminated sufficiently, even when a comprehensive program on improving service reliability is executed.

Our hypothesis is that additional attention at the planning stages leads to a substantial increase of service reliability. At all levels of public transport planning and operations, being strategic, tactical and operational, instruments and design choices are available improving the level of service reliability. We provide in this chapter a new comprehensive overview and we will illustrate relations between causes and improvement instruments, supported by a literature review and practical experience. At the operational level, remedial instruments mainly aim at reducing the effects while during the planning stages prevention of service variability and unreliability is possible. However, some operational instruments may require certain planning conditions to maximize their impact. During the planning stages our feedforward loop should be applied, as we introduced in Section 2.6. We adjusted the general principle of feedforward to public transport planning and operations with regard to service reliability. The public transport planning process should be adjusted according to the expected, operational disturbances enabling a higher level of service reliability. In this chapter, we present a new look at planning instruments, thereby selecting potential instruments improving service reliability.

The outline of this chapter is as follows. Section 4.2 starts with an overview of the causes of service variability and reliability. Section 4.3 then continues with describing service reliability improvements in practice. This section will describe the operational level and instruments applied at this level. In addition, a new control philosophy is presented of a light rail network in The Hague. Both the design and the actual results of a comprehensive reliability improvement program are shown, which is unique of its kind. In Section 4.4 we present possibilities of service reliability improvement during the planning of public transport. Both the strategic and tactical levels are described and we introduce instruments enabling enhanced service reliability. We propose a new public transport design process with regard to service reliability, consisting of a feedforward mechanism as part of the chain of planning and operations. In Section 4.5, the main conclusions of this chapter are given. In Chapters 5 and 6 we will continue on the feedforward mechanism analyzing instruments at strategic and tactical design, which are introduced in this chapter.

4.2 Causes of service variability and unreliability

4.2.1 Introduction

While the previous chapters dealt with the phenomenon of service variability and service reliability and how to quantify and calculate these, this section will present an analysis of the causes that lead to service variability and unreliability. Knowledge of these causes is the first step towards increasing the level of service reliability. In Sections 4.3 and 4.4, we will provide a new, comprehensive overview of the potential improvement instruments.

The mismatch between the schedule and operations has already been introduced in Chapter 2 while Chapter 3 provided practical examples. Two main types of service variability were shown, namely terminal departure variability and trip time variability. The latter may be divided into variability in driving time, stopping time and dwelling time. In addition to initial variability, Section 2.3 showed the mechanisms of variability propagation. In this section, the question will be answered what possible causes of the mismatch are. Several causes will be presented which are responsible for deviations and variability. Attention will be paid to whether they are internal or external, which imply the possibilities for the operator and public transport authority to deal with them. To identify the causes, we analyzed the processes of planning and operations with regard to service reliability and performed a literature review (Nelson and O'Neill 2000, Cham and Wilson 2006, Veisseth et al. 2007). Figure 4.1 shows the main causes of service variability and also indicates which element is affected. The next subsection will describe all these causes and their impacts. Section 4.3 will show what kind of operational instruments may be used to eliminate these causes or reduce their effects and Section 4.4 will introduce planning instruments aimed at a higher level of service reliability.

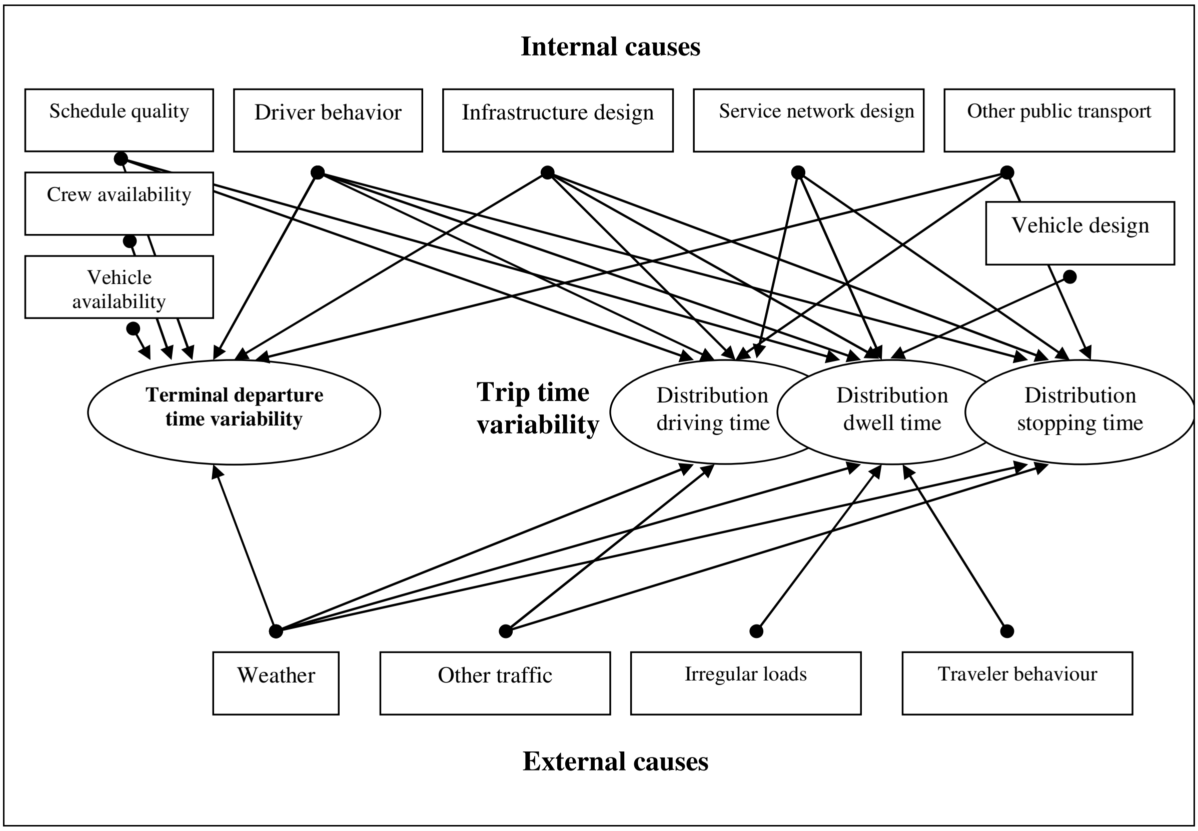


Figure 4.1: Main causes of service variability in urban public transport

4.2.2 Terminal departure variability

Departure variability at the terminal is of main influence on the mismatch between schedule and operations. Variability occurs if departure times differ (for instance late and early departures on the same route at the same terminal). Looking at the process at the terminal, the following elements may be recognized:

- Arrival of vehicle (from depot or previous trip);
- Alighting (if terminal is passenger stop);
- Vehicle inspection (optional);
- Turning the vehicle (using a tail track or loop);
- Drivers' break (including schedule slack time (optional));
- Change of driver (optional);
- Boarding (if terminal is passenger stop);
- Departure of the vehicle.

The succession of the elements depends on the design and type of the terminal. Some activities will be performed in parallel. After our analysis of the processes above, we found the causes for variability in departure times as presented below:

- *Crew availability*
  To depart on time it is necessary that resources are available and ready on time. Delays in previous trips and shifts may create departure delays.
- *Vehicle availability*
  In addition to crew availability, the vehicle should be ready and available on time as well.
- *Terminal infrastructure configuration*
  Especially in rail-bound traffic, the design of terminals may influence the departure delay. If the provided capacity is not sufficient, delays are to be expected, due to other public transport using the terminal as well (Kaas and Jacobsen 2008).
- *Schedule quality*
  If the schedule is loose (too much trip time in the schedule than actually needed), drivers tend to depart late (depending on their attitude and driving style). The other way around is a tight schedule that leads to an early departure. Another issue of schedule quality is the amount of slack in layover time. The amount of slack determines the possibility to recover from an arrival delay of the previous trip.
- *Driver behaviour*
  How disciplined is the driver to depart on time and does the driver adjust his departure time if delays are too be expected (e.g. in case of road works)?

As mentioned in Section 2.3, dealing with variability propagation, the arrival of the previous trip is also important. If vehicles tend to arrive late and slack is minimized, departures will be delayed as well. In Section 5.2, we will deal in detail with the impacts of terminal design on departure variability.

4.2.3 Causes of trip time variability

In Chapter 2, trip time variability is distinguished as one of the main elements of the mismatch between the schedule and operations. Even when the focus is on specific periods during the day and year, variability arises, as demonstrated in Chapter 3. The objective of this subsection is to find and describe its causes. In describing the causes, a distinction is made between internal and external ones. This clarifies which actor is able to improve which element. The analysis is done by dividing trip time into three components, namely driving time, stopping time and dwelling time.

Shalaby et al. (2001) show that trip time variation not only depends on service trip time (or line length) itself, but is also affected by the number of stops made, the number of signalized intersection passed and the number of vehicles per hour per lane. Abkowitz and Engelstein (1983) found that average trip time is affected by line length, passenger activity and number of signalized intersections. Most researchers agree on these basic factors affecting trip times (Abkowitz and Engelstein 1983; Levinson 1983; Abkowitz and Tozzi 1987; Strathman et al. 2000).

Considering the trip time components individually, we analyzed different processes during a vehicle trip to gain insights into the causes of total trip time variability. The first process we analyzed is the driving between stops, including accelerating, braking and unplanned stopping. In Chapter 3, empirical data demonstrated this variability is substantial. Since the causes of stopping may also be responsible for slowing down vehicles, these two components are presented in one overview. The causes presented below are responsible for actual driving time and stopping time variability.

Internal causes:

- *Driver behaviour*
  The driving style of every driver differs, resulting in faster or slower trips, creating variability in driving time. In addition, slowing down or stopping completely also depends on driving style.
- *Other public transport;*
  Both on the same route as on junctions, other public transport may affect the driving and stopping time variability. In case of signalized sections this influence is most of time even larger, especially when frequencies are close to the theoretical capacity of a track or junction. The probability of delays will then increase, also resulting in service variability (Goverde et al. 2001, Van Oort and Van Nes 2009a, Landex and Kaas 2009).
- *Infrastructure configuration*
  The configuration of the infrastructure (stops, lanes, junctions) may be designed in such a way that service variability may occur. This concerns for instance the capacity of the infrastructure. Another result of the configuration is the interaction with other public transport and traffic. If capacity is not sufficient (some) vehicles will suffer delays and variability will arise.
- *Service network configuration*
  The configuration of the service network may be of influence on service variability. Examples are the number of lines on the same route or stop and the length of lines. The kind of service network configuration may enforce other causes, as the impact of other traffic and driver behaviour. Longer lines for instance affect all causes mentioned. In the schedule, multiple lines may be presented as a higher frequent, coordinated service, while in practice service variability increases due to interaction between the different public transport lines. Another example is synchronization of lines. To ensure transfers, lines and schedules are synchronized. This dependency of lines may lead to additional variability, since delays are transferred between lines.

- *Schedule quality*
  The schedule may affect the way drivers operate. If the schedule quality is not sufficient, this may cause behaviour of drivers causing service variability. If the trip time is not planned correctly, for instance, some drivers may drive according to the schedule and some will drive how they are used to. This will thus introduce service variability.

External causes are:

- *Other traffic;*
  The influence of other traffic is mainly visible at junctions, both with traffic lights and without. Due to different situations for every single vehicle service variability arises. In addition to junctions, tracks shared with other traffic and areas shared with pedestrians for instance are causes for service variability as well. The extent to which this cause affects driving and stopping time variability depends on the level of right of way. This may vary from at grade to exclusive lanes (with shared intersections) or mixed operations.
- *Weather conditions.*
  Different kinds of weather and the different driver behaviour accordingly may result in variability (Hofmann and Mahony 2005). This mainly occurs when the weather is not in the regular state, since regular processes are disturbed then.

In general, the variability increases with the length of the line. Looking at dwell time, Section3.3.2 already demonstrated the probable size of the distribution of this trip time element. It was demonstrated that the dwell time variability was substantial and thus an important factor creating service variability and unreliability. The process of dwelling consists of the following elements:

- Braking;
- Opening doors;
- Alighting and boarding (serial or simultaneously);
- Closing doors
- Accelerating.

When analyzing this process, the following causes for variability in dwell times may be distinguished (if not explicitly mentioned above):

Internal causes:

- *Driver behaviour*
  With regard to dwelling, the driver behaviour concerning opening and closing doors and the extent to which is waited for late arriving passengers are of influence on service variability.
- *Vehicle design*
  Weidmann (1995), Lee et al. (2008) and Fernandez (2010) showed the impact of the number and position of doors of vehicles enabling an optimized dwell process. Vehicles and/or platforms enabling level boarding and alighting are also of influence. A suboptimal design, related to passenger behaviour, may result in dwell time variability.

- *Platform design*
  The platform design affects the (variability of) dwell times by affecting the passenger behaviour. The design may lead to a distribution of passengers over the platform enabling an optimal dwell process. Width, length, location of sheds and other facilities are important elements and if design is suboptimal, variability may arise.

External causes:

- *Passenger behaviour;*
  Several types of passengers have different boarding speeds (speed differs for instance due to age, experience, luggage) resulting in variability in dwell times. The way passengers make optimally use of the all doors of the vehicle is important too. This is related to vehicle and platform design.
- *Irregular loads.*
  Due to a different number of people boarding and alighting for every single trip, variability of dwell times will occur.

On an aggregate line level, the number of stops is of importance when looking at dwell time. Thus line length is important affecting variability of dwell times too (besides driving time) as is stop spacing.

4.2.4 Conclusions

Above, the main causes for service variability are presented categorized by terminal departure variability and trip time variability. The latter consists of three components that are driving, stopping and dwelling. Chapter 3 already demonstrated the impact of the variability of these components, all being substantial. Both internal and external causes are presented. The main internal causes are other public transport, driver behaviour, schedule quality and network and vehicle design. External causes are the weather, other traffic, irregular loads and passenger behaviour. This section showed that the result of planning stages, being the infrastructure network, the service network and the timetable, are part of the main causes. This implies thus that during the planning processes opportunities exist to enhance service reliability. The next section will focus on ways how to improve service reliability. First, the practical approaches are presented and afterwards, the possibilities at the planning stages are investigated.

4.3 Improving service reliability in practice

4.3.1 Introduction

Chapter 1 showed that service reliability is considered an important quality aspect of public transport by the public. In practice, much focus is on the operational level when dealing with improving service reliability. At the operational level, it is where variability arises and it seems logical to remedy this afterwards with instruments at this level. This section deals with the operational level and its remedial instruments. First, the operational level and its main characteristics are described. Secondly, operational instruments tackling service unreliability are presented and described. In addition, a practical case of service reliability improvement is presented. A new light rail network near The Hague is used as an illustration to show possibilities and actual effects of service reliability improvement. This case shows that the instruments applied at the operational level as such are not sufficient to achieve a sufficiently high level of service reliability. The next section then will show how instruments during the planning process will help to address this shortcoming.

4.3.2 Operational level of public transport

The operational level of public transport is the level at which the service is provided to the passengers. Actual trips in time and space are offered and passengers may use them to travel from origin to destination. All main characteristics of this level are summarized in Table 4.1 and will be explained in the next part of this section.

Table 4.1: Characteristics of the operational level of public transport

Level	**Time window**	**Input**	**Output**	**Actors**
Operations	Days-Real time	- Network - Schedules - Available crew - Available fleet	Public transport services (actual trips in time and space)	- Passengers - Drivers - Dispatchers

Service may be provided after the planning of both the network and timetable has finished. The time window of the operational stage is real time, but daily planning is involved as well. This concerns the actual planning of drivers and vehicles that is necessary due to a mismatch of the expected and actual number of available drivers and vehicles. The objective of the operational level is to operate as close to the schedule as possible. In urban public transport, often central dispatchers guard the operations having possibilities to adjust the operations if deviations (are going to) occur. Recent developments enable better communications between dispatchers and drivers in addition to real-time monitoring tools (Van Oort and Van Nes 2009a). The operational level is the actual product of public transport. Customers experience the service and partly based on this, they decide to travel next time again by public transport or another mode. To monitor the service level and customer satisfaction (enabling reporting and optimizations of the operations), measurements and surveys are conducted at the operational level. We distinguish two main types:

- *Supply monitoring*
  This type evaluates the provided service from a supply-side perspective and aims at quantifying what is offered. The most important one is Automated Vehicle Location System (AVL) ((Muller and Furth 2001, Strathman et al. 2002). AVL consist of a computer in the vehicle registers all "activities" of the vehicles (e.g. driving, stopping, doors open) with time and location. Management report programs, as Tritapt (Muller and Knoppers 2005), transfer the board computer data in useable information (e.g. graphs and tables) showing for example schedule adherence and speed. Although, traditionally, this type of monitoring is performed off-line, recent developments also enable real-time loops.

- *Customer satisfaction*
  Besides measuring what is provided, it is very important to know, how passengers experience the performance. Often, customer surveys are performed to measure this experience. Examples of items that are of importance are comfort, tidiness, sense of security, crew behaviour and reliability.

Besides customer satisfaction, surveys are used to find out how many passengers travel on each link (manually or automatic, using Automated Passenger Counters (APC)) and what the origins and destinations are. The results of these surveys are useful to optimize both strategic, tactical and operational design and service.

At the operational level, the operator is the main actor. Drivers and dispatchers have an important role concerning operational performance and adjustments. In addition, passengers are of influence at this level. In the previous section, it was already shown that the behaviour of both passengers and drivers influence the level of service variability. Thus when looking at instruments to improve service reliability, their perspective should be considered.

4.3.3 Operational instruments improving service reliability

In Cham and Wilson (2006), a distinction is made of types of improving instruments with regard to their impacts. The first category of instruments consists of instruments reducing (the impacts of) service variability. These are of a responsive remedying type. The second type of instruments is preventive. At the operational level, the main applied instruments are of the responsive type. In Figure 4.2, such responsive instruments are shown. These instruments are only used after disturbances have occurred and thus are regulators in a feedback loop. Due to this responsive character, they all are applied at the operational level. However, to apply some of these instruments, special conditions at the planning levels are required (concerning timetable planning for instance) to maximize the impact of the instrument. If such conditions are required at the strategic and/or tactical level, this is shown in Figure 4.2 as well. Section 4.3.3.1 will present the operational instruments without conditions at a higher level. Instruments that do require such conditions will be described in Section 4.3.3.2.

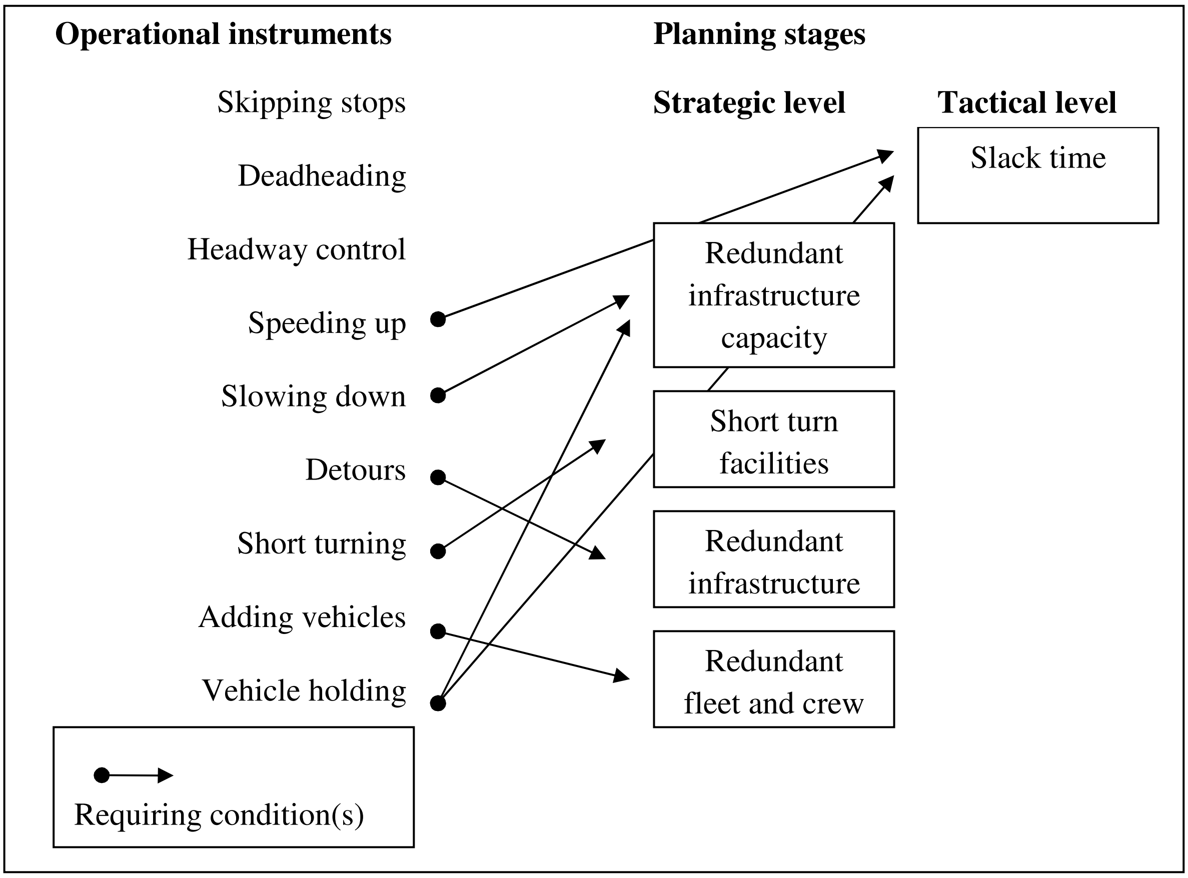


Figure 4.2: Operational instruments improving reliability requiring enabling conditions at the planning stages

4.3.3.1 Improving service reliability during operations

In literature and practice, many references are available of instruments which are helpful to apply these during operations. Section 4.3.4 will present an actual case of improving service reliability at the operational level. Operational instruments and their implications are summarized below. Figure 4.2 summarizes these instruments. All instruments are reductive, meaning they do not affect the causes itself, but only reduce (part of) their effects.

Skipping stops

Skipping stops means that some (minor) stops at the route are not served. When a vehicle is late and has to catch up, skipping stops may speed up the vehicle thereby decreasing the delay (as illustrated by Figure 4.3). However, passengers travelling to those stops have to transfer to the next vehicle. Information to passengers, both at the platform and in the vehicle, is thus very important. This strategy is only useful if the number of passengers travelling over the “skip- stop part” of the route is large and the number of boardings at this section is low. In Koffman (1978), Li et al. (1993) and Eberlein et al. (1998) more detailed research on this instrument is provided.

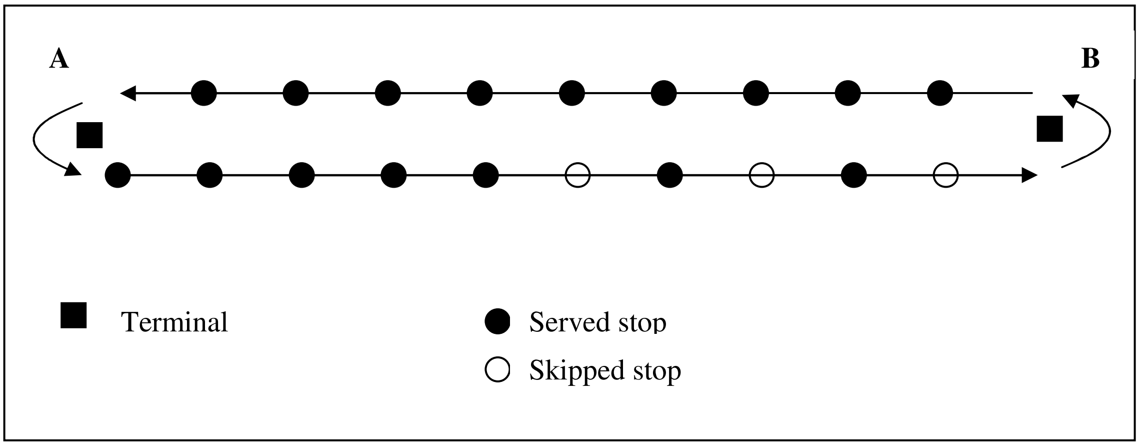


Figure 4.3: Skip-stop in direction A-B

Deadheading

Deadheading is a special mode of skipping stops (see Figure 4.4) namely that the last part of the route isn’t served for passengers anymore. The vehicles will speed up, because dwell time isn’t necessary anymore. Due to this speed up, the next trip (in the opposite direction) may depart on time from the terminal. Again, passenger information is the key success factor of this instrument. Similar to skip-stop strategies, the trade-off between passengers on the last part of the route and passengers in the opposite direction is essential. Deadheading may be applied for one run or all runs on a line. Eberlein et al. (1998) present detailed research on deadheading.

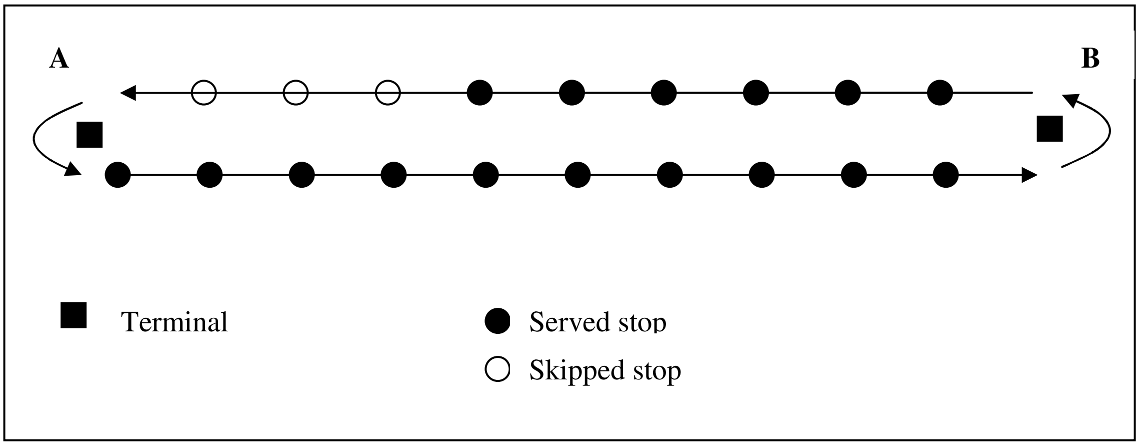
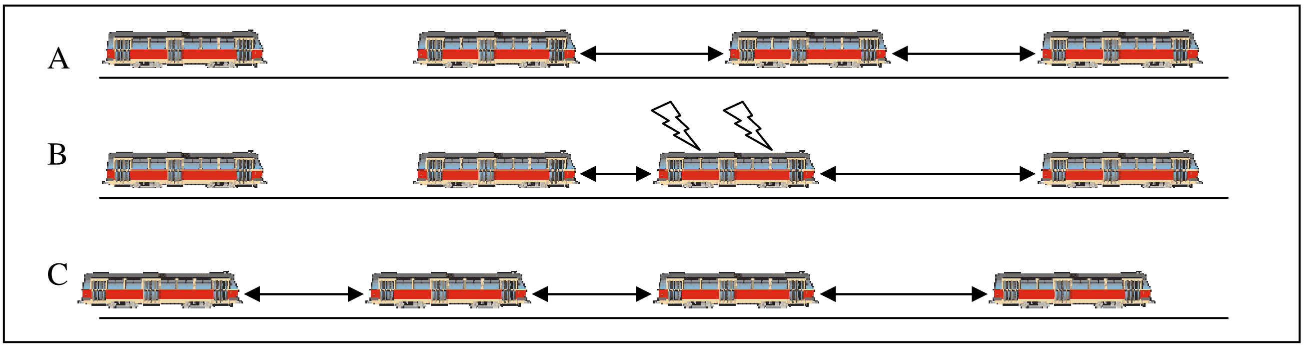


Figure 4.4: Deadheading in direction B-A

Headway control
Headway control implies regulating time intervals between successive vehicles. Exact departure times are of little interest when headways are short and passengers tend to arrive at random at the departure stop (see Section 3.3.3). Headways between successive vehicles are of more importance. If they are constant, average waiting time and overcrowding are minimized. Figure 2.11 in Chapter 2 illustrated the overcrowding due to irregularity.

When a vehicle is delayed in short headway services, headway control may be applied. Figure 4.5 shows the principle of headway control (Van Oort and Van Nes 2009a). Due to a delay, the headway before the vehicle increases and the headway behind it decreases. By delaying these vehicles, regularity will partly restore. This kind of control may be applied to all vehicles on the line or only a fixed amount near the delayed one. Either the control room may be in charge or the driver himself. In both cases, actual information should be available of location and headway adherence. Speeding up the delayed vehicle may be helpful as well, but is often hard, due to security restrictions. An actual case of The Hague, using this instrument, will be presented in Section 4.3.4. In Pangilian (2008) and Delgado et al. (2009), cases of headway control are presented as well.



A: Vehicles drive with equal headways
B: One vehicle gets delayed and the headway in front increases, behind it decreases
C: By slowing down successive and preceding vehicles the regularity will be partially restored

Figure 4.5: Principle of headway control

4.3.3.2 Operational instruments requiring planning conditions

A special category of operational instruments is the one with instruments requiring certain choices at the tactical and strategic level to maximize the impact of the instruments. These instruments are closely related to the output of the planning levels, being the network and timetable. Without such conditions, some instruments may still be applied, but service variability might not be reduced then or might even increase. During the design process it is important to already consider these instruments. Often, this is several years before actual operations. All instruments in Figure 4.2 are analyzed concerning the possible relationship with the timetable and network and are shown below.

Speeding up vehicles

Speeding up vehicles may consist of increasing the driving speed as well as decreasing the stopping times. If a vehicle gets delayed, the theoretically easiest solution is to speed it up. First of all, guarding traffic safety is very important when this instrument is applied. But another important issue is the design of the schedule. The amount of slack in the schedule (and the exact location of this slack) determines the extent to which speeding up (compared to the schedule) is possible. If an operational speed of 25 km/h is possible and the trip times are based on 20 km/h, speeding up is quite easy. If in this case trips are designed on an average of 24.5 km/h speeding up gets harder and the effect will be smaller. Gifford (2001), Banks (2002) and Chang et al. (2003) present a more detailed research on this topic. Vromans (2005) provides research on this topic in heavy railways.

Slowing down vehicles

Slowing down vehicles to increase schedule adherence may consist of both decreasing driving speed and increasing stopping time and is an effective instrument as well. If vehicles drive faster than they are planned to do (due to both operational and timetable issues), slowing down helps them to get back on schedule. The requirement in the network design for this instrument though is redundant capacity at the track or stop where speed is reduced. Especially if infrastructure is shared with other traffic or public transport, delays may be introduced for them. Mostly, the capacity constraint is important for rail bound service due to less flexibility, but also bus services may experience negative consequences of restricted capacity. The bus terminal in Utrecht in the middle of the Netherlands is such an example. About 200 buses use this terminal per hour and space is limited. In Gifford (2001), Banks (2002) and Chang (2003) slowing down vehicles is described in further detail.

Detours

A detour is an alternative route between parts of the original route. Detours are a very effective measure in case of blocked infrastructure. But also when infrastructure is still available (i.e. recurrent delays are experienced), schedule adherence may be enhanced by applying detours. If detour routes are available enabling vehicles to catch up (e.g. by shortcuts) schedule adherence may increase again, similar to the skip-stop instrument. However, this instrument mainly aims at non-recurrent delays. Important condition for applying this instrument is that the (redundant) shortcut infrastructure should be available (in time and space) and especially in rail bound systems they should be designed and constructed additionally. This will need attention at the strategic level and will increase the costs of the infrastructure. Road-based public transport systems may often use existing infrastructure as a shortcut. In Tahmasseby (2009), detours related to infrastructure design are analyzed.

Short turning

An often applied instrument to “win time” is short turning, which means that a vehicle turns into the opposite direction somewhere along the route (instead of at the terminal). This instrument may be both applied if infrastructure is blocked and in recurrent delay situations. When a vehicle is short turned, it only provides transport on a part of the route (see Figure 4.6). Before the end terminal is reached, the vehicle already turns. In this way it “wins” twice the trip time from the short turn node to the terminal. But to apply this instrument, first of all the short turn facility should be available. Again, for road bound public transport, this is easier than in the case of rail bound services. Secondly, the capacity of the short turn facility should be sufficient. This mainly depends on the configuration of the facility. Information provision to passengers is of main importance applying this instrument as well. Short turning may applied for one trip or all trips in a certain time period. More information on short turning is provided by Furth (1987), Shen and Wilson (2001) and Tahmasseby (2009).

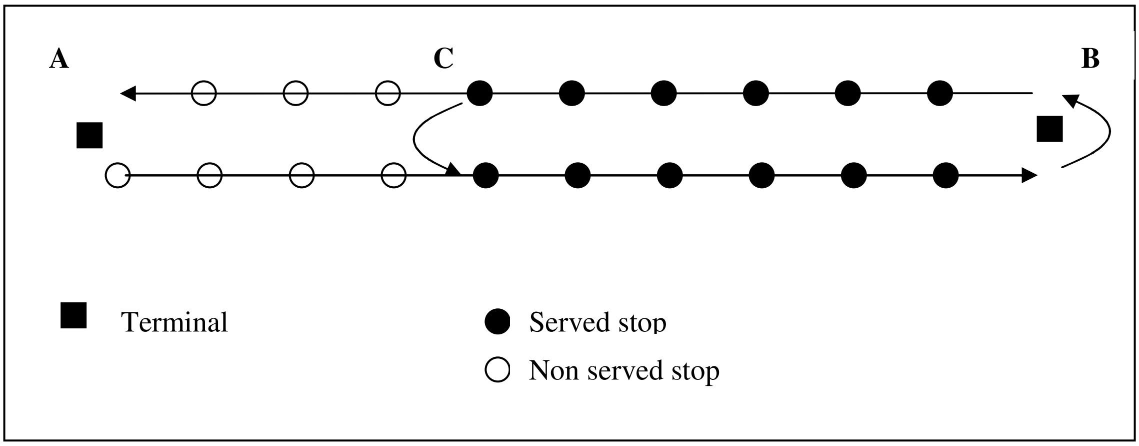


Figure 4.6: Short turning at point C

Adding vehicles (and crew)

Another instrument of restoring schedule adherence is adding vehicles and crew to the actual fleet concerned with the operations. If delays occur on a line and actual trip times are increasing, the actual provided frequency may decrease. Equation 4.1 shows the calculation of the number of vehicles needed (V), providing a certain headway (H) with a given cycle time (T^{cycle}, Equation 4.2). If trip time increases (and no slack is available), Equation 4.1 shows that headways will increase when the number of vehicles is fixed. Inserting a spare vehicle will relax this problem offering some slack. Of course this additional vehicle (and crew) should be available and taken into account during the strategic and tactical design. Especially adding vehicles during the peak hour, when the maximum of vehicles is used, is costly. However, vehicle availability during the off-peak hours may be hard too, due to maintenance activities and costs savings on spare crew.

$$V = \frac{T^{cycle}}{H} \tag{4.1}$$

$$T^{cycle} = T^{tripAB} + T^{layoverA} + T^{tripBA} + T^{layoverB} \tag{4.2}$$

where:

V	= *number of vehicles*
T^{cycle}	= *vehicle cycle time*
H	= *scheduled headway*
T^{tripAB}	= *scheduled vehicle trip time one direction (A to B)*
$T^{layoverA}$	= *vehicle layover time at terminal A*

Vehicle holding

A very common instrument of improving schedule adherence at the operational level is holding (see e.g. Dessouky et al. 2003, Fu and Yang 2002, Liu and Wirasinghe 2001 and O'Dell and Wilson 1999). Holding implies stopping a vehicle if it runs before schedule at a certain point, called holding point. At the holding point the decision of holding is taken, based on the actual schedule adherence and the holding strategy (e.g. applying maximum holding time). This implies design choices at the tactical level, as the method of designing the schedule (e.g. tight vs. loose) directly influences the holding process. Besides, as mentioned at the slowing down section as well, capacity should be sufficient at the holding point, implying redundant infrastructure capacity. Blockings due to holding should be prevented, either by shortening the holding process or extending capacity at the holding point. In Section 6.3, we will deal with this instrument in more detail.

4.3.4 Practical service reliability improvements, the case of RandstadRail[1]

4.3.4.1 Introduction

In practice, much attention is paid to service reliability improvements at the operational level. The previous section showed several instruments at that level. The following case shows the effects of some measures for reliability improvement of RandstadRail, a newly introduced light rail system (replacing former tram and train lines) in the Hague area, started to operate in 2007. This case study shows the significant benefits of control instruments that were applied for the new light rail system, but it also shows that the problem of service variability is not sufficiently solved with the instruments applied, how advanced these may seem. This supports our research hypothesis, stating that both instruments at the operational level and at the planning levels should be applied.

RandstadRail consists of two main networks (illustrated in Figure 4.7):

1. The former tram lines 3 and 6 in The Hague area connected to the former heavy rail line in Zoetermeer (called “Zoetermeerlijn”). HTM, the public transport company of The Hague operates theses lines;
2. The secondary, former, heavy rail line between The Hague and Rotterdam (called “Hofpleinlijn”) is connected to the metro network in Rotterdam. The public transport company of Rotterdam (i.e. RET) is operating this line.

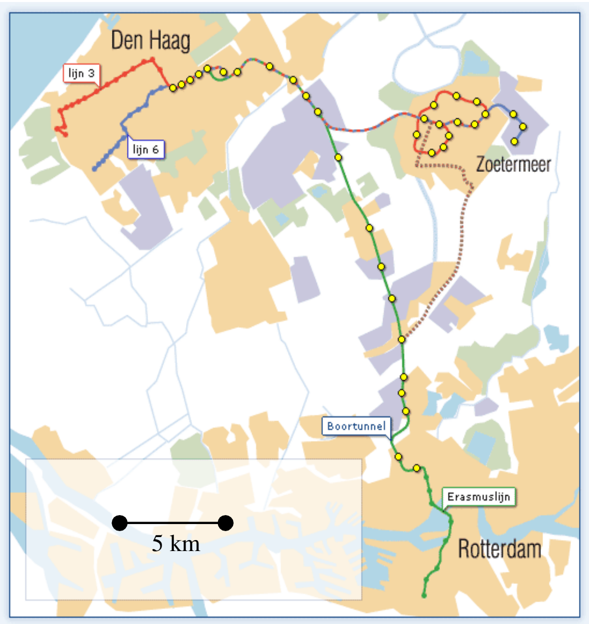


Figure 4.7: RandstadRail network

[1] This section is based on a reviewed article published in the Transport Research Records (Van Oort and Van Nes 2009a)

Our focus is on the Zoetermeerlijn, the connection of the former tram lines of The Hague with the former heavy rail line in Zoetermeer. This network consists of two lines, one of 33 km and 41 stops and one of 27 km and 31 stops. These two lines are supported by additional lines during rush-hour on parts of their route.

Before the start of RandstadRail, public transport services in The Hague were not controlled in a sophisticated way and during the trip, substantial trip time variability occurred. This variability exceeded the planned headways of RandstadRail (i.e. 2.5 minutes during peak hours). Without additional measures, these planned headways were not achievable and instruments had to be applied. The next section will describe these instruments in detail, being part of the control philosophy.

4.3.4.2 Control philosophy

As stated in the former section, variability in trip times must be prevented. To achieve this goal HTM designed a new, three-step control philosophy. Figure 4.8 illustrates these steps, which are described in more detail below. The steps present another categorization of control instruments, than presented in Section 2.6. The focus of Figure 4.8 is on the type of instrument, while Chapter 2 showed the different processes during public transport design, being strategic, tactical and operational. The preventing instruments are applied at all levels, while coping only focuses on the tactical level. Adjusting instruments are solely applied during operations.

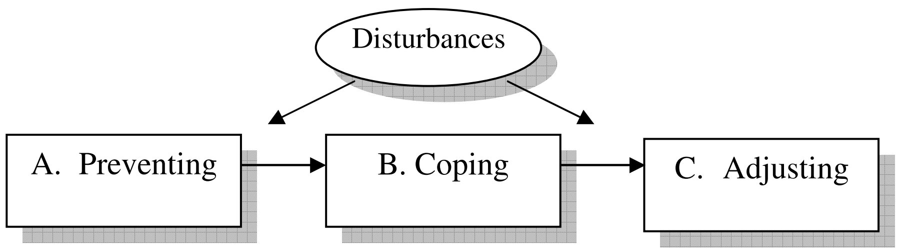


Figure 4.8: Control philosophy of RandstadRail

- *Step A: Preventing*
  The first step is preventing the variability from occurring. This is the most important step since an ounce of prevention is worth a pound of cure. Different ways exist to avoid variability. For RandstadRail, the main preventive adjustments were the improvement of the infrastructure (more exclusive lanes, traffic light priority and enhanced stops), new vehicles (with broader doors, level boarding and alighting and a display showing the actual schedule adherence to the driver) and the obligation to dwell anytime at every stop.

- *Step B: Coping with deviations*
  The second step in the philosophy is dealing with the deviation by planning additional time in the schedule at stops, trajectories and terminals. Small deviations may be solved this way. Carey (1998) and Israeli and Ceder (1996) deal with this topic as well. Adding additional time in the timetable enables late vehicles to catch up. This additional time is a trade-off of operational speed and reliability (as discussed by Furth

and Muller 2009). The larger the amount of slack time is, the higher service reliability will be, but the lower the average operational speed of the vehicles (if vehicles are not allowed to drive early) will be as well. The slack time may be added to different parts of the trip time, being driving time, dwell time and layover time.

- *Step C: Adjusting operations*
  Variability may still occur even after steps A and B are completed. In that case, the final step, adjusting, is performed. In Section 4.3.3, several operational instruments have been described. Adjusting the operations of RandstadRail is done by the dispatchers in the central dispatch room. They have a total overview of all vehicles and their punctuality. Dedicated software tools are used to adjust operations and inform drivers as well as passengers. The first goal is to guard punctuality. Dispatchers are warned by the system, when punctuality is about to exceed certain thresholds. The secondary goal is to achieve regularity. If it is not possible to restore schedule adherence (e.g. because disturbances are too large) the dispatcher may apply headway control. This principle was explained in Section 4.3.3.

4.3.4.3 Improvement of actual operations

After the start of RandstadRail services, a study of the actual effects of the applied instruments was performed. RandstadRail confirms an improvement of terminal departure punctuality. The percentage of trips departing with a deviation between –1 and +1 minute increased from 70% to 95%. Figure 4.9 shows the standard deviation of the dwell time of all stops in the city before and after the transformation of tram line 6 into RandstadRail 4 (RR). At almost all stops the standard deviation decreased. Table 4.2 shows that the average dwell time improved from 28 to 24 s. per stop and the standard deviation has been reduced from 20 to 7s. This enables more reliable operations with a higher level of service quality.

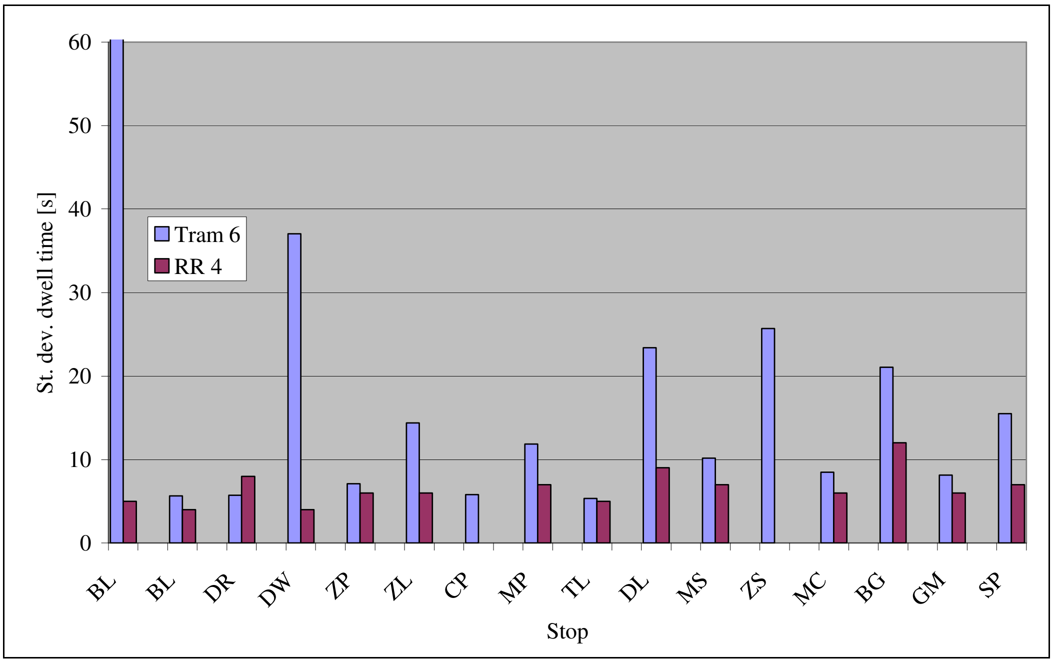


Figure 4.9: Standard deviations of dwell times per stop before and after the introduction of RandstadRail line 4

Table 4.2: Average dwell time of former tram line 6 and of new RandstadRail line 4

	Average dwell time	Average standard deviation
Tram line 6	28 s.	20 s.
RandstadRail 4	24 s.	7 s.

Table 4.3 shows the average total unplanned stopping time per trip before and after the transformation of tram line 6 into RandstadRail. The average value of delay has decreased and the de standard deviation is also smaller. Figure 4.10 shows the average length of unplanned stopping along the line before and after the introduction of RandstadRail. This figure clearly illustrates the decrease of this loss of time.

Table 4.3: Average unplanned stopping time of former tram line 6 and new RandstadRail line 4

	Average total unplanned stopping time	Average standard deviation
Tram line 6	90 s.	60 s.
RandstadRail 4	20 s.	30 s.

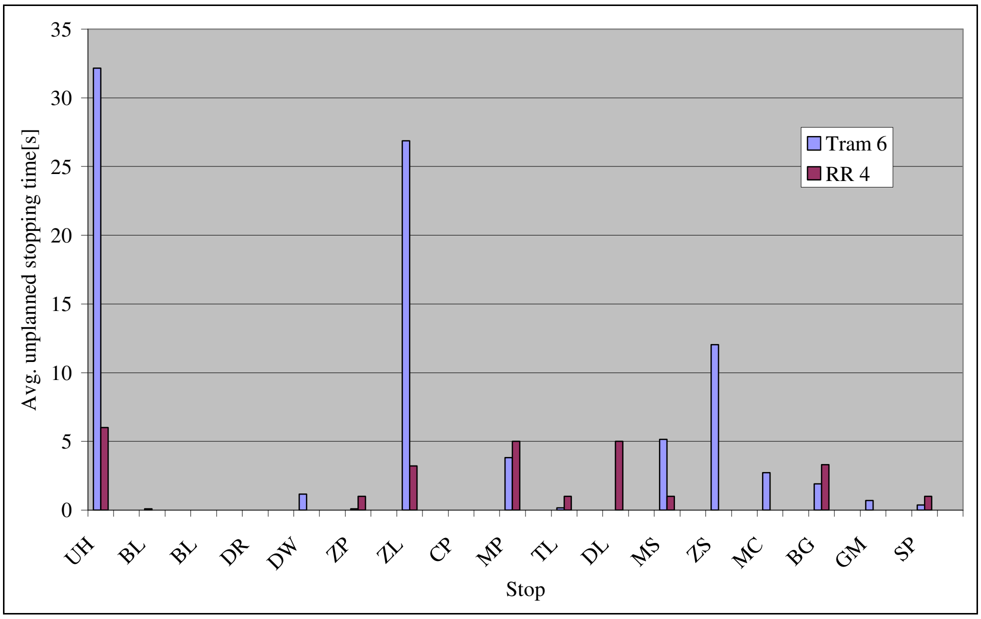


Figure 4.10: Standard deviations of unplanned stopping between the stops before and after the transformation of tram line 6 into RandstadRail line 4

Figure 4.11 shows the 15th and 85th values of schedule deviations at all stops of RandstadRail 4 before and after the application of the control philosophy. This figure shows that the deviations are reduced and that negative deviations (i.e. driving too early) have been reduced. Due to higher schedule adherence average travel times of passengers are decreased. However, the level of service variability is still substantial and the level of service reliability may be improved further.

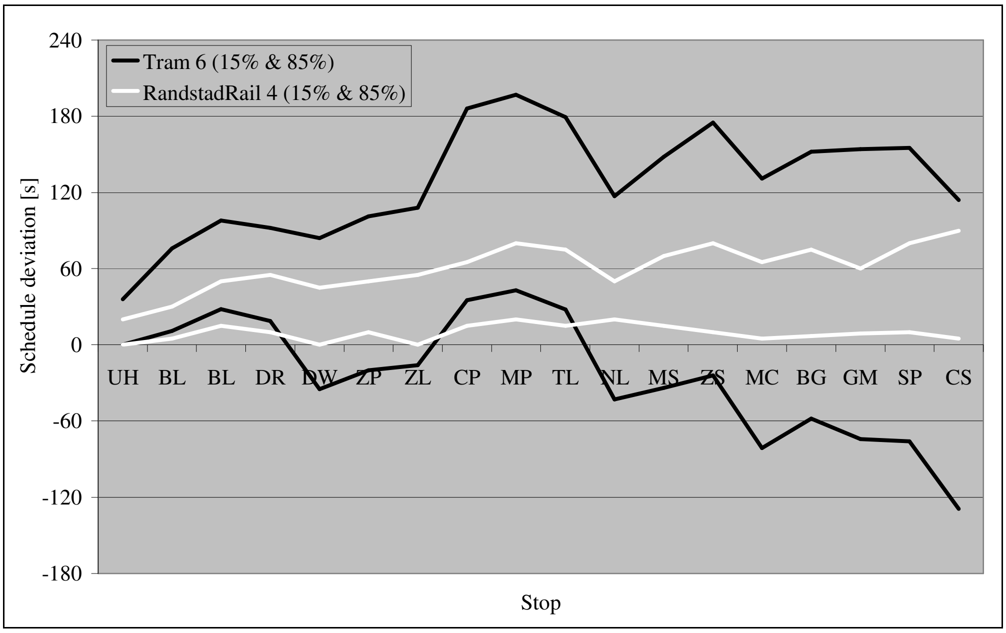


Figure 4.11: Schedule deviation of former tram line 6 and of new RandstadRail line 4 (15- and 85- percentile values)

4.3.4.4 Conclusions

This subsection showed the impacts of an extensive control philosophy aiming at enhanced reliability of operations. With the introduction of a new light rail system called RandstadRail, much attention is paid to the improvement of operational quality. After some years of operations, it is proven that its service reliability indeed has been improved. However, it is shown that unreliability is not sufficiently removed. Even with so much effort on control instruments, unreliability has not sufficiently vanished. This supports our hypothesis that additional instruments are necessary. Although some instruments during the planning stages are applied (for instance exclusive lanes and vehicle design) design has to be adjusted more at both the tactical and strategic levels, thereby enabling more reliable urban public transport services. In Section 4.4, such instruments and design choices are presented. In Chapters 5 and 6 we will demonstrate that these instruments may improve service reliability. Only the combination of both operational measures (as described in this chapter) and instruments and design choices at the tactical and strategic level, presumably will lead to a sufficiently high level of quality due to enhanced reliability.

4.3.5 Conclusions

Service reliability is an important quality aspect of public transport. In practice, much attention is paid to improve service reliability. Several instruments are applied to reduce the effects of service variability for instance. However, most attention is paid in practice to applying operational instruments only. This section showed several of such instruments, as skip stopping and short turning. It was also shown that some operational instruments require special conditions during the planning stages (for instance slack time and redundant infrastructure). An actual case of service reliability enhancement has been presented in this section as well. It was shown that much reduction of service variability was achieved by applying several instruments. A reduction of dwell time variability by introducing level boarding and alighting and adjusted stop design was demonstrated, next to decreased stopping time due to an improved level of right of way and traffic light priority. However, it was also demonstrated that even with the application of these instruments, there is still a substantial level of service unreliability left. In the presented case, some strategic and tactical instruments were applied as well (e.g. exclusive lanes and new vehicles), but the main focus wasn't on the planning levels. The hypothesis of our research is that at these levels promising opportunities exist to significantly improve service reliability. These planning instruments will, together with the application of operational instruments, achieve a much higher level of service reliability. The next section will present this class of instruments.

4.4 Improving service reliability in the planning process

4.4.1 Introduction

As stated in Chapter 2, unreliability occurs due to a mismatch of planning and operations. Section 4.2 provided causes for the mismatch that are shown by Figure 4.12. Since the match of these two aspects determines the reliability, the solution is also divided in two options. Both adjusting the operations to the planning or the planning to the operations are ways of improving the level of service reliability. The previous section showed operational instruments to improve service reliability. This section will describe the planning of public transport and will provide design choices and instruments capable of improving service reliability. During the planning of public transport many design choices are made with impacts on operations. It is demonstrated in our research that these choices set constraints for the operational level to deal adequately with disturbances and unreliability.

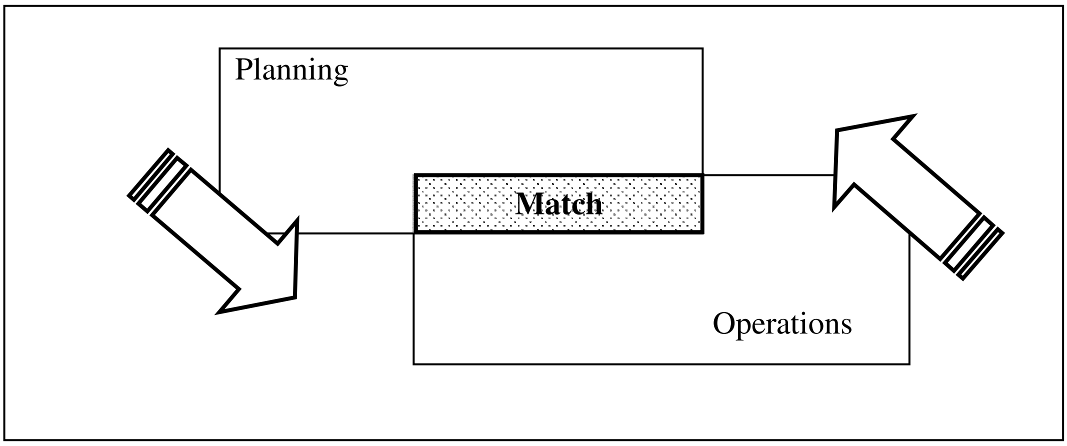


Figure 4.12: Two opposing ways of improving service reliability

4.4.2 Planning process of public transport

Figure 2.2 in Section 2.2 presented the chain of public transport planning and operations. Prior to the operations, as described in Section 4.3, the network and schedule are designed, which are output of the strategic and tactical level respectively. Table 4.4 shows the main characteristics of these levels. They will be described in more detail in the next subsections.

Table 4.4: Characteristics of the planning levels of public transport

Level	Time window	Input	Output	Actors
Strategic	> 2 years	- Political ideas - Historical trends - Existing network - Socio-economic trends	- Infrastructure network - Service network - Capacities	- Authority - Operator
Tactical	1-2 years	- Network - Constraints of crew/fleet	- Crew schedule - Fleet schedule - Public schedule	- Operator - Unions

4.4.2.1 Strategic level

At the strategic level (design) choices are made for a time window of mostly 2 years. At this level, the framework of public transport is determined, taking into account political requirements and demands, historical and future trends and developments (both spatial and transport) and optimization issues. Main variables are the amount of money available, both for operations and investments and the desired level of service. The main output of this stage is the network, consisting of both the infrastructure and the service network. Indicative frequencies are designed at this stage as well. To provide the planned service, the size and type of fleet is determined as well as the size of the crew. Concerning the strategic level, our research mainly focuses on the network design.

The main elements of a transport infrastructure (in our case bus and urban rail) are intersections, links (i.e. tracks and (exclusive) lanes), stops and terminals. The design of all infrastructure elements may have an impact on attainable service reliability. At intersections, impact of other traffic as cars and bikes may disturb the process of operation. In addition, other public transport may cause a delay at intersections as well. In most cities, a hierarchy exists of priority within public transport. For instance in The Hague, light rail has priority over trams. Next to that, trams have priority over buses. Links are potential cause for variation in trip time as well. This mainly depends on whether public transport is the exclusive user of the links or not (using exclusive lanes, tunnels or at grade tracks for instance). Capacity is a main issues dealing with links. Especially when signalling is applied (Kaas and Jacobsen 2008, Van Oort and Van Nes 2009a) capacity is limited and when frequencies are high, deviations are to be expected. Capacity is important regarding stops too. In case of only one line operating with a medium headway, capacity is no issue. But if more lines use the same stop and/or frequencies are high, stop capacity might become an issue and lack of it might lead to delays. Terminals are also of main interest. Functioning as the starting point of the line, disruption will amplify (due to bunching, see Section 2.3.2). Normally, terminals provide some slack in the schedule so delayed arriving vehicle may depart on time again. But if the design is not optimal, delays will knock on in the other direction.

The infrastructure enables the design of a service network consisting of lines, stops and frequencies. Besides line routes and locations of stops, the number of lines and stops are important factors as well. Several kinds of general service line types exist and are analyzed and applied all over the world. In Figure 4.13 we show the main ones (based on Vuchic 2005).

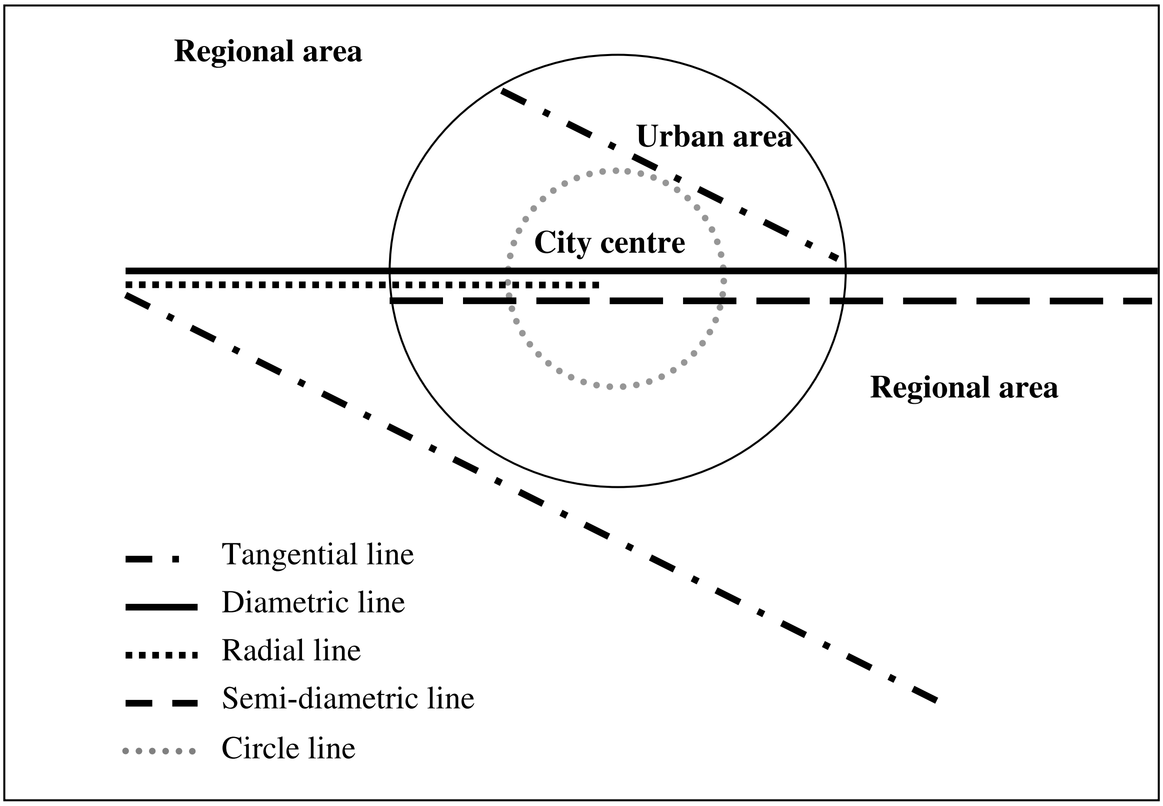


Figure 4.13: Types of urban public transport service networks (Source: Vuchic 2005)

A radial line provides service between the region and the heart of the city centre, while a diametric line is a combination of two radial lines. Semi-diametric lines are in fact extended radial lines, providing a connection over the city centre to the border of the urban area. A tangential line is a connection without reaching the city centre, enabling fast connections between regional areas. Circle lines are a special type of tangential lines. They do not operate in the heart of the city centre but operate around it (or around the urban area) enabling transferless travelling between border areas. In most urban areas, a mixture of the above mentioned network types are used. All types have different characteristics, which is important to note when lines are analyzed.

The main output of the strategic level is the planned service level and required number and type of vehicles, infrastructure network and crew. Often at this level, the public transport authority takes the decisions concerning the network, supported by the advice of operators and consultants. This design process is very complex since urban public transport planning is always a part of total urban planning. This leads to tradeoffs and compromises, concerning budget and space. With regard to the vehicles and crew, the operator is often in the lead. In the Netherlands, organizations of public transport passengers have some influence in the output of this level as well. In this field of actors, different objectives and requirements exist which leads to additional complexity. At the strategic level, little attention is paid explicitly to service reliability. However, some of the causes mentioned in Section 4.2 are strongly related to this level. In Section 4.4.3 we will present strategic instruments dealing with enhancing service reliability.

4.4.2.2 Tactical level

At the next stage, the tactical level, the details of the service plan are determined, namely the exact timetables for passengers, crew and vehicles are designed. The time window of this level is one or two years ahead of the actual operations. Besides the input of the strategic level, it is very common in urban public transport to use feedback data of the operations as well at this level. Historical trip times are often used to design a new timetable (Van Oort and Weeda 2007). Determining the number of drivers and vehicles is a complex job in large networks and is more and more supported by optimization applications. Next to scheduling to provide public transport services, maintenance of vehicles must be considered in the schedule as well. Much research is available on both crew and vehicle scheduling (Bodin et al. 1983, Freling et al. 1999, Haase et al. (2001) and Huisman et al. 2005). In our research the focus is on the public timetable, which is the schedule the passengers use. Crew and vehicle scheduling are not considered.

At this level, the main player is the operator. The objective is to minimize the number of required resources, given a required level of service. At this level, the public transport authority has to approve the output. Most of times, user groups have influence at this stage as well. Besides, in the company itself, driver organizations (e.g. unions) play an important role in approving the schedules. They often check if all agreements are met, regarding trip and layover times, break lengths and working hours.

At the tactical level, little attention is paid explicitly to service reliability. However, Section 4.2 illustrated that some causes of service unreliability are present at the tactical level and that some operational instruments require special conditions at this level. In Section 4.4.3 we will elaborate on the possibilities of improving service reliability at the tactical level.

4.4.2.3 Feedback and feedforward

In the previous subsections we discussed about the two planning levels in public transport while the operational level was presented in Section 4.3. Besides the linear relation between the strategic and operational level, feedback and feedforward may be part of the process as well. Chapter 2 showed the general principles of feedback and feedforward control. In Figure 4.14 the existing feedback loops in public transport, both real-time and long-term, are shown. The long-term loop, using automatic passengers counting (APC) and Automatic Vehicle Location (AVL) and customer surveys (as presented in Section 4.3.2), has a time window of months to years. Timetables and network configurations might be adjusted thanks to feedback. With regard to service reliability however, this is applied scarcely in practice. The main applied loop in practice is the constructing of timetables using actual data as input (Van Oort and Weeda 2007). The real-time feedback loop enables direct adjustments in the operations. Timetable deviations require implementing a set of instruments minimizing the impacts of such deviations. Section 4.3 already presented that at the operational level all instruments are part of the real-time feedback loop.

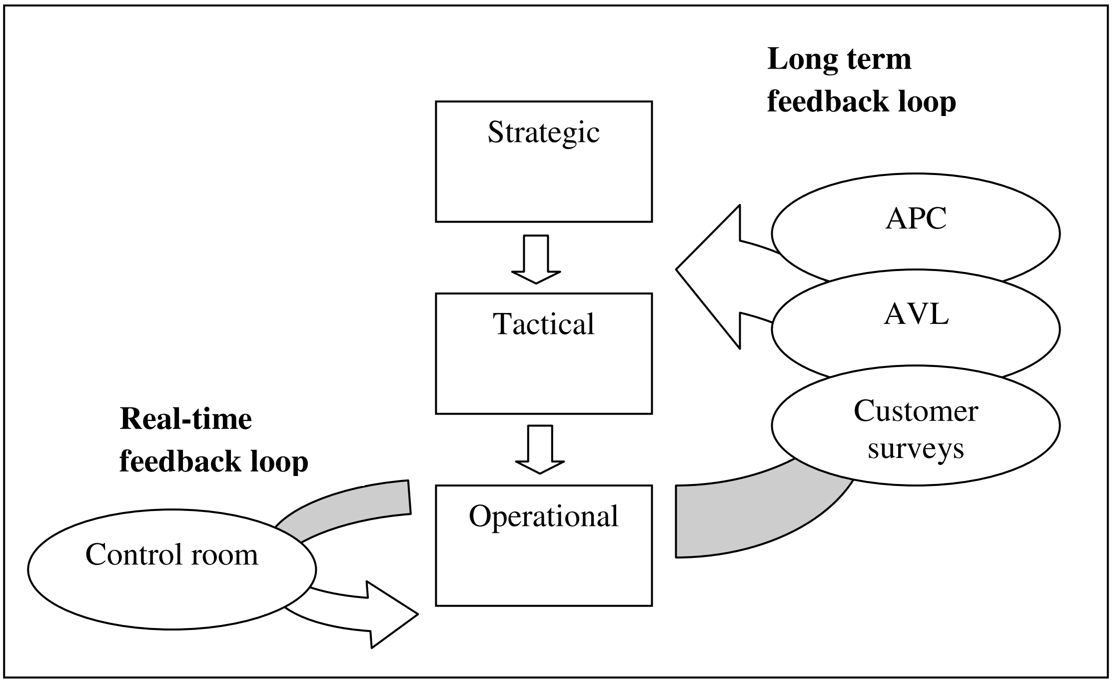


Figure 4.14: Feedback-loops in urban public transport planning and operations

Besides these feedback-loops, feedforward mechanisms are important too. At the strategic and the tactical level, forecasts of the impact of instruments or adjustments of network and schedule would be very useful. Accurate predictions of effects help designers to optimize the system without applying trial and error in real life. Examples of feedforward loops are described by Koutsopoulos and Wang (2006) and Kanacilo and Van Oort (2008), which illustrate an enhanced network and timetable design by using a tool predicting service reliability. Concerning service reliability, these feedforward loops are limited in practice. However, analyzing the causes in Section 4.2 and the operational instruments in Section 4.3, possibilities exist during the planning to incorporate the dynamics of the operational process and to improve service reliability. Section 4.4.3 will elaborate more on the feedforward loop in public transport planning and operations, presenting planning instruments.

4.4.3 Planning instruments improving service reliability

The main objective in our research is to enable enhanced service reliability of public transport by improving the strategic and tactical planning. Looking at possibilities to improve the match of operations and planning, at all three levels of planning and operations, design choices and instruments are available. However, both in literature and practice, the main focus of improving service reliability currently is at the operational level only. Section 4.3 showed such operational instruments. In this section, an overview of possible instruments and design choices at the planning levels is provided to enable selecting promising instruments significantly improving service reliability. These instruments will be discussed in more detail in Chapters 5 and 6.

In Section 4.3, the responsive instruments were presented while the second category of instruments consists of preventive ones. These instruments prevent that service variability and unreliability will arise. Table 4.5 presents such instruments. One of the possibilities of preventing service variability is education and training of drivers, teaching them how to act in such a way that variability due to their behaviour is limited. Issues may be for example driving style, but also illness ratio reduction is of interest with regard to crew availability. Passengers may be coached as well, preventing service variability. Showing passengers the effects of boarding through one door instead of spreading over all doors is an example of passenger education. Another instrument is the design of the platform, which encourages passengers to distribute over the platform enabling smoother boardings. The vehicle design is also of influence, both with regard to the interior (possible throughput, method of ticket selling (e.g. vending machines or drivers)) and the exterior (number and size of doors for instance)). In addition, the spare drivers and vehicles determine to which extent variability may be prevented when actual crew or fleet availability is limited. Although these issues are of importance, in our research we focus on network design and timetable design and thus we do not consider fleet or crew, nor are possibilities investigated concerning behaviour of drivers and passengers. All the other instruments of Table 4.5 will be described in the following subsections.

Table 4.5: Preventive instruments for service reliability control

Instrument	Level	Causes affected
Training and education of drivers	Operational/Tactical	Drivers' behaviour, crew availability
Passenger education	Operational/Tactical	Passenger behaviour
Spare drivers	Tactical	Crew availability
Vehicle maintenance and spare vehicles	Tactical	Vehicle availability
Trip time determination	Tactical	Schedule quality
Interior design vehicle	Strategic	Vehicle design
Exterior design vehicle	Strategic	Vehicle design
Priority at traffic lights	Strategic	Other traffic
Platform design	Strategic	Passenger behaviour
Terminal (capacity) design	Strategic	Infrastructure configuration, other public transport
Stop (capacity) design	Strategic	Infrastructure configuration, other public transport
Exclusive lanes	Strategic	Infrastructure configuration, other public transport, other traffic
Coordination of lines	Strategic	Service network configuration
Length of lines	Strategic	Service network configuration
Stopping distance	Strategic	Service network configuration
Synchronization of lines	Strategic	Service network configuration

4.4.3.1 Improving reliability by appropriate network design

The strategic design may affect the level of service reliability. At the strategic level, two layers are distinguished, namely the infrastructure layer and the service network layer. Separated per layer, the possibilities for improving service reliability are summarized below.

Infrastructure layer

In the strategic design of public transport, infrastructure facilities are part of the design. Examples of design choices concern links and stops of the network, next to terminals and intersections. The following instruments are relevant with regard to service reliability.

- *Terminal design*
  As mentioned in Section 2.3, variability of terminal departures is one the main factors of variability of operations. Figure 4.1 showed several aspects influencing the process of departing (on time). One strategic issue is the configuration of the terminal. In rail bound traffic, this design has a main impact if intensities are large. Capacity constraints limit the number of possible vehicles turning per hour and especially the dynamic character of actual operations has a negative impact. Considering these issues explicitly during design may increase the level of service reliability (see Section 5.2 for details).
- *Exclusive lanes*
  As stated in Section 4.2, one of the causes of service variability and unreliability is other traffic. By introducing exclusive lanes for public transport, driving times are less affected and stopping times will decrease, which helps to achieve a higher level of service reliability (TRB 2003, Vuchic 2005 and Ceder 2007).
- *Stop design*
  Similar to terminal design, stop design (both road and rail bound) may limit vehicle capacity. Combined with high intensities and variability this might lead to additional delays. Taking service reliability into account during the design may improve the level of service reliability during operations
- *Priority at traffic lights*
  Introducing priority at traffic lights may decrease (variability in) stopping times. This will decrease the variability of trip times and thereby decreases unreliability. Several researches have been performed regarding this topic (see for instance Ceder 2007, Chang et al. 2003, Currie and Shalaby 2008). Besides absolute priority (public transport never has to stop or even brake), conditional priority has been introduced (see for instance Muller and Furth 2000). Only late vehicles receive priority, which means that early vehicles have to wait. In Selman and Furth (2009) priority is considered related to the timetable as well. Besides the disadvantage of a technical connection of the schedule, actual punctuality and the traffic light algorithm, this method still leads to stopping times for some vehicles at traffic lights. In addition, the influence of the schedule parameters is of extreme importance as applying a tight schedule will result in all vehicles being late and thus receiving priority.

Service network layer

The available infrastructure network enables a design of the service network. This network consists of lines, stops and frequencies. The design of the service network determines the exact routes and stops. In addition, interaction with other lines is determined (e.g. transfer synchronization or line coordination on the same route). Below, instruments are shown regarding service reliability.

- *Stopping distance*
  One of the largest sources of service variability appears to be the dwell time, as shown in Chapter 3. These differences occur partly because of changes in number of passengers. If there are no passengers on a stop and nobody wants to get out, the vehicle does not need to stop and there is no dwell time. At the level of designing the network attention should be paid to this variation of dwell times to determine the stop

spacing. To improve service reliability, it's best to always have some passengers at a stop, so the vehicle needs to stop every time. This prevents large distributions to occur. Of course the optimal stop spacing is a trade-off of more aspects (see e.g. Van Nes and Bovy 2000 and Van Nes 2002), but service reliability should be taken into account as well.

- *Length of lines*
  Long lines offer many direct connections, serving many stops. Although, the longer the line, the higher the probability of increasing service variability. At the design stage both effects should taken into account, resulting in a trade-off between these two aspects. At this moment, service reliability is not explicitly taken into account at the strategic level. This may lead to suboptimal designs.
- *Coordination of lines*
  In urban public transport networks it is very common to provide several lines on the same route. At a specific branch of the network, combined frequencies are high and many direct connections are offered. Although this design choice seems to improve the network quality at the strategic level, it actually depends on the quality of service at the operational level whether the combined planned frequency and even headways may be provided. In the design process, the expected variability should be taken explicitly into account. Besides attention at the strategic level, coordination also requires attention during the design of the timetable at the tactical level.
- *Synchronization of lines*
  Synchronization of lines is important concerning transfers. In a public transport network, it is hardly possible to connect all origins and destinations, so transfers are unavoidable. To reduce one of the negative impacts of transfers, being passenger waiting time, synchronization of lines may be applied. Frequencies and schedules are synchronized enabling smooth transfers between lines. In fact, this instrument is thus relevant at both the strategic and tactical stage. Much research has already performed on this topic. This instrument concerns both strategic and tactical design, since the timetable is of importance too.

4.4.3.2 Improving service reliability by appropriate timetable design

From the analysis of operational instruments in Section 4.3.3, it was concluded that some of the operational instruments require satisfying conditions at the planning stages. The desired impact of these instruments is maximized if during the planning stages, service reliability is explicitly taken into account. At the tactical level, this concerns slack time allocation in trip and dwell times, with or without a holding strategy. To positively influence service reliability already at the tactical level, the following possibilities exist:

- *Determining trip times*
  As mentioned earlier, planning a tight or loose schedule may have major impact on passengers. The main issue is driving early vs. driving late. Considering these issues while planning the schedule may lead to a better schedule, regarding travel time.
- *Vehicle holding*
  Section 4.3 already presented holding as an operational instrument. As mentioned, holding requires much attention at the tactical level. The amount of holding depends on the type of schedule being loose or tight. If the design of the schedule is optimized concerning holding strategies, this instrument is preventive as well. This design issue has a large impact on operations and travel time of passengers. A trade-off between service reliability and travel speed will arise. The more vehicles are held, the more services will become reliable, but the more travel speed will decrease.

4.4.4.3 Selection of potential planning instruments

Above, several instruments and design choices are presented that enable consideration of operational dynamics during the planning stages and that may improve the level of service regularity. We are looking for instruments improving service reliability in urban public transport at the tactical and strategic level, since in practice much attention is already paid to operational instruments. Much research is already available on the planning instruments of priority at traffic lights, exclusive lanes and synchronization. The implementation of bus lane schemes and traffic signal priority are the most used solutions in this field (as shown by e.g. Levinson and St. Jacques 1998, Waterson et al. 2003, Jepson and Ferreira 1999, Hounsell and McDonald, 1988). Both Ceder (2007), Vuchic (2005) and the Transit Capacity and Quality of Service Manual (TRB 2003) present the different methods and effects. Theory is supported by practical cases. Ceder (2007) describes the results of the introduction of priority measures in 6 European cities, with their impact on travel times and number of passengers. An increased ridership of 10% is measured for instance in Athens. Nash (2003) provides practical results of implementing such priority measures in the city of Zürich, Switzerland. More detailed research on the impacts of priority and bus lanes may be found in Chang et al. (2003), Shalaby (1999), Newell (1998), Eichler (2005), Neves (2006), Kimpel et al. (2005) and Mesbah et al. (2008). Similar to priority, Ceder (2007) and Vuchic (2005) give an overview of the issues which need to be considered in synchronization. More detailed and applied research is for instance done by Bookbinder and Ahlin (1990), Wong and Wilson (2006) and Ceder and Tal (2001).

The instruments we are looking for should offer good possibilities to improve service reliability and should be less researched so far. The case of RandstadRail presented in Section 4.3 showed that some design instruments are already common practice (for instance traffic light priority and exclusive lanes). But even with the application of these instruments, service variability is still substantial. The instruments which we will investigate in more detail are trip time determination, vehicle holding, terminal design, line coordination and line length design. Chapters 5 and 6 will elaborate more on the added value of these instruments. Chapter 5 focuses on strategic design and Chapter 6 on tactical design.

The selected instruments adjust the process of public transport thereby being a regulator in the feedforward loop. Figure 4.15 shows the feedforward loop, with the addition of the strategic and tactical instruments. In Chapter 2, the principles of feedforward were introduced concerning planning and operations of public transport. To achieve a high level of service reliability, this feedforward loop should be applied.

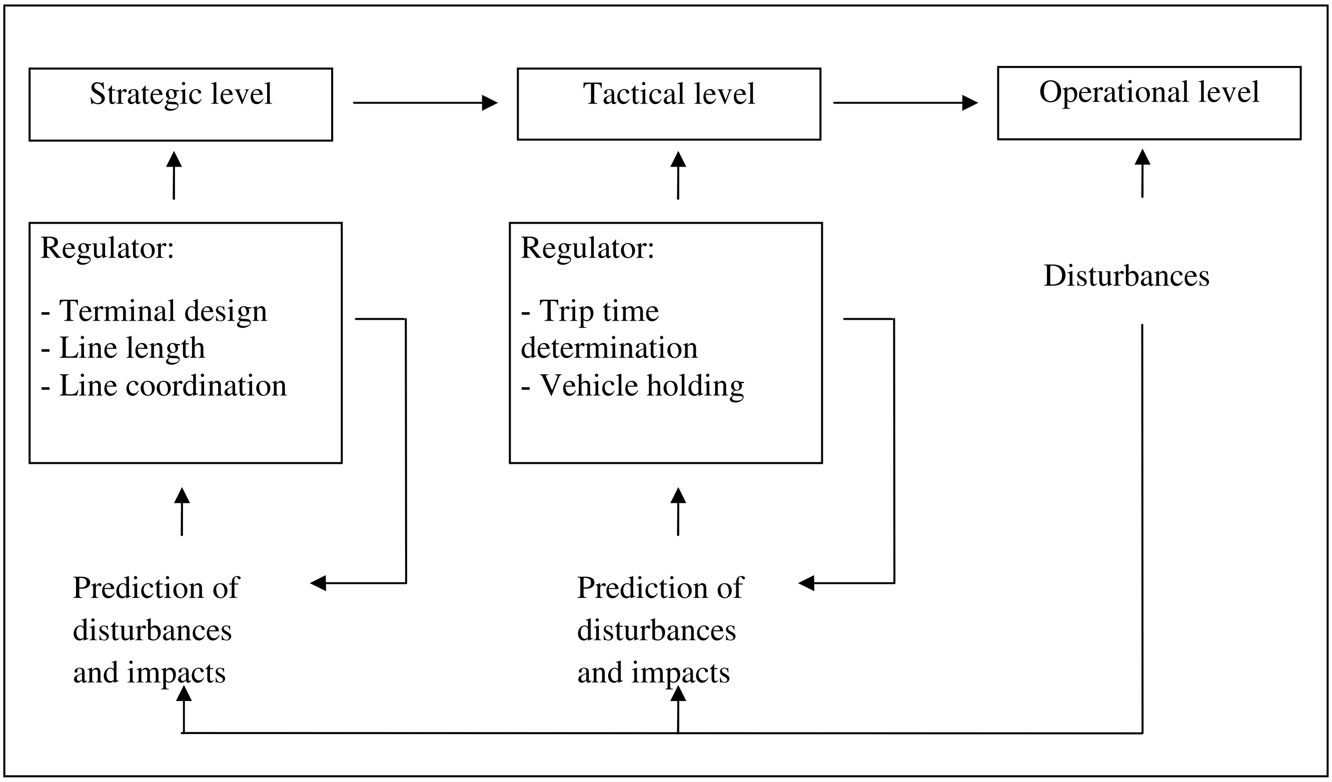


Figure 4.15 Feedforward loop in public transport planning, including our investigated instruments at strategic and tactical level

To apply the feedforward loop, shown in Figure 4.15, it is necessary that at the strategic and tactical design, a forecast of the expected disturbances is possible. This will be done by prediction tools (based on monitored data), which we developed in this research (Van Oort and Van Nes 2004, 2006, 2009, 2010). In addition, the impacts of the disturbances on passengers, the expected level of service reliability, should be predicted as well. In this way, an iterative improvement process of the regulator is possible, optimizing the impact of passengers. In Chapters 5 and 6, we will present methods and tools enabling these predictions which we developed, using and extending our framework presented in Section 2.6.

4.4.4 Conclusions

In this section, the planning process of public transport has been investigated and we explored the opportunities to apply the feedforward mechanism in the public transport design process proposed in Chapter 2. The previous section stated that concerning service reliability in current practice most attention is paid to the operational level. In contrast, in this section, we addressed the possibilities of service reliability improvement during the planning stages. This section showed that several instruments are available at both the strategic and tactical level of public transport design. Some of these instruments, for instance traffic light priority and exclusive lanes, are already common practice. However, most of them are not regularly studied or applied with regard to service reliability. During the network design the instruments of line length, line coordination and terminal design are proper ways to improve the level of service reliability, while trip time determination and vehicle holding are valuable instruments during the schedule design. These instruments are selected since they offer good possibilities to improve service reliability and less research is available so far. They will be investigated in more detail in Chapters 5 and 6.

4.5 Summary and conclusions

In this chapter we presented and discussed possible planning instruments to increase the level of service reliability. To generate these instruments, firstly we have summarized the causes of service variability. The causes have been categorized by terminal departure variability and variability of trip times. Terminal departure variability occurs at the start of the trip and is influenced by for instance terminal capacity, fleet and crew availability, schedule quality and network design. Trip time variability has been analyzed by distinguishing three components that are driving, dwelling and stopping. Several causes of variability of every element are provided. Both internal and external causes are presented. The main internal causes are other public transport, driver behaviour, schedule quality and network and vehicle design. External causes are the weather, other traffic, irregular loads and passenger behaviour. Both the departure variability and the variability of trip times lead to unreliable services. The configurations of both infrastructure and service network proved to be possible causes for service variability and unreliability. Optimizing the design of these networks thus may lead to enhanced service reliability.

This chapter presented a detailed analysis on operations control. Instruments at this level are mainly responsive, which means that they are applied after the disturbances have occurred and do not remove the causes. Some instruments at this level, such as vehicle holding, proved to be more effective if certain conditions in the planning are met. A case study showed that during the design and introduction of the new light rail system near The Hague, called RandstadRail, much effort has been put into applying instruments to improve service reliability. A comprehensive set of control instruments was introduced. It was shown that a large decrease in service variability was achieved. Both dwell and stopping time variability was reduced substantially. Nevertheless, the level of service reliability may still be improved. In this case, only the strategic instruments of priority and exclusive lanes were applied, which means that more strategic and tactical instruments may be applied thereby reducing unreliability of operations.

In this chapter, a comprehensive overview of instruments which may be applied during the design of a public transport network is presented and discussed. This way, the design of the infrastructure, the service network and the timetable are optimized with regard to the level of service reliability. While in Chapter 2, the principle of feedforward was introduced concerning planning and operations of public transport aiming at a high level of service reliability, this chapter proposed planning instruments that facilitate this feedforward mechanism. Upcoming Chapters 5 and 6 will present the results of the analysis of five of such instruments at the strategic and tactical level, namely terminal design, line length, line coordination, trip time determination and vehicle holding, using detailed data of the public transport network in The Hague. These instruments are selected since they offer good possibilities to improve service reliability and less research is available. They adjust the process of public transport thereby being a regulator in the feedforward loop. Chapter 7 will investigate what the combination of these instruments might yield in practice.

5. Service reliability improvements at strategic level

5.1 Introduction

In the previous chapter we selected three strategic planning instruments, namely terminal design, line coordination and line length design, potentially enabling enhanced service reliability. In this chapter, we discuss these instruments and demonstrate their positive impacts on passenger travel time, due to an increased level of service reliability. In this chapter, we apply methods of calculating service reliability as introduced in Chapter 2 to assess the impacts of design choices. The new indicator, that is average additional travel time per passenger, is used to express how service variability affects passengers. At the strategic level, both the service network and supporting transport infrastructure are designed. Especially in rail networks these designs are heavily interconnected. Chapter 4 already gave a detailed description of this design level and its actors.

Traditionally, the following main variables for the network design may be distinguished (Egeter 1995, Van Nes 2002):

- Line density;
- Stop density;
- Service frequency.

Line density is the total length of lines served in a certain area. This determines the spatial coverage of public transport. The stop density is the number of stops served in a certain area. The more stops, the shorter the distance from origin to the stop is, but the slower the system will be. The last important aspect is frequency; the number of vehicle trips during the day. This determines the availability in time of public transport.

In Egeter (1995) it is shown that the above criteria lead to some network design dilemmas, when a design is made with fixed costs. These dilemmas are:

- Stop density vs. passenger travel time;
  The more stops there are, the shorter the access time to a stop will be. However, the operational speed of the system will decrease, which increases passenger travel time.
- Frequency vs. link density;
  If more links have to be served, a fixed budget implies a lower frequency on those links, compared to the situation with less links.
- Frequency vs. line density.
  This dilemma is closely related to the previous one. Designing more lines implies a lower frequency on these lines compared to a network with fewer lines. In this dilemma, transfers are of importance as well, since more lines may offer more direct connections (with lower frequencies).

Another perceived general dilemma in public transport design and operations is that of the operator and the passengers. The first actor mainly focuses on costs, while the second one is most concerned about service quality (Guihaire and Hao 2008). However, the more passengers are served (due to for instance higher quality), the more income will be collected by the operator.

These dilemmas illustrate the trade-off in public transport design between the individual passenger and the aggregate level. In general, service reliability is not an explicit goal at the strategic design. It is considered in a qualitative way, but no detailed quantitative consideration is given most of times. When service reliability is explicitly considered during the strategic design, new design dilemmas will arise and existing ones will be extended. We will elaborate in more detail on this issue in the next section.

In Chapter 4 we distinguished two types of planning instruments at the strategic level, being infrastructure and related service network. We will investigate both types in this chapter using our control framework presented in Chapter 2. By simulating the operational process using both empirical and theoretical data we will gain insights into the travel time effects of the instruments. We also used the insights we gained from our international survey, for instance types of lines to investigate and values of variables, to create valuable results for public transport system all over the world.

Traditionally, infrastructure design is mainly focusing on costs and technical options. Service network design focuses more than infrastructure design on passengers, although the main objective is mostly scheduled travel time (and costs), not considering the reliability of the services. As presented in Chapter 4, feedback and feedforward control is necessary at the strategic level to deal with service reliability. Actual data of operations are required to understand and estimate the impacts of certain design choices and these will be used to predict the magnitudes of effects of new instruments.

As illustrated in Chapter 4, the departure variability at the terminal is of importance with regard to service reliability. In this chapter, we describe the process of departure at the terminal in case of rail bound services and we assess the impacts of the terminal configuration on delays by simulating the terminal process based on actual data. A case study shows the large impacts of departure delays on passenger travel time and a detailed analysis of three general terminal types provides insights into the impacts of terminal design with different values of deviations, frequencies and turning times. We demonstrate that taking service reliability explicitly into consideration in terminal design, leads to new insights concerning impacts of operations. Our research supports proper terminal design, enabling a higher level of quality of public transport operations.

With respect to the design of the service network, we will investigate two instruments, namely line length and service coordination. The network design of urban public transport has been an important research domain in transportation science over the last decades (see Van Nes 2004 for a literature overview). However, the impacts on service reliability have been given less attention.

In our presented research on line length, we introduce a new dilemma in the design phase, which is service reliability vs. line length. Longer lines offer more direct connections, but tend to be more sensitive to service deviations creating unreliability and additional travel time for passengers. We analyze this trade-off in detail using our control framework of Chapter 2 and we will demonstrate that, even though more transfers are needed, shorter lines may lead to less average travel time per passenger. Coordination of schedules of multiple lines on a shared track is an often applied instrument to provide higher frequencies at a route with multiple lines. Although this may be very effective in schedules (offering half the headway for example), it depends on the quality of operations of the coordinated lines whether the assumed coordination will have the desired effect in practice as well. We developed a simulation tool, based on our control framework of Chapter 2 that enables assessment of the impacts of such coordination on passengers using actual data of trips and passenger flows. We will perform both a case study and a theoretical analysis to gain insights into the passenger effects of this design choice. Both coordinated lines and long lines offer serious benefits to passengers. However, we will demonstrate that these benefits depend on the operational quality of the lines and that cases exist where the benefits of introducing coordinated or long lines are negative.

The chapter is organized as follows. In 5.2 the analysis of terminal design is shown. The research of coordination is presented in 5.3 and we will demonstrate the impacts of line length on service reliability in Section 5.4. A summary and conclusions are given in Section 5.5. Chapter 7 will provide a synthesis, analyzing the interaction and combination of the presented instruments, considering also instruments at the tactical level, to be dealt with in Chapter 6.

5.2 The instrument of terminal design[1]

5.2.1 Introduction

This section describes an investigation into the effects of various urban rail terminal configurations on reliability of services, based on simulation studies. The objective is to show what the impacts are of terminal design on service reliability and thus on passengers. Besides terminals, the results may also be used for short turning infrastructure facilities. Such facilities enable service restoration if a part of the infrastructure is temporarily unavailable (as described by Tahmasseby et al. 2009).

Both in literature and in practice, little effort is devoted to the correlation between infrastructure configuration and service reliability, although a high level of reliability may never be achieved without a proper design of terminals, stops and junctions. In Lee (2002) it is stated that with increasing ridership and rising expectations on rail service quality, terminal capacity and performance have become a major concern for public transport authorities. Research on the effects of terminal configuration on quality of service is presented in Lee (2002), but the results are limited to only one type of terminal, while in practice multiple types are applied. It also concludes that there is a lack of well–established concepts and tools in the existing rail literature that a public transport agency may use to assess capacity and performance of heavily utilized rail terminals. In Vescovacci (2003), interesting results on capacity assessment are shown as well. However, this focus is on junctions.

In this section we present an assessment we performed of the impacts of terminal configurations on service reliability (Van Oort and Van Nes 2010). The most commonly used configurations are chosen and they establish the basic configurations. They may be used to develop other types. Only stub-end terminals are analyzed, since in general, loop terminals are less complex enabling simple capacity calculations and in addition capacity is not a restriction in general for this type (Lee 2002). The main variables in our terminal research are the number and locations of switches and the number of available tracks. However, schedule variables, frequency, layover time and the crew relief process are of importance as well.

This section starts with an illustration of the impacts of unpunctual terminal departure on service reliability. To demonstrate this, our new indicator (average additional travel time per passenger) is used. The reliability buffer time, as introduced in Chapter 2 as well, is also considered. The next section will describe the investigated terminal types, after which the research approach and results are presented. The results are presented as average vehicle delay at the terminal, indicating the average additional travel time, using the analysis of Section 5.2.2. The section finishes with main conclusions.

[1] This section is based on a reviewed article published in the Transport Research Records (Van Oort and Van Nes 2010)

5.2.2 Service reliability effects of punctual departure at the terminal

In Chapter 2 we showed the importance of on-time departure at the terminal. Earlier research also stated that the punctuality at the terminal ($p_{i,1}$) greatly affects the additional travel time of all passengers on the line (Van Oort and Van Nes 2009a). We performed a case study (in which we calculated the expected effects based on actual data) in The Hague to assess the effects of departing on time from the terminal on the average additional travel time per passenger on the complete line by eliminating the effects from non-punctual terminal departure. The modelling framework of Chapter 2 has been applied to which Equations 5.1 and 5.2 are added. They are used to assess the effects of punctual departure on schedule adherence on the complete line, after which the passenger effects may be calculated. Assumed punctual departure at the terminal leads to calculated new departure times at all stops on the line ($\tilde{D}_{l,i,j}^{act,new}$, Equation 5.1). The new departure times lead to new calculated punctuality values ($\tilde{d}_{l,i,j}^{departure,new}$, Equation 5.2).

$$\tilde{D}_{l,i,j}^{act,new} = \tilde{D}_{l,i,j}^{act} - \tilde{d}_{l,i,1}^{departure} \tag{5.1}$$

$$\tilde{d}_{l,i,j}^{departure,new} = \tilde{D}_{l,i,j}^{act,new} - D_{l,i,j}^{sched} \tag{5.2}$$

where:

$\tilde{D}_{l,i,j}^{act,new}$ = *calculated actual departure time of vehicle i on stop j of line l (in case of punctual departure at the terminal)*

$\tilde{D}_{l,i,j}^{act}$ = *measured actual departure time of vehicle i on stop j of line l*

$\tilde{d}_{l,i,1}^{departure}$ = *measured departure deviation of vehicle i on stop j=1 (terminal) of line l*

$\tilde{d}_{l,i,j}^{departure,new}$ = *calculated departure deviation of vehicle i on stop j of line l (in case of punctual departure at the terminal)*

$D_{l,i,j}^{sched}$ = *scheduled departure time of vehicle i on stop j of line l*

Given the recalculated punctuality of all trips and at all stops, an updated average additional travel time per passenger results, using the model Equations 2.17-2.23 in Chapter 2. This model assumes that the change in punctuality along the whole line is affected only by the punctuality change at the first stop and no delay propagation is assumed. This will lead to an underestimation of the new, calculated punctuality per stop, since in real time the effects of bunching will increase the initial deviation, as presented in Section 2.3. Despite this underestimation, the model is able to clearly illustrate the importance of punctual departure for service reliability and the impacts on passengers.

For several tram lines in The Hague, the decrease of additional travel time per passenger, including reliability buffer time (RBT), compared to prevailing situation is calculated when departure punctuality would be 100% (being the upper bound of what is achievable by increased schedule adherence at the terminal). The values for the time weighting parameters θ to calculate the additional travel time (in Equation 2.26 in Chapter 2), are assumed to be (as proposed by Furth and Muller 2006)):

- $\theta_{waiting}$ = 1.5
- $\theta_{waiting,RBT}$ = 0.75

The characteristics of the lines are given in Appendix B. Figure 5.1 shows the corresponding results. Actual passenger and trip time data of April 2007 (AM peak) are analyzed by using the Tritapt-tool (Muller and Knoppers 2005). The differences between lines are caused mainly by the actual punctuality characteristics of the lines (the actual schedule adherence of line 12 is low for instance). If the terminal departure punctuality is already at a high level, fewer benefits will be yielded of course.

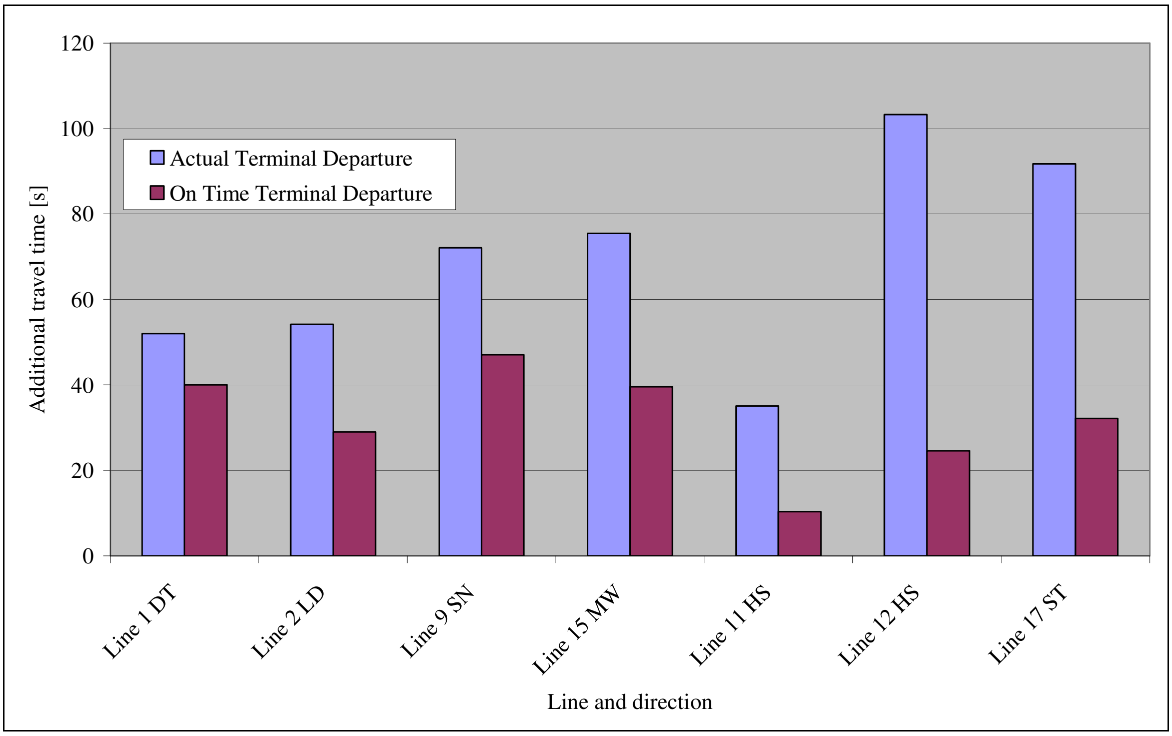


Figure 5.1: Calculated effects of on-time departure at terminal on additional travel time per passenger

Figure 5.1 clearly shows that departing on time may lead to large passenger travel time reductions, up to about 1.5 minute on average per passenger.

5.2.3 Urban rail terminal types and characteristics

Rail terminals may be designed in many forms: hundreds of types exist over the world. The key design variable is whether to choose a loop or a stub-end. Although loops require a lot of space, most of the time their capacity is larger than for stub-end terminals (Lee 2002), Vescovacci 2003). When bi-directional vehicles are used and space is lacking, a stub-end terminal is often chosen. The main benefit of this type is that it does not require much space. The disadvantage compared to loops is that that turning the vehicle may require additional time and that capacity is limited, which might lead to delays. The latter aspect is reason for us to study this terminal type in detail.

Figure 5.2 shows the three most common types of stub-end terminals and the traffic processes at these terminals. They have zero, one or two tail tracks. These three types are analyzed in our research to be presented below.

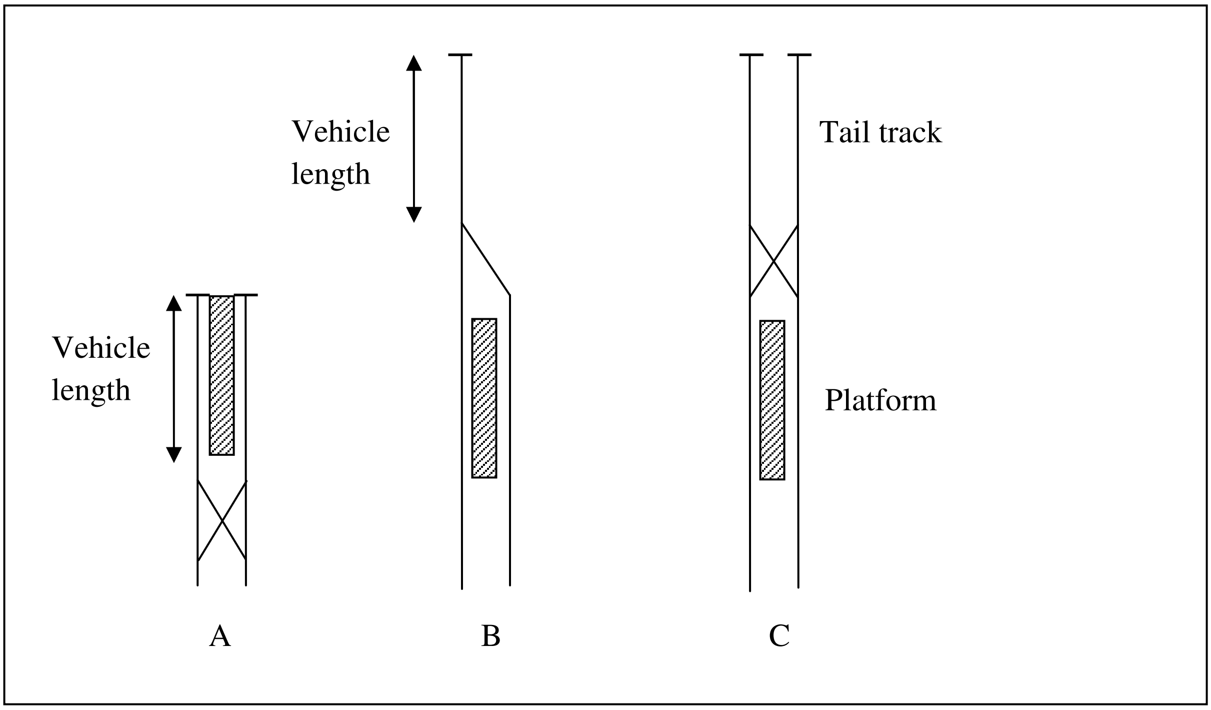


Figure 5.2: Three commonly used terminal types

Type A enables turning before the platform, the other two after the platform. At type A, the vehicle arrives at and departs from the same track, while at type B and C these two actions are performed at different platforms. Note that besides the double crossovers illustrated in Figure 5.2, universal crossovers are often designed as well (Figure 5.3).

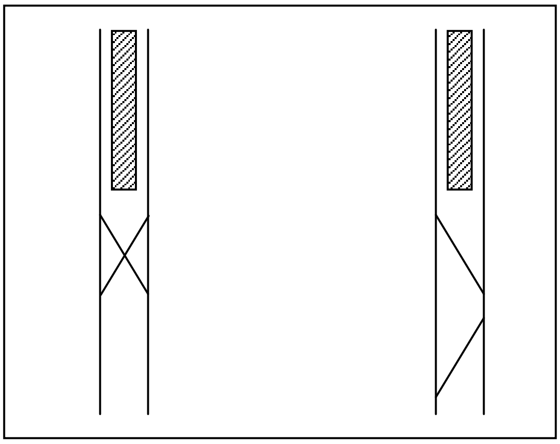


Figure 5.3: Double (l) and universal (r) crossovers

The difference between double and universal crossovers, in terms of capacity, is that for the latter the driving times necessary to proceed from the switch to the platform differ per track. But in general, this is only a limited amount of time (if the crossovers are located close to each other). Besides enabling the turning process (as shortly described in Chapter 4), terminals may also be used for parking vehicles. One vehicle may be parked at type A, although still only one track may be used for the turning process and capacity would drop. At type B, no parking is possible without blocking the turning process. Type C has space for one parked vehicle at one tail track. Note that the turning process changes to type B then.

Additional parking spaces might be achieved by extending the platform tracks (type A) or the tail tracks (type B and C). To optimize flexibility, space usage and understandability for passengers, an island platform is chosen. As a result of this, both tracks may be used by vehicles, saving potential delays due to passengers who have to change platforms when the departure track is changed.

In our international survey (see Section 3.2.3), terminal design was one of the topics as well. Figures 5.4 and 5.5 show the results of these terminal based questions. These figures show the location of the crossovers and whether arrivals are coordinated when multiple lines use the terminal. It is shown that crossovers before and after the stop are preferred. This enables a turning process of A or C, dependent of for instance time of day and frequencies accordingly. Most operators coordinate the arrivals of lines using the same terminal.

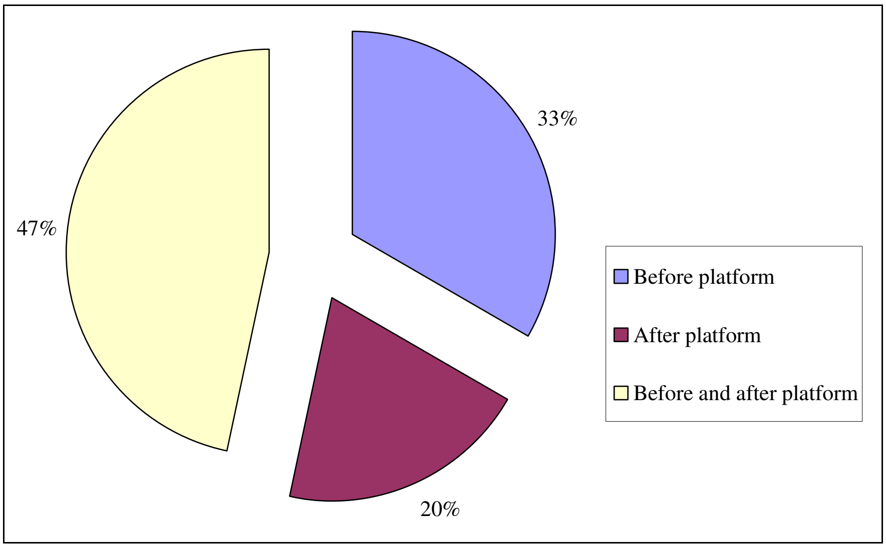


Figure 5.4: Answers to "Where do you prefer the switches to be located?"

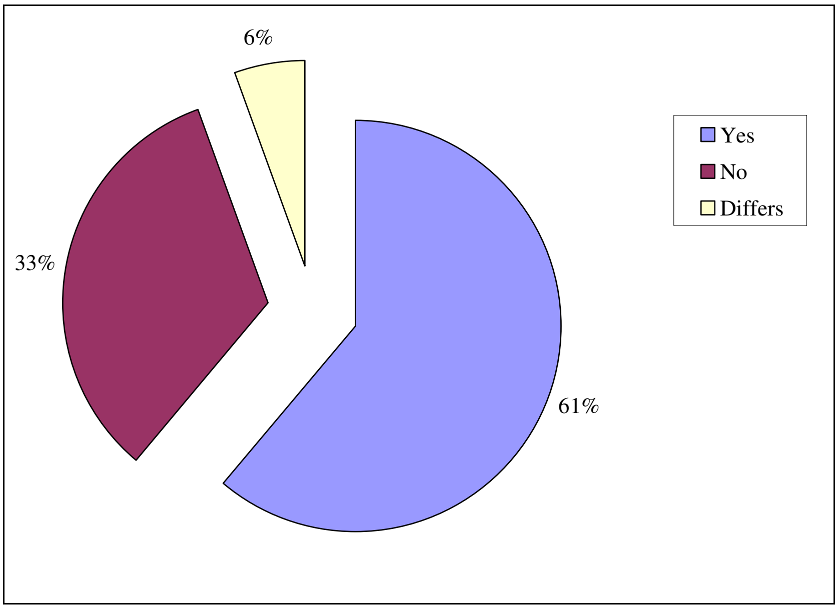


Figure 5.5: Answers to "In case of multiple lines using the terminal, do you coordinate their arrivals/departures?"

The analysis of these three types may also be used for assessing the effects of short turning infrastructure on the line. Short turning is a very widespread instrument to restore service after major disturbances and in many rail networks, additional switches are constructed to enable short turning. Type A is similar to short turning with double crossovers before the platform, while in C the crossovers are located after the platform. Type B is similar to short turning infrastructure where only one crossover is available. This could be both from the right track to the left track or vice versa. The short turning possibilities of these types are shown in Figure 5.6.

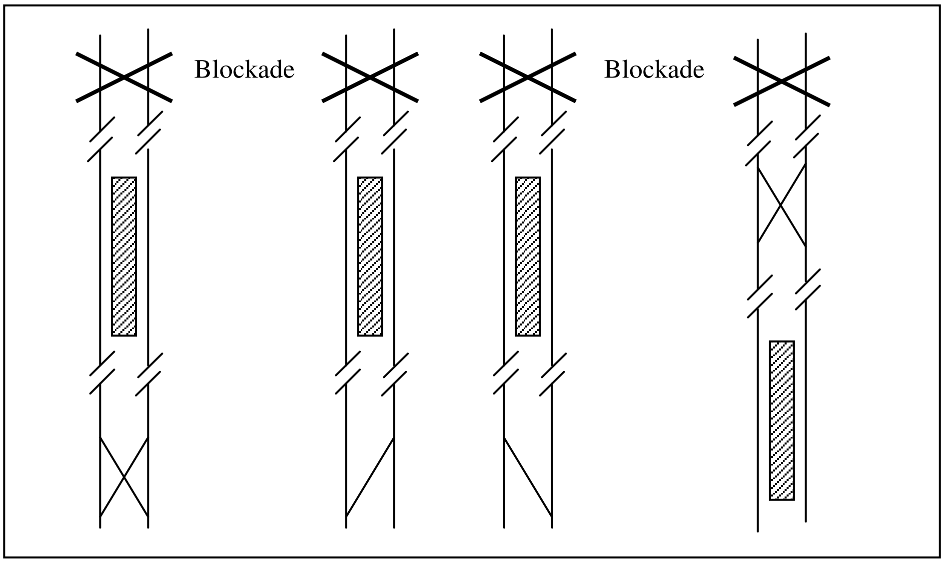


Figure 5.6: Short turn nodes when infrastructure is blocked

Regarding capacity, the infrastructure elements clearly offer restrictions. Furthermore, timetable and operational issues may be restrictive as well. The main factors affecting capacity are:

- Number of lines;
- Frequency;
- Coordination in case of more lines;
- Distribution of arrival times of vehicles;
- (Slack in) layover time.

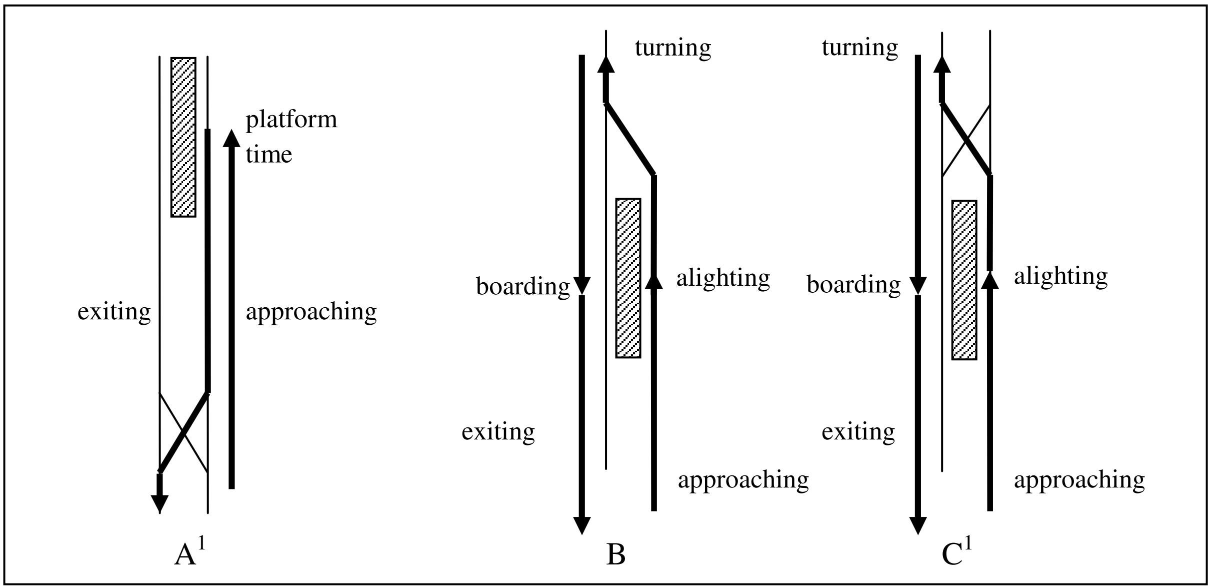
In addition to these variables, the method of changing the driver is of great importance; is the driver relieved at every turn (possibly saving the walking time from the front end to the rear end of the vehicle) or does he remain in his own vehicle, resulting in additional layover time (i.e. walking time)?

In our research, the time elements at the terminal are combined to "occupancy time". This time consists of the following elements for type A (which are illustrated in Figure 5.7):

- *Approach time*
  The time required to drive from entering the terminal at the switches to arrive at the platform. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches)

- *Platform time*
  The time between arrival at the platform and the time when the vehicle is ready to leave (according to the schedule and union agreements). Generally this time consists of:
  - Dwell time
    The time needed for passengers to alight or board
  - Technical turning time
    The time to start up the vehicle to depart in the opposite direction (e.g. walking time of the driver to go the other part, start up the board computer)
  - Break
    The time the driver is allowed to rest (if not relieved)
  - Synchronization time
    The time needed to depart by schedule again. This time occurs if the cycle time (consisting of trip time and layover time) is not an exact multiple of the headway.

- *Exit time*
  The time required to drive from departing at the platform to leaving the terminal at the switches. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches).



[1] *The other tail track may be used for turning as well*

Figure 5.7: Terminal types and traffic processes

For terminal type B and C the occupancy time consists of (illustrated in Figure 5.7):

- *Approach time*
  The time required to drive from entering the terminal to arrive at the platform.
- *Alighting time*
  The time required for passengers to exit the vehicle after arrival at the terminal
- *Tail track approach time*
  The time required to drive from the platform to the tail track. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches)
- *Tail track time*
  The time between the arrival of the vehicle at the tail track and the moment it is ready to leave (according to the schedule and union agreements). Generally this time consists of:
    - Technical turning time
      The time to start up the vehicle to depart in the opposite direction (e.g. walking time of the driver to go the other section, start up the board computer)
    - Break
      The time the driver is allowed to rest
    - Synchronization time
      The time required to depart on schedule again. This time occurs if the cycle time is not an exact multiple of the headway.
- *Tail track exit time*
  The time required to drive from departure at the tail track to arrive at the platform. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches).

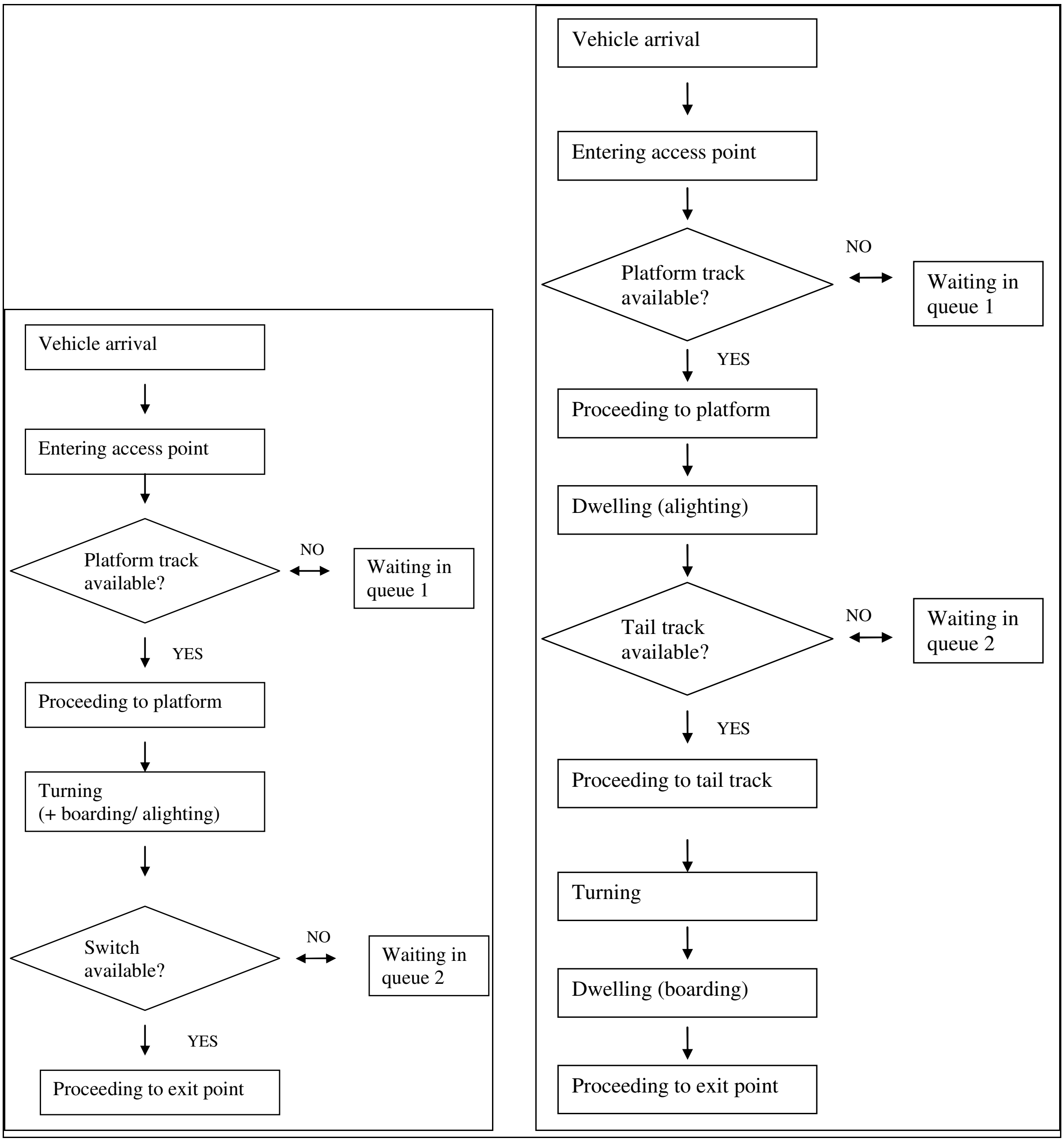
- *Boarding time*
  The time required for passenger to enter the vehicle
- *Exit time*
  The time required to drive from departure at the platform to leaving the terminal.

It is important to note that in case of no tail tracks certain time components, such as dwelling and technical turning, may partly overlap, thereby saving total occupancy time. The break and synchronization time might be combined with boarding time in the case of one or two tail tracks. If signalling is applied the time mentioned above is extended by typical signalling time components, as switching time and clearance time. However, in our research we only address non-signalized terminals, which are often applied for tram and light rail services.

5.2.4 Approach of terminal design analysis

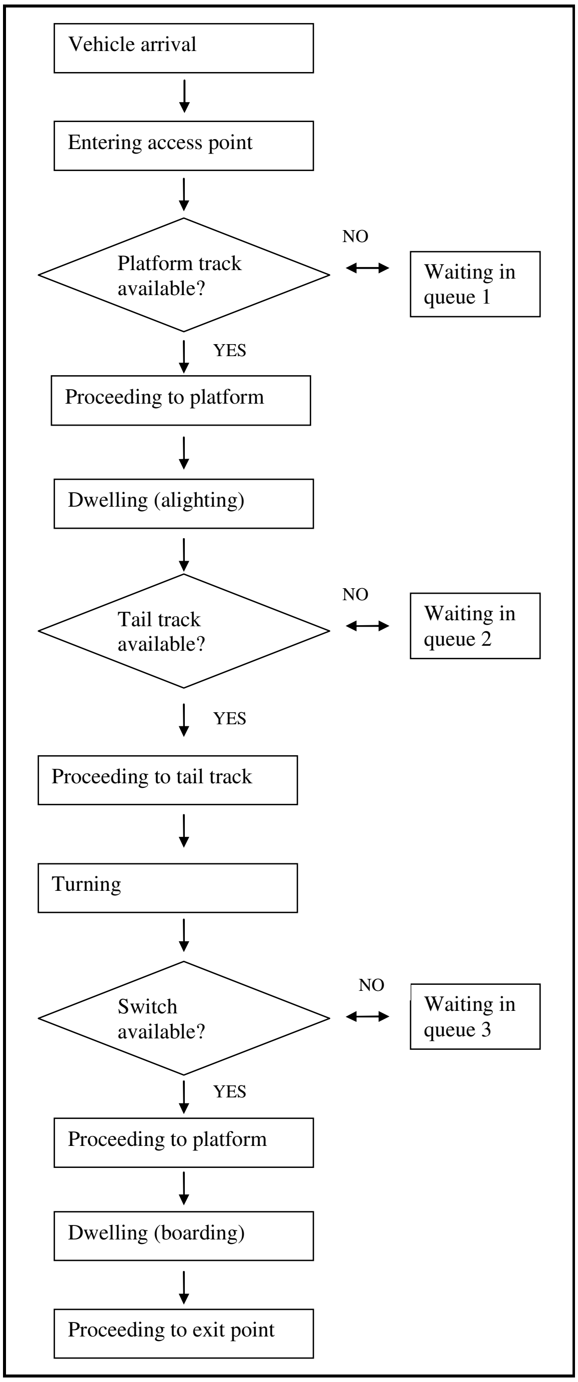
To assess the performance of terminals, the three key types are analyzed in a quantitative way, with respect to vehicle delays. The average delay per vehicle due to congestion at the terminal is the output of our analysis. The effects of various values for the main variables on the delay are assessed in order to develop graphs enabling quick scans during design. A meso-simulation tool has been developed to estimate the impacts of the configuration of terminals shown in the previous subsections on service reliability. The tool generates arriving vehicles, considering both the schedule and deviations. Checks are made whether tracks are available. If not, waiting time is calculated until a track is available. At the platform track, turning is simulated as well as the departure of the vehicle. The output is the size and the probability of the delay per vehicle due to capacity restrictions. Without additional measures (e.g. slack in layover time), this delay will prevent vehicles from departing on time, leading to additional travel time for all passengers on the line. The previous subsection already elaborated on this aspect. In our research we investigated three types of terminals, shown by Figure 5.7 and we calculated the average vehicle delay, indicating the average additional travel time per passenger.

The simulation steps for all three types of terminals are shown by Figure 5.8. Note that for type C three waiting queues are considered, while types A and B only have two possible queues. If no platform track is available, the vehicle has to wait in queue 1 (located at the access point). Queue 2 is located on the platform track and is used if a vehicle wants to depart while another one is entering (terminal type A) or when no tail track is available (terminal type B and C). If a vehicle is ready to depart the right tail track of terminal C and another vehicle just enters the left tail track, this vehicle has to wait as well (queue 3). To prevent waiting due to use of the double crossovers by another vehicle, the preferred arrival track is the one where departing does not interfere with arriving.



Platform type A *Platform type B*

Figure 5.8 A and B: Simulation steps for three terminal types (A= no tail tracks, B= one tail track and C= two tail tracks)



Platform type C

Figure 5.8 C: Simulation steps for three terminal types (A= no tail tracks, B= one tail track and C= two tail tracks)

The following input is used for the analysis. The model was run 30 times (one rush-hour) with various combinations of these variables to calculate the average delay per vehicle, which was sufficient to achieve reliable results.

- Service frequency: 4 to 24 vehicles per hour

- Occupancy time: 60-600 s. This time consists of:
    - Approach time
    - Technical turning time
    - Layover time
    - Exit time

  Section 5.3.3 described these elements in more detail
- Number of lines using the terminal: 1 and or 2
- Arrival pattern: Arrival pattern of vehicles is modelled by using scheduled, even, headways and a distribution function of deviations, shown in Figure 5.9. For the latter the values are based on general empirical data of tram lines in The Hague.

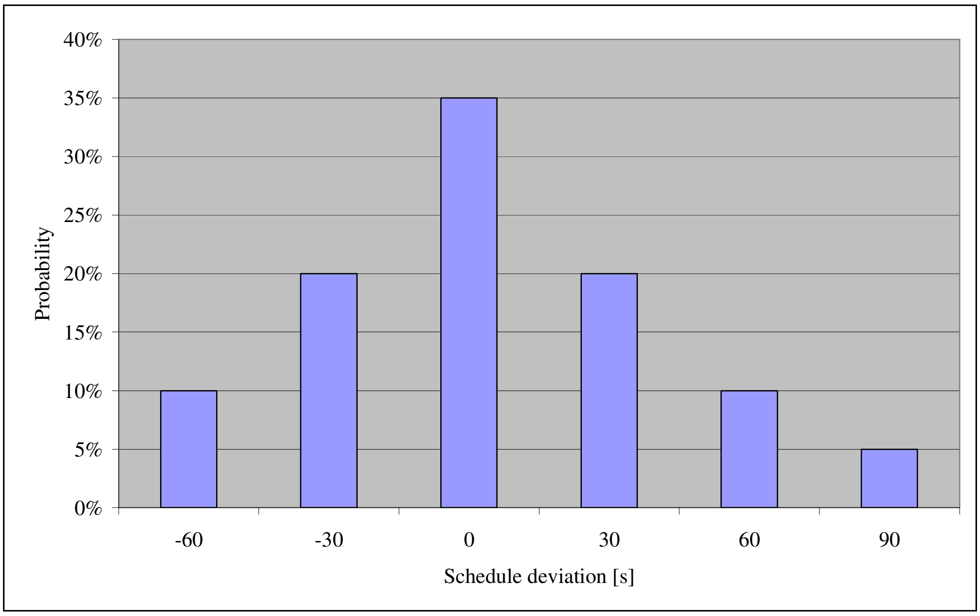


Figure 5.9: Variability in input arrival time deviations

The average delay per vehicle is calculated by assessing the delays at all the queuing locations (as described in the previous section), taking into account the number of vehicles which have passed the specific queue.

The average delay per vehicle is shown in Figures 5.10, 5.11 and 5.12, respectively, for the three types of terminals. In these figures the occupancy time is one axis and on the other is the number of vehicles entering the terminal per hour. Arrival deviations as shown in Figure 5.9 are used as input. Besides, two values for the static occupancy (O^{static}) are indicated as well (for every frequency analyzed); the white circles show the 50% static occupancy and the black circles show the 100% value (i.e. in theory, the terminal is utilized to the maximum extent). Equation 5.3 shows the calculation of the static occupancy of a terminal. We will demonstrate that static occupancy does not provide a proper indication of capacity if operational dynamics are considered. It is assumed that the dwell time is shorter than the turning time (terminal B and C).

$$O^{static} = \frac{F^{sched} * T^{occ}}{3600 * n_{tracks}} \qquad (5.3)$$

where:

O^{static} = *static occupancy*
F^{sched} = *schedule service frequency*
T^{occ} = *vehicle occupancy time (consisting of the elements described above)*
n_{tracks} = *number of tracks for turning*

Besides the analysis proposed above, also its sensitivity is checked by adjusting the arrival deviation or the number of lines.

5.2.5 Results of terminal analysis

In this section, the results of our terminal analysis are shown. Figures 5.10-5.12 show the average delay per vehicle (categorized by colour) as function of the total frequency and the occupancy time (as explained in Section 5.3.3). In these figures the circles indicate the static occupancy levels of 50% (white) and 100% (black). For all types, the average vehicle delay increases if frequency and/or occupancy time increases (thus the lower left corner is the lowest average delay per vehicle and the upper right corner is the highest), but to what extent this happens, differs per terminal type. All results show that due to the incorporation of stochastic events, the delay occurs before the static occupancy is 100%, which is in the deterministic case the moment that all capacity is used. This result demonstrates that stochastic calculations provide different insights in the capacity and impacts on service reliability than the static assessment. Using this method the design of terminals enabling a high level of service reliability is supported.

5.2.5.1 Results per terminal type

The results for the terminal type A without tail tracks (Figure 5.10) show that in case of only a few vehicles per hour, delays arise almost in the case of 50% static occupancy (the average vehicle delay increases near the green circles). If frequency increases, delays start to occur when the static occupancy exceeds values of about 75% (in between the white and black circles). For all frequencies analyzed, no delays occur if occupancy time is less than 240 s. If this value increases, the average delay increases quickly if the frequency is 20 vehicles or more per hour (colour categories change quickly). Occupancy time of 420 s. creates significant delays for frequencies over 8 per hour.

If a terminal type with one tail track (B) is applied (Figure 5.11), the difference between the 50% and 100% of static occupancy is small (the distance between the white and black circles is small). Delays occur much sooner than in the case of the other two terminal types, due to the limited space for turning vehicles. No effects are to be expected if the occupancy time is less than 120 s. Frequencies equal or larger than 16 vehicles an hour show a large increase in delays if occupancy time exceeds this value. In general, delays arise if static occupancy is between 50 and 100%, about 75%. Figure 5.11 also shows that if the frequency is 4 vehicles an hour or lower, no delays are to be expected at all.

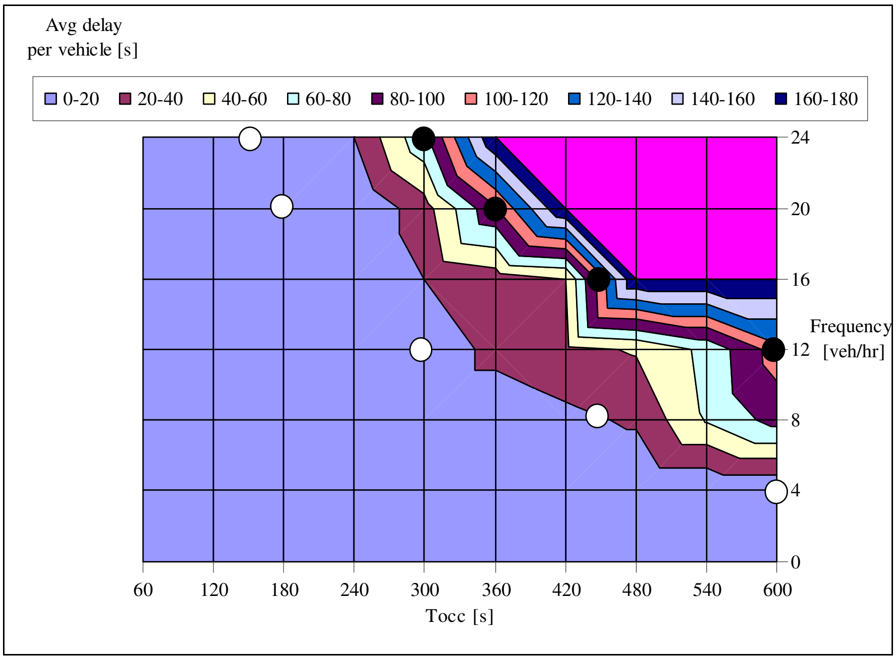


Figure 5.10: Average delay per vehicle as a function of occupancy time and service frequency, no-tail track (A) terminals

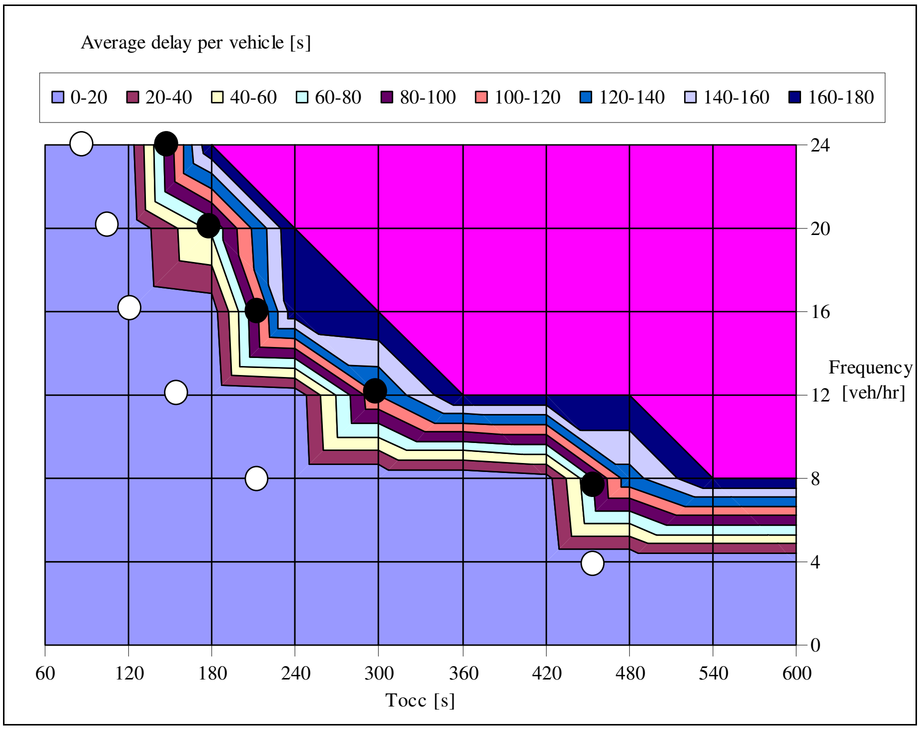


Figure 5.11: Average delay per vehicle as a function of occupancy time and service frequency, one tail track (B)

The results of the two tail track terminal (C) analysis (Figure 5.12) show that this type provides the best opportunities for dealing with larger numbers of vehicles. Below an occupancy time of 240 s. no delays are to be expected at all and for frequencies lower than 12 vehicles an hour, even 600 s. of occupancy time does not lead to significant delays. However, when the static occupation exceeds 90%, delays tend to increase quickly.

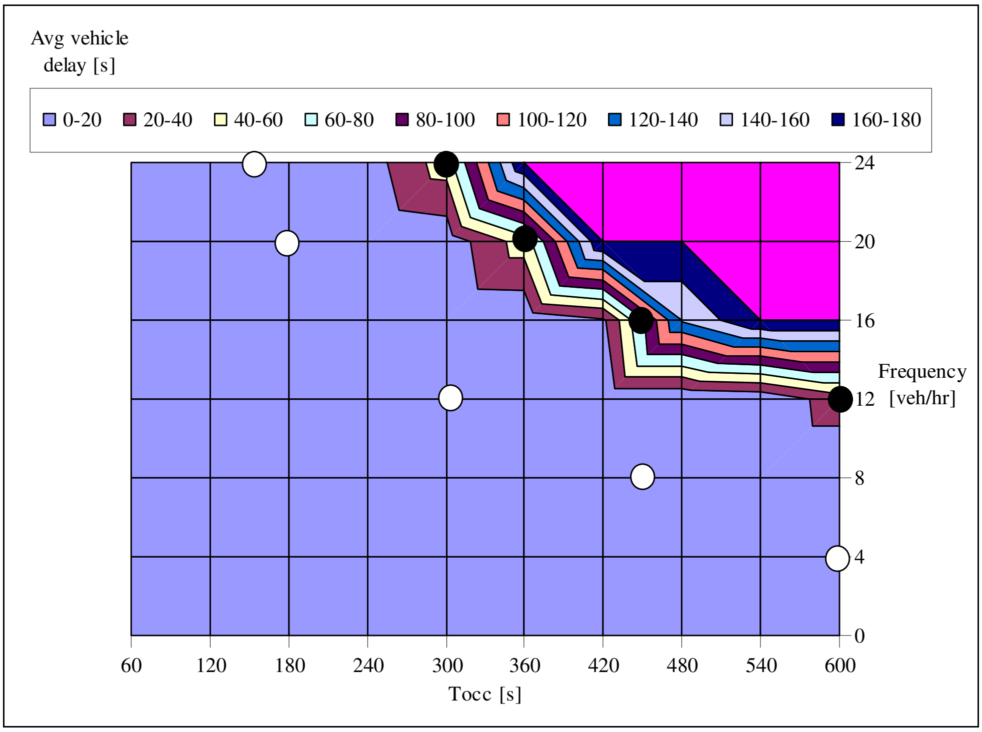


Figure 5.12: Average delay per vehicle as a function of occupancy time and service frequency, two tail tracks (C)

5.2.5.2 Impacts of arrival deviation and number of lines

In this subsection we show the effects of larger variability in vehicle arrival time deviations on the average vehicle delay. The frequency is set to 12 vehicles an hour. Figure 5.13 shows the adopted distribution of deviations of vehicle arrival time. This arrival pattern is more deviated than the one applied in the previous analyses. The standard deviation increased from about 40 s. to 100 s. Figure 5.14 shows the expected average vehicle delay for all three terminal types. The resulting average delay in the case of the regular schedule distribution is also shown.

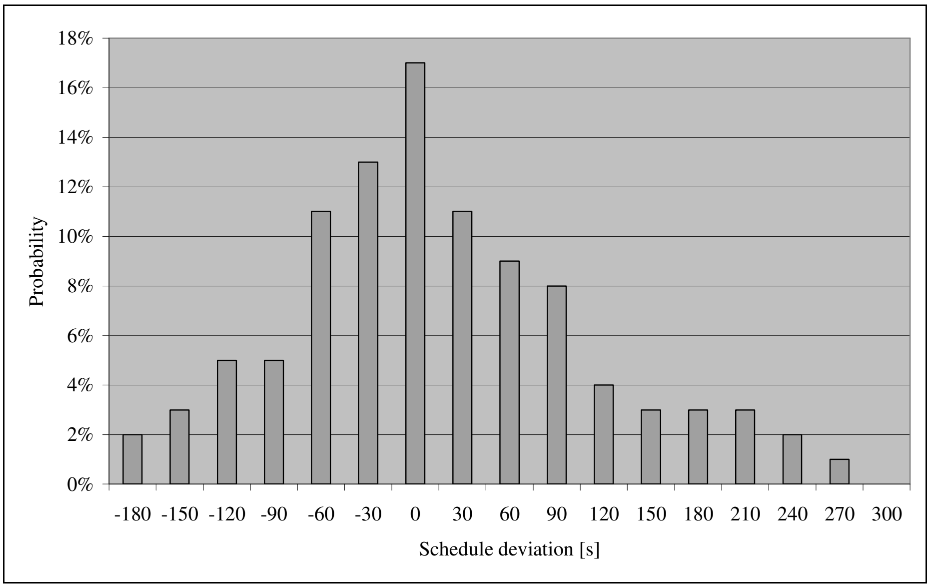


Figure 5.13: Distribution of adopted schedule deviations, heavily disturbed case

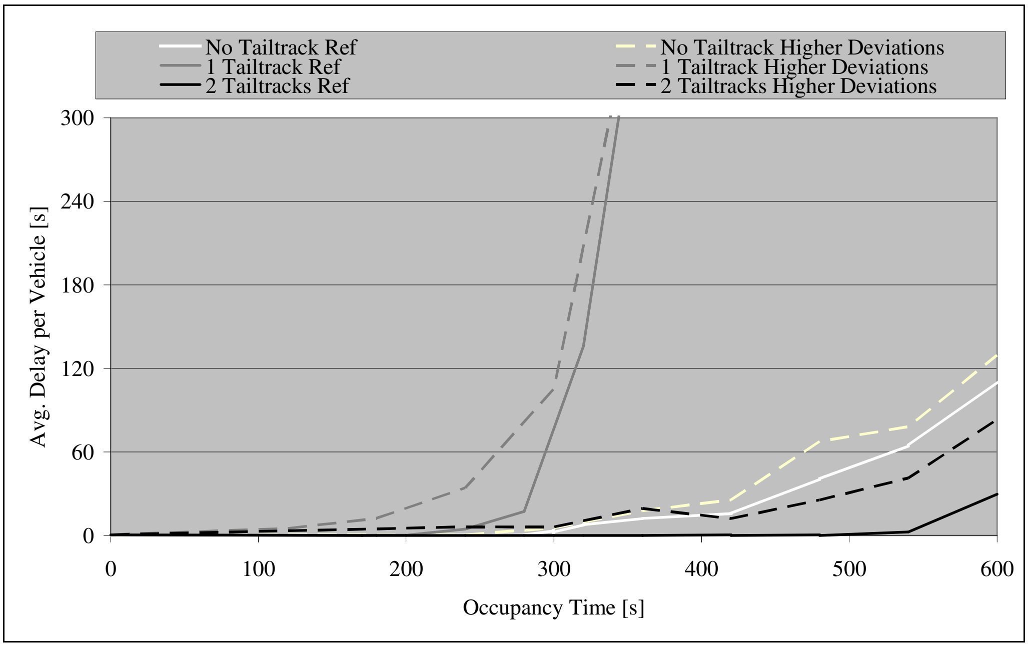


Figure 5.14: Effects of schedule deviations on average delay per vehicle at various terminal types

The difference between the dashed and straight lines illustrates the difference between the average vehicle delay of the reference case (with a regular arrival distribution) and the case with a more distributed arrival pattern. The effect of larger variability is negative: the average vehicle delay has increased in all cases. Compared to the regular distribution of deviations (Figure 5.9) the average delay is about 20 s. longer. If the one and two tail track types are analyzed, delays also start to occur with a lower value of occupancy time. The distribution of deviations is thus important to take into account when designing terminals. In urban public transport practice, often only the schedule is considered, which simply results in a static analysis, underestimating the average delay per vehicle as a result of terminal design.

The number of lines may influence service performance as well. For the total frequency of 12 vehicles an hour, an analysis is made of both one line and two line terminal types. Both lines have the same schedule deviation distribution (Figure 5.9) and they are not optimally coordinated (no evenly scheduled headways). Note that if they are optimally coordinated there is no difference between one or two lines (if both lines have a similar schedule adherence). The difference between the scheduled arrivals of both lines (off-set) is set to 3 min. (and 7 min.). Figure 5.15 shows the results. The difference between the dashed and straight lines illustrates the difference between the average vehicle delay of the reference case (with a single line) and the case with multiple lines (and an equal total frequency).

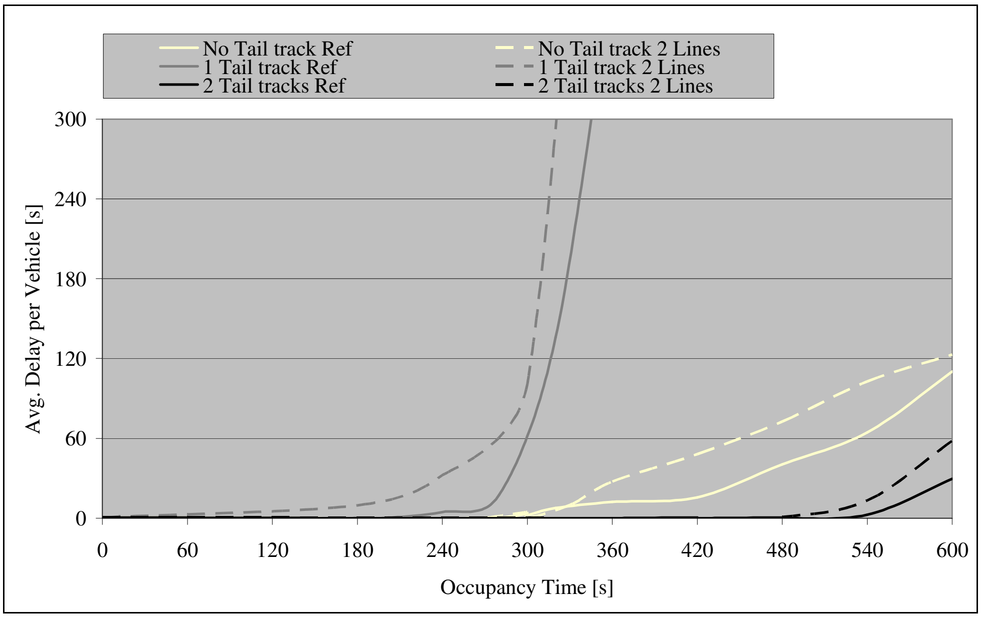


Figure 5.15: Effects of number of lines at terminals on average delay per vehicle, total frequency of 12 veh/hour

Figure 5.15 clearly indicates that the effect of two lines is negative, compared to one line offering the same total frequency. Besides the increase in delays, the occupation time, when delays are getting introduced decreases as well (in case of 1 and 2 tail track terminals). These results show that in assessing terminal capacity and impacts on service reliability, the number of lines and their (lack of) coordination is important to consider.

5.2.6 Conclusions

This section has dealt with the impacts of rail terminal design on service reliability caused by terminal departure delay. We showed in a case study that punctual terminal departure may decrease additional waiting time by 2 minutes on average for all passengers on the line. To achieve punctual departures, we calculated the effects of terminal configuration on vehicle delays. For three general types of terminals, calculations (based on simulation) of the average delay per vehicle show the effects of frequency on the one hand and terminal occupancy time on the other. The results show substantial impacts of arrival time variability and the number of lines using the terminal. Higher arrival deviations result in larger average vehicle delays. This effect also occurs when multiple lines use the terminal. It is shown that using stochastic variables, delays will occur, although they are not to be expected in the static case. The best performance regarding service reliability is achieved, when double crossovers are situated after the platforms. Single tail tracks facilitating the turning process are only acceptable if frequencies are low. However, due to cost savings, they are often used in practice as short-turning facility for high frequent services. Our findings show the large impact of occupancy time on expected delays. It is recommended to minimize this time by designing short distances between switches and platform and tail tracks. A dilemma arises between investment costs and service reliability. Increasing frequencies and large deviations force to consider limited capacity, while planning infrastructure. If not, delays will occur and additional instruments are necessary to solve them. This may be more expensive in the long run. In designing terminals it is recommendable to assess terminal capacity considering service dynamics and to calculate the impacts on service reliability. In Chapter 7 we will reflect on the cost-effectiveness of terminal design. The analysis in this section is based on variables that are valid outside The Hague as well, as demonstrated by our international survey (see Section 3.2.2). The survey also showed that the demonstrated terminal types are used all over the world, so the results might be used there as well.

5.3 The instrument of line coordination[1]

5.3.1 Introduction

We stated in Chapter 4 that the combination of service reliability and public transport network planning in case of urban transport is rarely analyzed. In practice however, public transport network designers also propose network structures that either (implicitly) assume a certain level of service reliability or are even especially focused on improving the service reliability. In Chapter 4 we introduced a typical example of such a network structure, namely the case where (parts of) multiple lines are running in parallel on the same route, enabling line coordination. The basic idea is that passengers on that route will have a more frequent transport service and more direct relations. Another strategic planning instrument is the introduction of additional public transport services for the more heavily used parts of a line (short-turn services). Figure 5.16 shows the network configurations mentioned above.

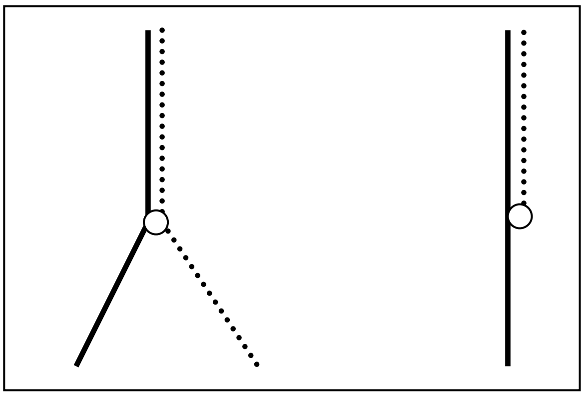


Figure 5.16: Coordination of two partly overlapping lines (left) or short-turn service (right)

[1] This section is based on a reviewed article published in Public Transport (Van Oort and Van Nes 2009c)

These network designs clearly have a relationship with service reliability. Two lines on a route may offer an evenly spaced half headway if the lines are coordinated. In addition, a short-turn service line (dotted line in right part of Figure 5.16) is assumed to be less deviated than a complete line (dotted line in left part of Figure 5.16). However, in the planning stage the impacts on service reliability are often analyzed only in a qualitative way. Since the key question in public transport network design is what is achieved in terms of demand versus the related costs, it is obvious that a quantitative analysis would be more appropriate. To this end, this section provides insights into the effects of line coordination on service reliability. Our framework from Chapter 2 is applied in a theoretical analysis of the impacts of line coordination on service reliability as well as applied in a practical case study.

One of the topics in the international survey (Section 3.2.3), was about coordination. The percentage of operators coordinating the schedule when multiple lines operate partly on the same route is 71%. Main variables in the choice process of coordination are the number of shared stops, the number of lines and the frequencies of the lines.

The first section presents how the framework of Chapter 2 is applied, enabling calculations on line coordination. After this section, the approach and results of the line coordination research are presented. Both a case and theoretical calculations are provided. The section concludes showing the main findings.

5.3.2 Approach of coordination analysis

5.3.2.1 Applied modelling framework

The objective of our analysis of line coordination is to show the impacts on the average additional travel time per passenger. In Chapter 2 we presented an analytical framework for dealing with unreliability during the planning of public transport. For the specific case of coordination, this framework is extended and presented in this section. We only address short-headway services and random arrivals of passengers, implying that service regularity is important.

In public transport network design, a trade-off is searched between passenger benefits and operator objectives. Given a specific network design an assessment is made of the quality offered to the passenger. In this context different related characteristics may be used such as passenger waiting times, frequencies and headways. The traditional approach (presented and analyzed by Van Oort and Van Nes 2004) is to calculate the waiting time by using only the scheduled frequency (F_l^{sched}) or headways (H_l^{sched} ; related as Equation 5.4 shows) resulting in waiting times of half the headway, while in reality service regularity plays a role as well (see Chapter 2). As a result the experienced passenger waiting time is different from the traditionally computed waiting time, thus a distinction may be made between perceived frequency (F_l^p) and scheduled frequency (F_l^{sched}), or in other words, the perceived headway and the scheduled headway (Hakkesteegt and Muller 1981). The perceived headway is defined as the headway that given a regular service would result in the waiting time perceived by the passenger. This implies that the perceived headway is twice the average experienced waiting time given the expected service regularity (Equation 5.5), since in regular service the expected waiting time is half the headway (as shown by Equation 2.16 in Chapter 2). The perceived frequency (F_l^p) may thus be defined as shown in Equation 5.6. Since the expected waiting time is at least half the headway (see Equation 2.16), the perceived frequency is always smaller than or equal to the scheduled one, showing the negative effect of service variability. Please note that these formulations are applicable at the level of stops (requiring the index *j*) as well as at the level of the line. See Chapter 2 for derivations and associated assumptions.

$$F_l^{sched} = \frac{60}{\mathrm{H}_1^{\mathrm{sched}}} \tag{5.4}$$

$$H_l^p = 2 * E(\tilde{T}^{waiting}) \tag{5.5}$$

$$F_l^p = \frac{60}{H_l^p} \tag{5.6}$$

where:

F_l^{sched} = *scheduled service frequency on line l*

F_l^p = *perceived service frequency on line l*

H_l^{sched} = *scheduled headway on line l*

H_l^p = *perceived headway on line l*

Figure 5.17 shows the dependency of perceived frequency from irregularity (expressed as PRDM, see Equation 2.15) for different scheduled frequencies (calculated by using Equations 5.4-5.6). It can be seen that if the Percentage regularity deviation mean (PRDM) is 100%, i.e. bunching, the perceived frequency is half the scheduled frequency, or in other words, the vehicles operate in pairs (Hakkesteegt and Muller 1981).

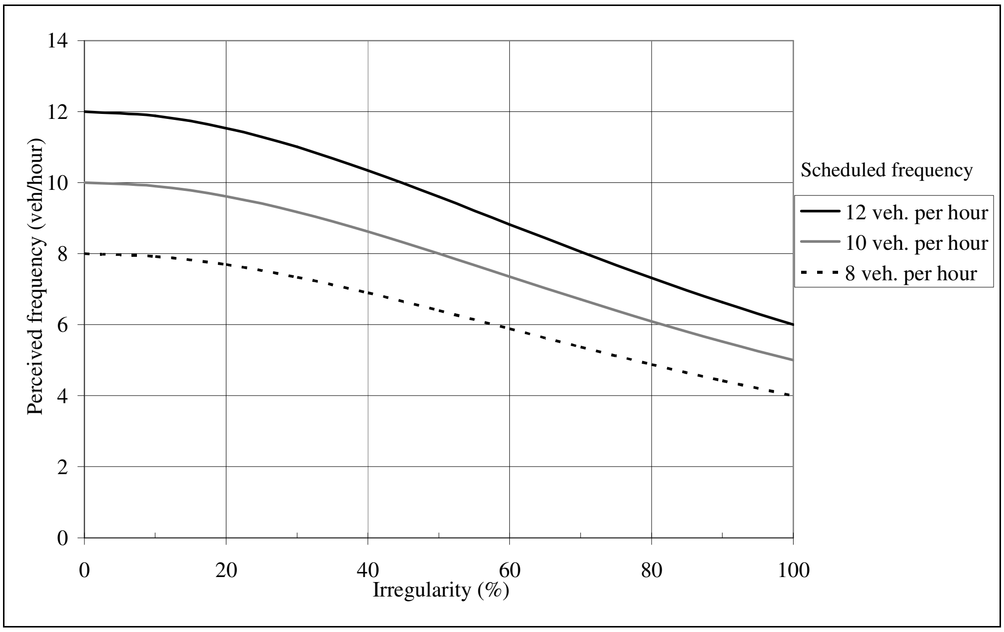


Figure 5.17: Dependence of perceived frequency from irregularity [PRDM] in case of short-headway services and random passenger arrivals (Source: Hakkesteegt and Muller 1981)

If a public transport planner intends to propose network structures that require coordination between lines, such as multiple lines having the same route, he should consider the impacts of regularity, or irregularity, on the expected performance of the network. However, as stated before, the traditional approach is to derive the passenger waiting time from the scheduled frequencies only. If the network improvements are primarily focused on improving the regularity, planners might use a qualitative assessment in terms of a substantial improvement of regularity. However, if it would be possible to determine the perceived frequency, public transport planners may easily determine the full impacts of the proposed network changes on the performance of the public transport system, including the impacts on the service regularity. The next section presents such an approach and an application.

The purpose of the approach is to make an estimate of the service regularity for a given stop, given a proposal for a network configuration, especially in the case of parallel lines having the same route. Given that estimate, the impacts on the level of demand may be determined. This will be presented in Chapter 7.

5.3.2.2 Line coordination tool

To gain insights into the effects of coordination on perceived frequency and the average additional travel time per passenger, we developed a line coordination tool, based on our framework of Chapter 2. The input of the tool is a description of the proposed network configuration such as the number of lines, their frequencies and whether it is intended to apply a coordinated timetable or not. Furthermore, a description of the punctuality of the transport services is required in terms of a probability distribution of the vehicle arrivals or departures. Ideally this description should be based on actual data of the system performance today, such as collected with an operations monitoring system such as the Tritapt-tool (Muller and Knoppers 2005). If such historical data is lacking or it is expected that substantial instruments at the operational level will be implemented, an educated guess should be made, preferably based on comparable public transport lines.

The estimation procedure in the model works as follows (illustrated by Figure 5.18):

1. The starting point of the analysis is the network proposal. Based on the network proposal, the timetable is constructed. Given the set of lines, their frequencies and the coordination strategy a timetable for the arrival and departure of the vehicles at each relevant stop is generated by the regularity analysis tool. The network and timetable imply certain operational costs.
2. Simulation of operational performance: Given the probability distribution for each line a randomization procedure in the analysis tool determines a series of the actual arrival and departure times for each vehicle trip, thereby determining the actual departure time at each stop. This procedure is repeated for given number of iterations. The arrival and departure times are sorted and stored;
3. Calculation of the regularity: Given the simulated arrival and departure times at the stops the analysis tool calculates the PRDM and covariance of the headways are (Equations 2.15 and 2.12 in Chapter 2). In case of unequal headways, this step determines the average headway and its variance;
4. Determination of the waiting time and the perceived frequency at the stops: Given the headway characteristics for each stop the expected waiting time is determined (Equation 2.16 in Chapter 2), which then is used to calculate the perceived headway and thus the perceived frequency. Next to that, the average additional waiting time per passenger is calculated as well. In this analysis, reliability buffer time (RBT) is not included, as stated by Chapter 2.

5. Estimation of the impacts on demand: given the calculated change in perceived frequency and the average additional travel time per passenger, an estimate may be made of the relative change in ridership and benefits. This step will be presented in Chapter 7.
6. Based on both the costs and benefits, a decision may be made about the network proposal.

This procedure may be repeated for all periods of the day. The sum of the changes in demand per period determines the expected revenues, which in general should outweigh the costs involved.

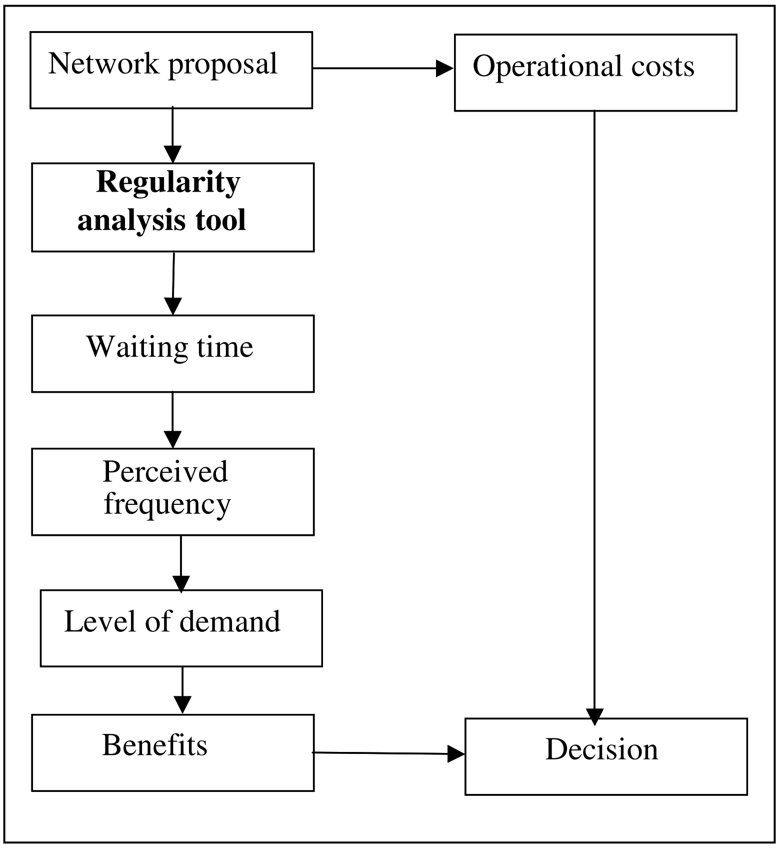
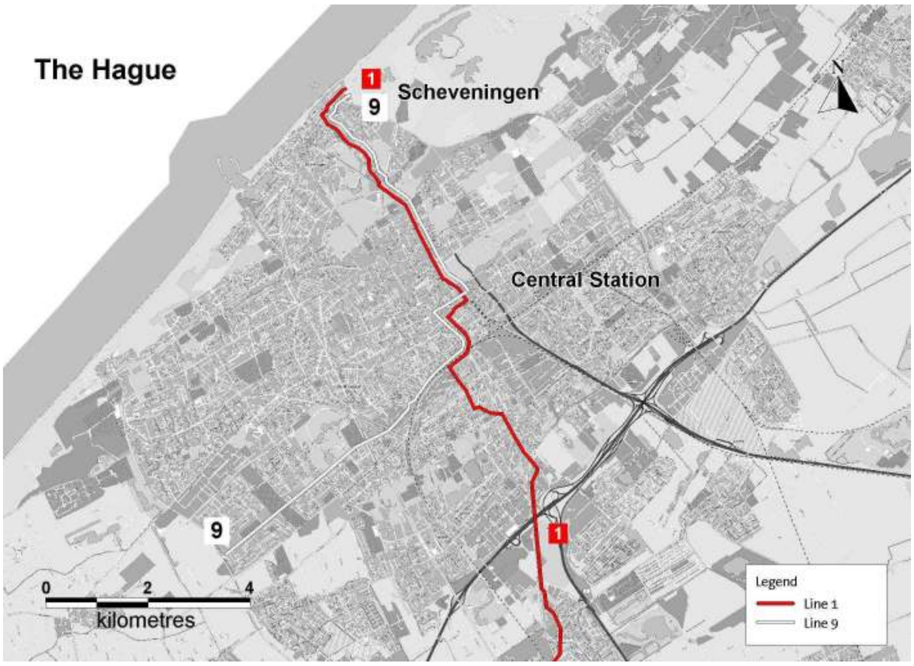


Figure 5.18: Workflow using the regularity analysis tool to assess the impacts of network changes

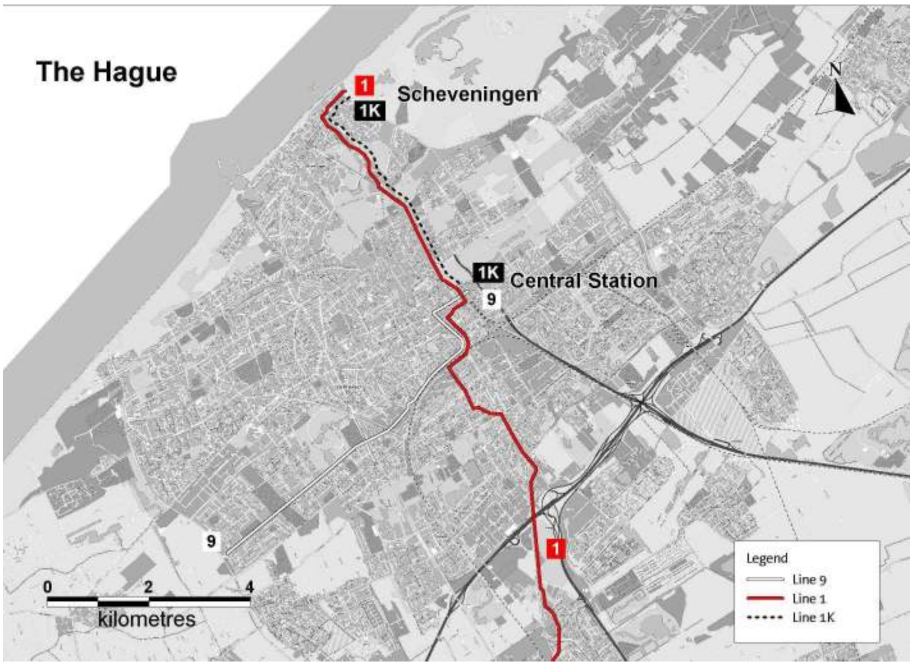
5.3.3 Results of line coordination analysis

5.3.3.1 Case study: Koninginnegracht in The Hague

This section presents an analysis of an actual coordination case through application of the tool for the so-called Koninginnegracht-route corridor in the city of The Hague in the Netherlands (Figure 5.19A, situation 2002). This route starts at The Hague Central Station and ends in Scheveningen, a sea-side resort. It is served by two tram lines, 1 and 9, which have different starting points. Tram line 1 starts in the city of Delft, while tram line 9 starts in the southern part of The Hague. The regularity of these two tram lines on this route is considered to be poor, because of the long routes these lines have run before joining on their common route part. Therefore it is proposed to limit the service on the Koninginnegracht-route to tram line 1 only and to introduce an additional service (tram line 1K) between The Hague Central Station and Scheveningen (Figure 5.19B). Tram line 9 is reduced to the route between the southern part of The Hague and The Hague Central Station.



A



B

Figure 5.19: Network layout for the case study (A= reference 2002; B=proposal)

The consequences of this change in network structure are diverse. Splitting tram line 9 into a reduced tram line 9 and tram line 1K requires more vehicles. Furthermore, passengers from

The Hague South to destinations close to the Koninginnegracht-route have to make a transfer. The key benefit of the network change is the improved service quality on the Koninginnegracht-route. A qualitative assessment of this improvement is that the current situation shows a very poor regularity, while in the new situation coordinated and regular services are possible. An optimistic estimate might be that the quality changes from highly irregular to highly regular public transport services, implying a doubling of the perceived frequency. Given the importance of a proper assessment of the benefits for the regularity on this route, a more sophisticated approach is required and thus the tool described in the previous section was used for a quantitative assessment.

The comparison of the current situation (Figure 5.19A) and proposal (Figure 5.19B) deals with both directions on this route. For each direction an assessment is made for the regularity effects at the start of the common route segment.

Tables 5.1 and 5.2 show the results of coordination for both directions for the two peak periods (for a complete analysis see Van Oort 2003). These tables show the current supply characteristics, i.e. frequencies and coordination strategy, and the resulting performance characteristics, namely waiting times, perceived frequencies, as well as change in perceived frequency and the effects on additional travel time.

It can be seen that in the direction of Scheveningen (Table 5.1) the regularity will still remain rather poor: the PRDM is estimated to be 46%. As a result the change in perceived frequency remains small. This is due the relative high irregularity of tram line 1 when it arrives at The Hague Central Station. The proposed changes in the network have no influence on the regularity of the route between Delft and the starting point of the Koninginnegracht-route and should therefore be considered as given. This predefined irregularity nearly precludes improving the regularity by replacing tram line 9 by tram line 1K.

In the other direction (Table 5.2), however, the resulting regularity is rather good: a PRDM of only 20%. As a result, the changes in perceived frequency and level of demand are substantially higher, namely up to 38%. The largest differences are found in the case that coordinated services are introduced.

Table 5.1: Impacts of coordination on regularity for the Koninginnegracht route from The Hague Central Station to Scheveningen

	Morning peak (7-9)		**Evening peak (16-18)**	
	Reference	Proposal	Reference	Proposal
Frequency (line 1/line 9)	6/6	6/6	6/5	6/6
Coordinated services	Yes	Yes	No	Yes
PRDM [%]	56	46	63[1]	46
Expected waiting time [min]	3.3	3.0	3.7	3.0
Average additional travel time per passenger [min]	0.8	0.5	1.0	0.5
Perceived frequency [trams/hour]	9.1	9.9	8.1	9.9
Change in frequency [%]	+8		+22	

[1] *Estimated using the expected headway and its variance*

Table 5.2: Impacts of coordination on regularity for the Koninginnegracht route from Scheveningen to The Hague Central Station

	Morning peak (7-9)		Evening peak (16-18)	
	Reference	Proposal	Reference	Proposal
Frequency (line 1/line 9)	6/6	6/6	6/5	6/6
Coordinated services	No	Yes	No	Yes
PRDM [%]	58	20	60[1]	20
Expected waiting time [min]	3.3	2.6	3.6	2.6
Average additional travel time per passenger[min]	0.8	0.1	0.9	0.1
Perceived frequency [trams/hour]	9.0	11.5	8.3	11.5
Change in frequency [%]	+29		+38	

[1] *Estimated using the expected headway and its variance*

The differences between the two directions show two interesting phenomena. First, if one of the lines is already irregular at the beginning of the route it is not possible to achieve a substantial improvement in regularity by introducing a short-turn line. In this case other instruments for improving the regularity of tram line 1 are more appropriate. Second, the findings for the direction to The Hague Central Station show that the reference situation is less bad than was assumed. Therefore, the impacts of the improved regularity are smaller than might be expected based on an intuitive approach. This analysis thus clearly shows that a quantitative analysis is essential for judging such network proposals.

5.3.3.2 Theoretical analysis of impacts of line coordination

When designing urban public transport networks it is interesting to have an indication whether combining (parts of) two lines on the same route provides real benefits for the passengers. This is relevant if parallel line structures or short-turn services are considered, or when it is intended to introduce a dedicated lane, which is used by a number of public transport lines.

In order to gain insights into the effects of different values of variables as punctual deviation distribution, we performed theoretical research indicating the potential change in regularity if two lines operate on a single route with or without coordination. These graphs are based on the standard deviation of the punctuality of each line, expressing service variability. The analysis has been performed for the case of two lines having a frequency of 6 vehicles per hour. In the coordinated case these lines are scheduled in such a way that the average headway is 5 minutes. If there is no coordination the second line departs 1 minute later than the first.

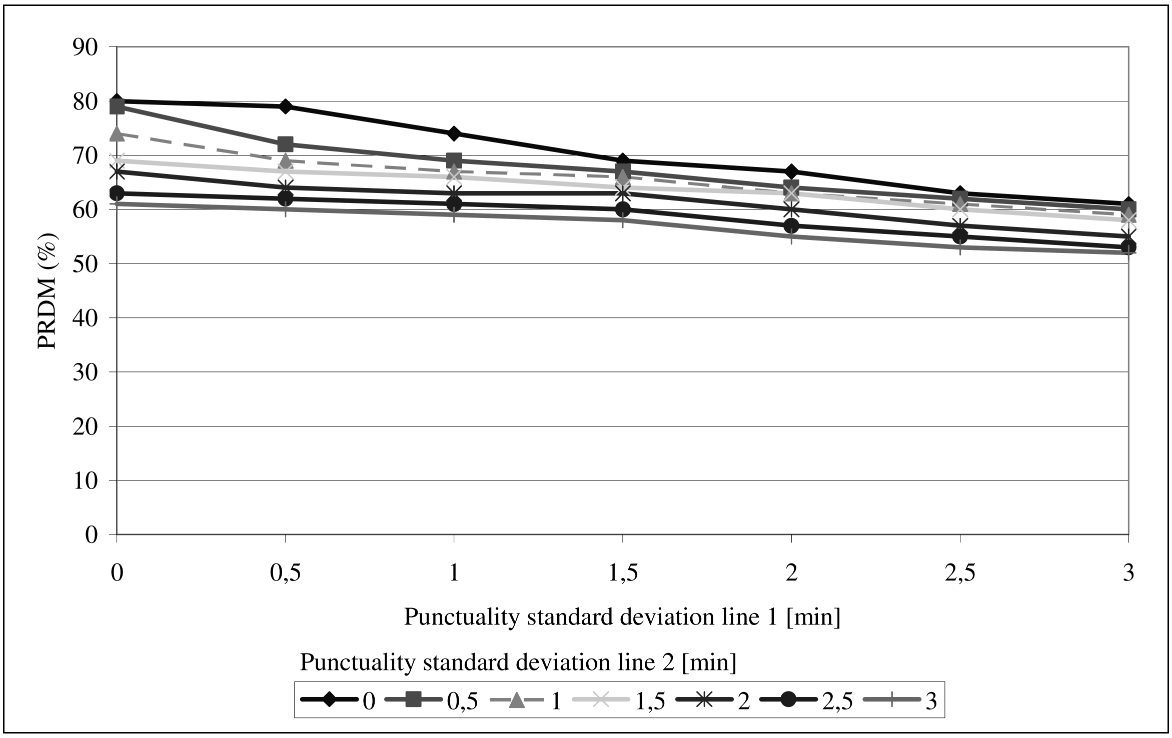


Figure 5.20: Regularity (PRDM) as a function of the punctuality of line 1 for different values of the punctuality of line 2, uncoordinated case

Figure 5.20 shows the regularity level as a function of the standard deviation of the punctuality for both lines in the uncoordinated case. The horizontal axis shows the standard deviation of the punctuality of the first line, while each curve relates to a punctuality standard deviation of the other line. The vertical axis represents the value of the regularity defined by the PRDM. If both lines are very punctual, the regularity for the combination of both lines is very poor (80%). In fact, an increase of the variation of the punctuality leads to a better regularity, the best value in the graph being 52%.

Comparing this graph with the coordinated case (Figure 5.21) clearly shows that coordinated services have a much better performance. In the case of very punctual services the regularity is perfect (0%). However, in the case of unpunctual services the regularity deteriorates to 55%.

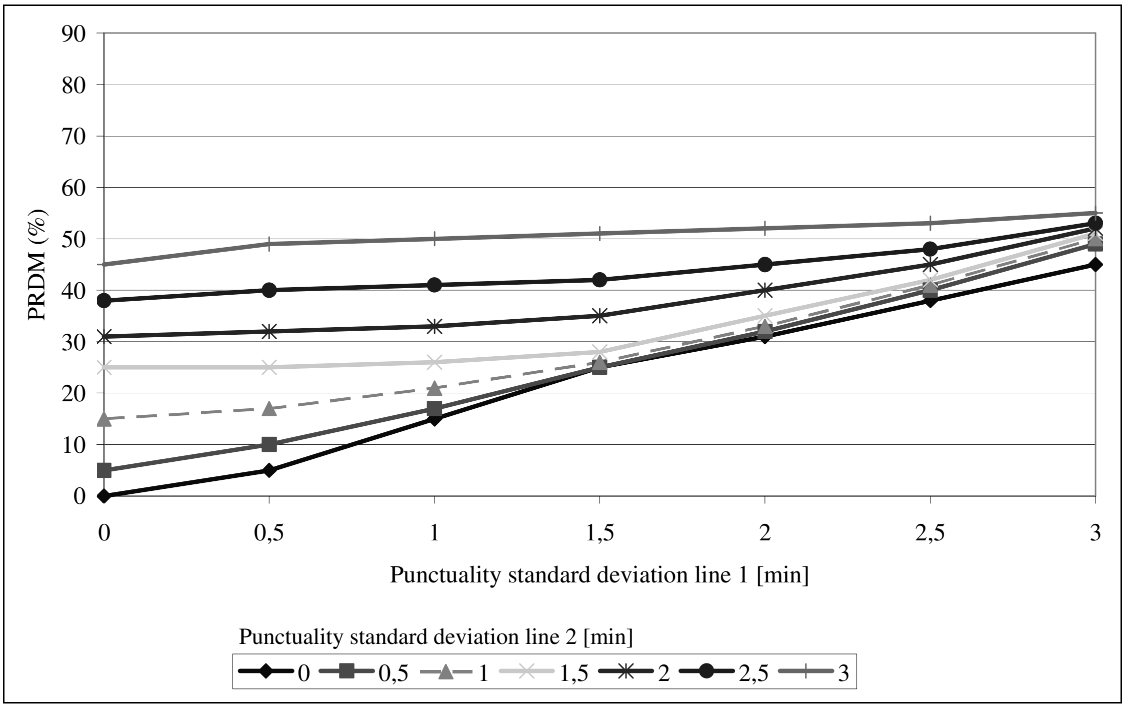


Figure 5.21: Regularity (PRDM) as a function of the punctuality of line 1 for different values of the punctuality of line 2, coordinated case

These graphs may be used to assess the impacts of coordinating services or of reducing the variation in the punctuality. Figure 5.22 shows the reduction of the PRDM as a result of coordinating services. For highly unpunctual services the impacts on the regularity is limited. For services having a medium punctuality (standard deviation of 1.5 minutes) the PRDM may be reduced with 40%, while in the case of very punctual services a reduction of 80% is feasible.

The results for the situation in which coordinating of services is combined with improving the punctuality are shown in Figure 5.23.

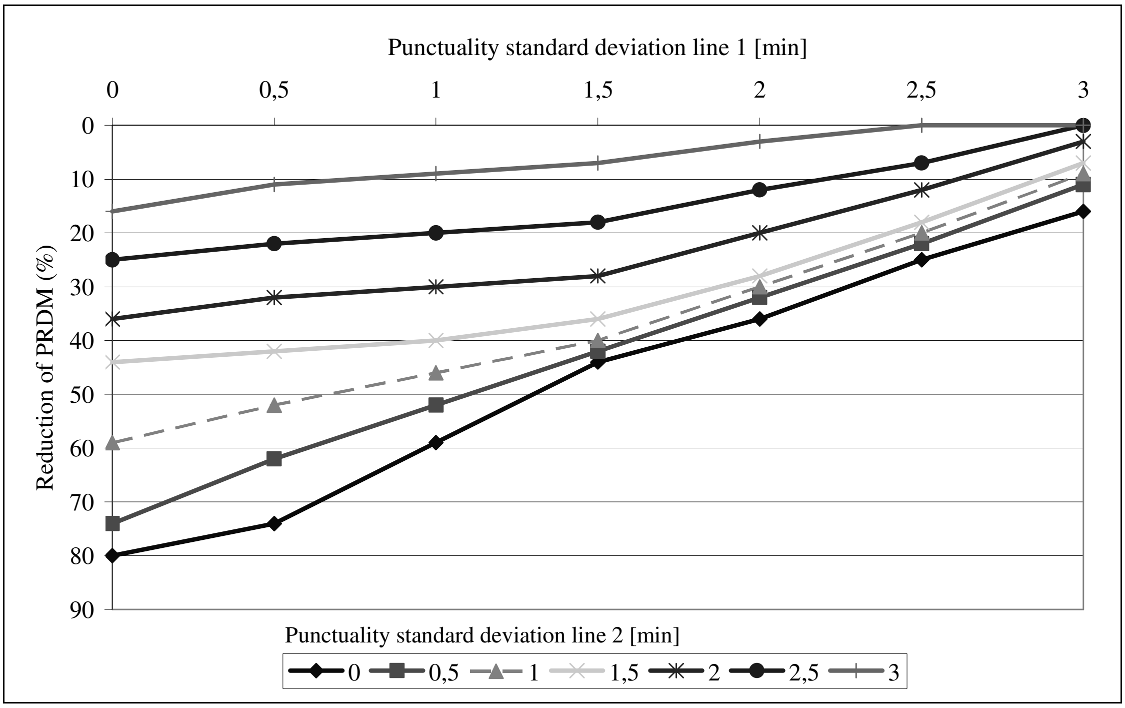


Figure 5.22: Reduction of the PRDM as a function of the punctuality of line 1 for different values of the punctuality of line 2 due to coordinating the transport services

This clearly shows that in the case of unpunctual services a substantial improvement is possible. The largest improvement, however, is found in the case of lines having a medium punctuality level. The additional reduction of the PRDM then varies between 17 and 20%. Of course, in the case of punctual services the benefits of improving the punctuality are small.

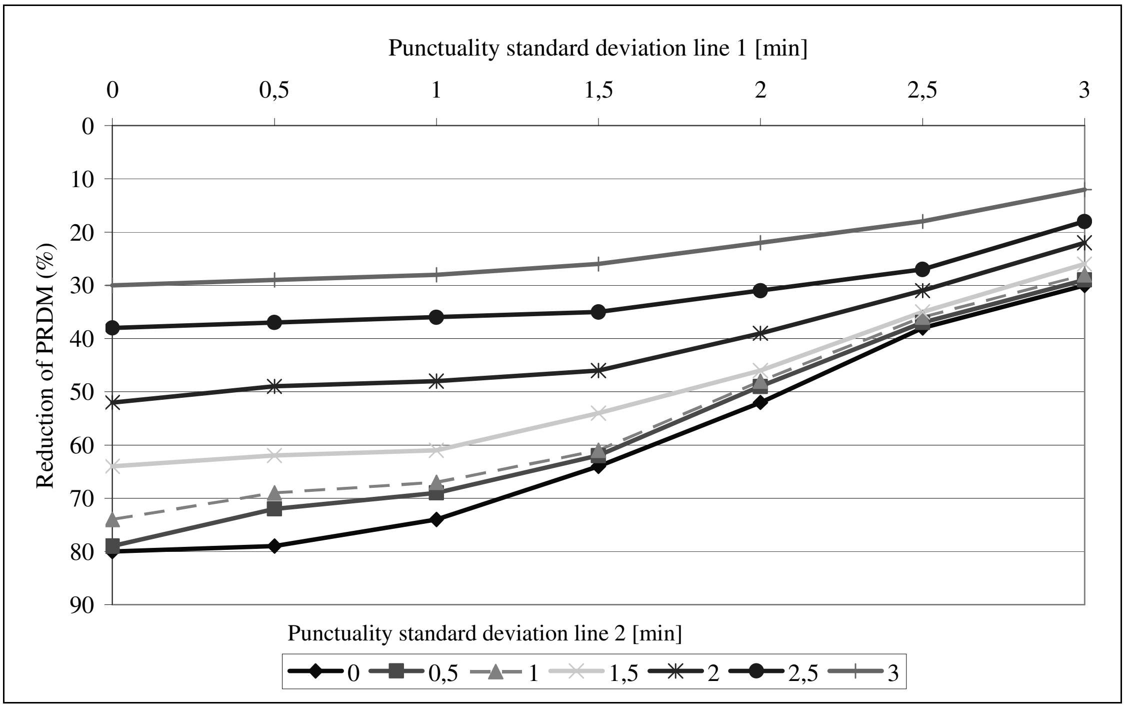


Figure 5.23: Reduction of the PRDM as a function of the punctuality of line 1 for different values of the punctuality of line 2 due to coordinating the transport services and improving the punctuality by reducing the standard deviation by 1 minute for both lines

These graphs may be applied to the case of the tram lines described in the previous section. In the reference case there are two lines with poor punctuality; the standard deviation of both lines is about 3 minutes (direction Scheveningen). In the new situation the punctuality of tram line 1 remains unchanged, while the punctuality of tram line 1K is very high. Using Figure 5.21 it can be seen that the original value for the PRDM was 55% and in that in the new situation it will be 45%. If the punctuality of tram line 1 is improved to say a standard deviation of 1.5 minutes the PRDM will be reduced to 25%. Furthermore, it can be seen that for the regularity it is not necessary to have a perfect punctuality for the short-turn tram line 1K. If both lines have a standard deviation of 1.5 minutes the PRDM becomes only 3% higher (28%). In this case improving the punctuality of tram line 1 is more beneficial than introducing a short-turn service.

5.3.4 Conclusions

In Chapter 4 we introduced the instrument of line coordination, which has been analyzed quantitatively in this section. An approach has been described that may be used to assess the impacts of network changes on the service reliability on a public transport route. Both a theoretical analysis and a case study showed that more realistic estimates than the traditional approach using a quantitative analysis are achieved when service dynamics are considered explicitly. Applying the framework from Chapter 2 it was demonstrated that line coordination is a proper instrument of service reliability improvement, but service dynamics should not be neglected in the planning stage. A case study showed increased perceived frequencies of 5-40% and the theoretical results are similar. Our international survey (see Section 3.2.3) showed that the topic of coordination is applied in many cities over the world. Especially the theoretical results in this section are useful to improve service reliability in other cities than

The Hague, since only general characteristics of lines are required. A more detailed analysis is beneficial as well, but requires more detailed input.

5.4 The instrument of line length design [1]

5.4.1 Introduction

This section deals with the design parameter line length, which was proposed in Chapter 4 as a potential instrument to improve service reliability. In public transport, there has been a tendency to connect or extend lines. An example of such a connection is RandstadRail (as introduced in Chapter 4). This new light rail system replaced and connected two tram lines, two former heavy rail lines and one metro line. The added value of these new links is a more direct connection from origin to destination. Passengers do not have to transfer anymore to reach the city centre, for example, which saves travel time. But when a line is extended there is a chance of an increase in variability and thus unreliability of transport services. This may lead to additional travel time.

During the design process, it is important to take both effects of extending or connecting lines into account; both time savings and the possible additional travel time due to larger unreliability. Our international survey (Section 3.2.3) showed that none of the operators uses a maximum line length during the network design. We analyzed this design dilemma in this section in a quantitative way, using our framework calculating average additional travel time per passenger due to unreliability and transfers (Van Oort and Van Nes 2009b).

This section starts with a description of design dilemmas at the strategic service network design. Afterwards, the new dilemma incorporating service reliability is presented. The next part of the section presents a research approach and results of our analysis of the impacts of line lengths and service reliability.

5.4.2 Network design dilemmas

In the introduction of this chapter, series of network design dilemmas are given. One dilemma that has to be added when service reliability is explicitly considered is line length vs. service reliability. There is a positive relation between line length and variability of trip times which leads to unreliability. Figure 3.11 in Chapter 3 shows the standard deviation of trip time as a function of the distance for all bus and tram lines in The Hague. Variability of trip times leads to poor schedule adherence and longer travel times for passengers. Section 3.3.4 shows the relation between variability in trip times of vehicles and travel times of passengers. Since long lines tend to be less reliable it would be interesting to take this explicitly into account at the moment of designing these lines. Designing shorter lines or splitting existing ones might mean an improvement. However, the effect of that choice is that fewer direct connections are offered, which means additional transfers and thus additional travel time and uncertainty about connections. The question to be answered in this section is: What is the effect of splitting public transport lines into two parts on travel times, taking into account the effects of variability and of a possible additional transfer?

[1] This section is based on a reviewed article published in the Transportation Research Records (Van Oort and Van Nes 2009b)

Figure 5.24 illustrates the effects of decreasing line length. Line 1 operates from A to B. The variability of driving time increases along the line. Line 2 is the same line as line 1, but this line it is divided into two parts: From A to C and from C to B.

Two main differences exist between lines 1 and 2:

- The variability of line 2 is less;
- Introduction of a transfer at C for line 2.

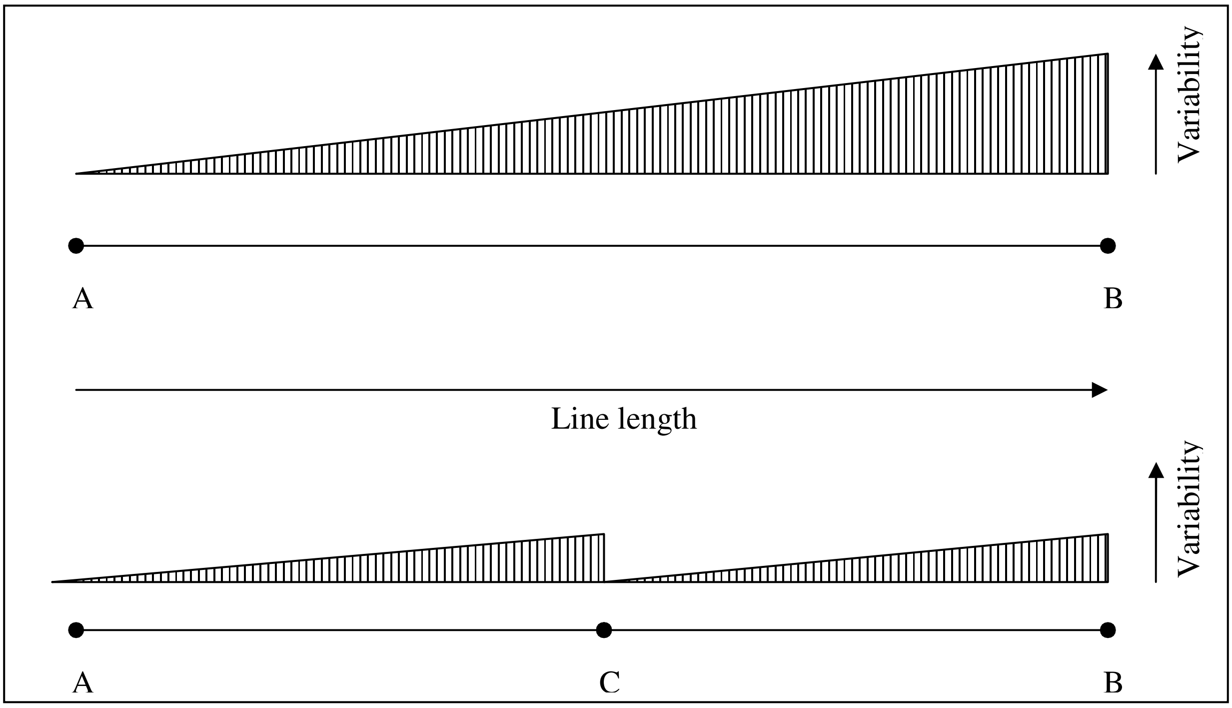


Figure 5.24: The effects of splitting a line (at C) on vehicle trip time variability

The additional transfer will lead to additional travel time for passenger passing point C and the decrease in variability will lead to better schedule adherence and shorter additional waiting times for passenger travelling between C and B. The trade-off between the additional transfer and better schedule adherence depends on the following variables:

- Travel patterns of passengers: the location of point C is important in terms of the number of passengers travelling over C;
- Frequency: Both waiting time at C due to transferring and waiting times at other stops depend on the frequency of the line;
- The schedule adherence: additional waiting time at the stops depends on the deviation of the timetable.

From an operator point of view, splitting lines might lead to additional costs (Lehner 1953). This should be taken into account during design as well. This section focuses on the passengers effects. Chapter 7 will present a more comprehensive overview.

5.4.3 Approach of line length analysis

In our research, we want to investigate what the effects of line length and splitting lines are on the average additional travel time per passenger. For the specific instrument of line length, we applied our framework (see Chapter 2) to gain insights into the passenger effects of this strategic design choice.

In the case of splitting the line into two parts, a transfer is introduced, leading to additional waiting time for passengers who want to pass this point. Equations 5.7-5.9 show the related formulae, including for the average effects for all passengers on the complete line (T_l^{Add}). At the transfer point the vehicle departure deviation is assumed to be zero and the punctuality develops as it did on this part before splitting the route. The additional time that is required for transferring per passenger is shown by Equation 5.7. We assume no coordination between the two lines and punctual and regular departures. The arrival stop of the feeder line is assumed to be the same as the stop of the second line, so only waiting time is accounted for (which is half the headway as shown by Equation 2.16).

In the end, all waiting times per stop are added, taking into account the relative number of passengers at a stop ($\alpha_{l,j}$, see Equation 2.18 in Chapter 2) and, if relevant, the number of passenger who have to transfer ($\beta_{l,j}$). The result is the average additional travel time for all passengers on the line (Equation 5.9). This is calculated for the scenario of one long line and two short lines with a transfer. This makes it possible to the compare two scenarios and to analyze the design dilemma of line length and transfers.

$$T_{l\_passenger}^{Add,transfer} = \frac{H_l^{sched}}{2} \qquad (5.7)$$

$$T_l^{Add,transfer} = \beta_{l,j} * T_{l\_passenger}^{Add,transfer} \qquad (5.8)$$

$$T_l^{Add} = T_l^{Add,transfer} + T_l^{Add,waiting} \qquad (5.9)$$

where:

H_l^{sched}	= *scheduled headway on line l (second line)*
$T_{l\_passenger}^{Add,transfer}$	= *average additional waiting time on line l due to transferring at transfer point per transferring passenger*
$T_l^{Add,transfer}$	= *average additional travel time per passenger on line l due to transferring*
$\beta_{l,j}$	= *proportion of passengers of line l travelling between stop j and j+1*
T_l^{Add}	= *average additional travel time per passenger on line l*
$T_l^{Add,waiting}$	= *average additional waiting time per passenger on line l at the stops*

The approach described above is used for a case study conducted in The Hague. Actual data of vehicle trip times and the number of passengers are used to calculate the effects of splitting long lines into two parts. Line 1, a tram line of 20 km, is used as an example. At the end of this section, additional results of other tram and bus lines are given. Appendix B gives the main characteristics of the lines used in this case.

As stated earlier, the pattern of boarding and alighting is of great influence in the case of introducing a transfer to improve overall reliability. Two examples of stops of line 1 illustrate the effects of this factor. In Figure 5.25 the part of passengers who are passing a certain stop are given as a percentage of the total numbers of passengers. The stop “CT” (i.e. City Centre) has a percentage of 12% through passengers, which means that 12% of all users of this line travel over this point. At the stop "He" (i.e. Heerenstraat) more passengers are passing. This part of line 1 is used by a large number of passengers, but not many are boarding or alighting here.

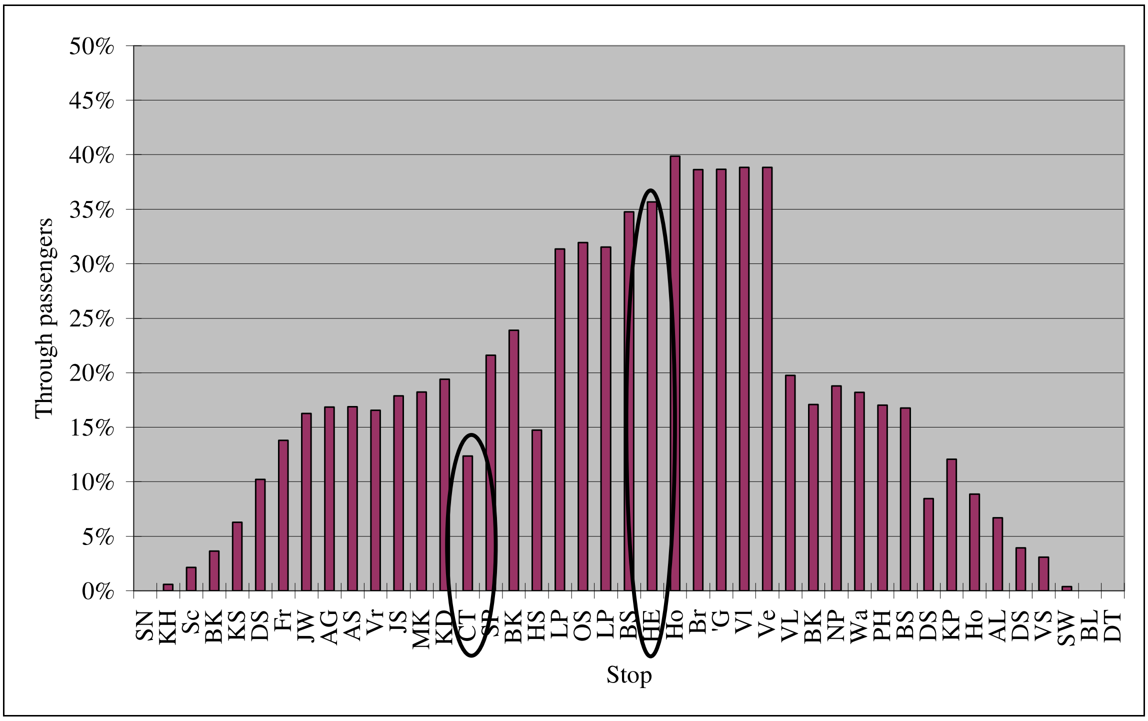


Figure 5.25: Number of passengers passing a stop as a percentage of total boardings on tram line 1

5.4.4 Results of line length analysis

In this subsection two computations are made of the average additional waiting time per passenger if both stops are used to divide line 1 into two parts. The locations to split the line are chosen regarding the number of through passengers or the division of the line in two equal parts.

The first scenario is City Centre ("CT") as a transfer point. This location is chosen, because many passengers exchange at this stop. The results of splitting are as shown in Table 5.3. Figure 5.26 illustrates the effects of variability on average additional waiting time per passenger per stop.

Table 5.3: Average additional travel time per passenger due to variability of trip times and transfers for line 1 (Transfer at City Centre)

Scenario	**Average additional travel time T_l^{Add} [s]**	**Average additional waiting time at stops $T_l^{Add,waiting}$ [s]**	**Average additional transfer time $T_l^{Add,transfer}$ [s]**
Line 1 Reference	100	100	0
Line 1 Two Parts	73	36	37

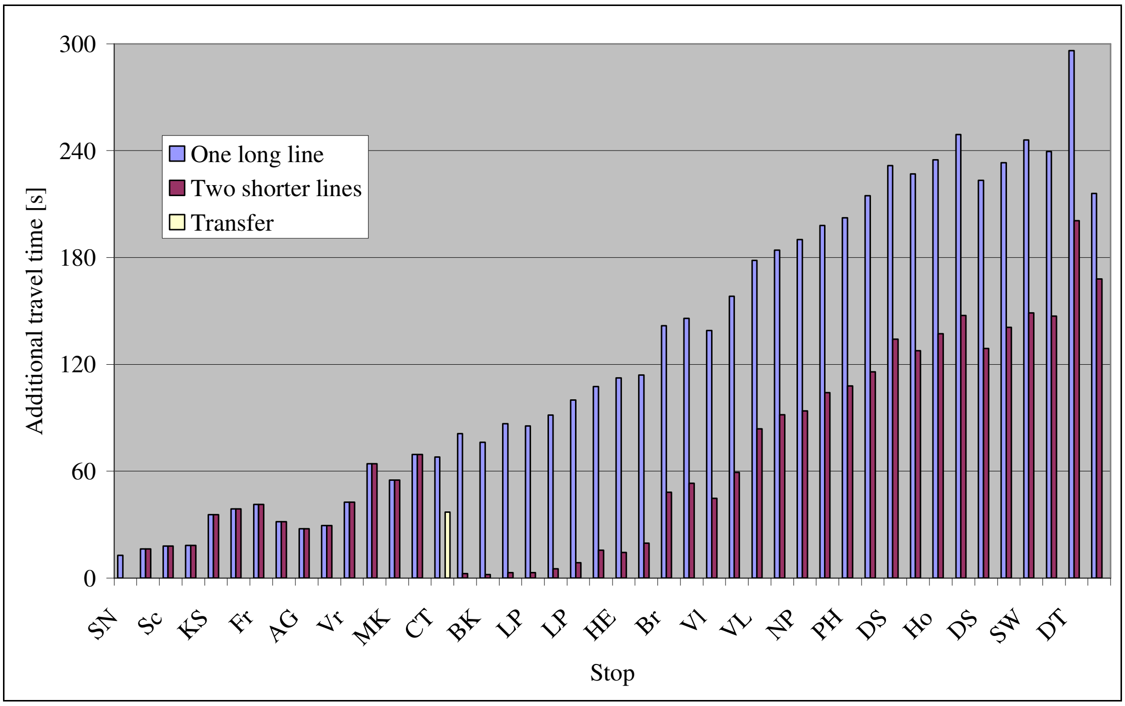


Figure 5.26: Additional travel time per passenger due to variability of trip times and transfers per stop of line 1, split at "CT"

These figures show a large decrease of the average additional waiting time per passenger at stops. The punctuality restores after the transfer location and so does the additional waiting time. Introducing a transfer leads to additional waiting time, but because of the small number of passengers making a transfer this effect is not great and is even smaller than the decrease in additional waiting time due to splitting.

Another possible transfer point is the middle of line 1. Splitting the line here divides the line in two equal parts. The results of splitting are shown in Table 5.4 and Figure 5.27.

Table 5.4: Additional waiting time per passenger due to variability of trip times and transfers for Line 1 (transfer at Heerenstraat)

Scenario	**Average additional travel time T_l^{Add} [s]**	**Average additional waiting time at stops $T_l^{Add,waiting}$ [s]**	**Average additional transfer time $T_l^{Add,transfer}$ [s]**
Line 1 Reference	100	100	0
Line 1 Two Parts	172	65	107

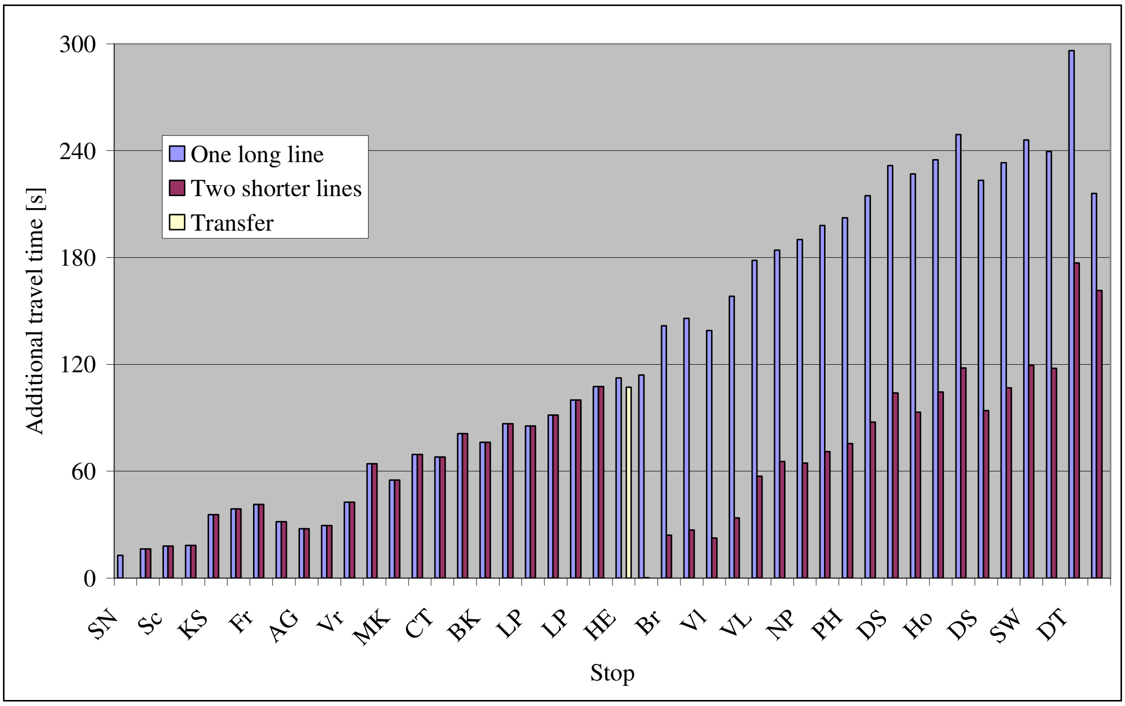


Figure 5.27: Additional travel time per passenger due to variability of trip times and transfers per stop of line 1, split at "HE"

The results presented in Figure 5.27 show a decrease in waiting time at the stops due to shorter lines. Because the line length in the case of two lines is shorter, the variability does not reach high values, leading to less additional waiting time at stops. However, the introduction of the transfer will lead to more waiting time and because the number of through passengers on this stop is high, many passengers will suffer from this transfer penalty. This additional waiting time due to transferring is not compensated by the benefit of a higher schedule adherence. In the contrary to the former case above, splitting the line is not beneficial in this way.

The results of the analysis of more lines in The Hague are shown in Figure 5.28. Per line the average additional travel time per passenger is illustrated as a result of average additional waiting time and transfer time. Both the current ("long") and the expected ("short") additional travel time when the line is divided into two short lines are shown. The effect of splitting the lines differs per line, because of differences in travel patterns and punctuality characteristics. The additional waiting time due to transferring on line 15/16 is very small, because this line actually consists of two lines, which are connected to each other only because of operational efficiency, not to offer more direct connections. It can be seen that this efficiency measure increase the additional travel time by 50%. This effect is probably not considered when deciding to integrate both lines.

The effect of splitting is positive for line 17 as well; the effect is about 30% less additional waiting time.

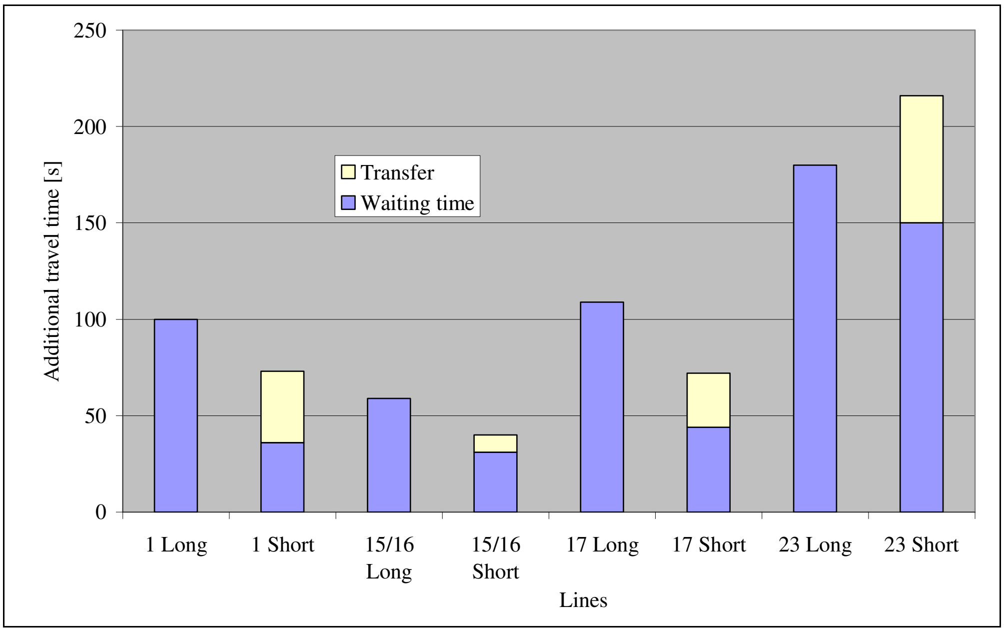


Figure 5.28: Effects of splitting lines on average additional waiting time per passenger

Although it was to be expected that splitting bus line 23 would decrease the additional waiting time as well, line 23 is by far the longest and least punctual line in The Hague, the effect of splitting is negative. Figure 5.29 (showing the number of through passengers) illustrates the main reason for this effect, namely that there is no ideal location for a transfer point on this line. The number of through passengers on the main part of the line is never below 18%.

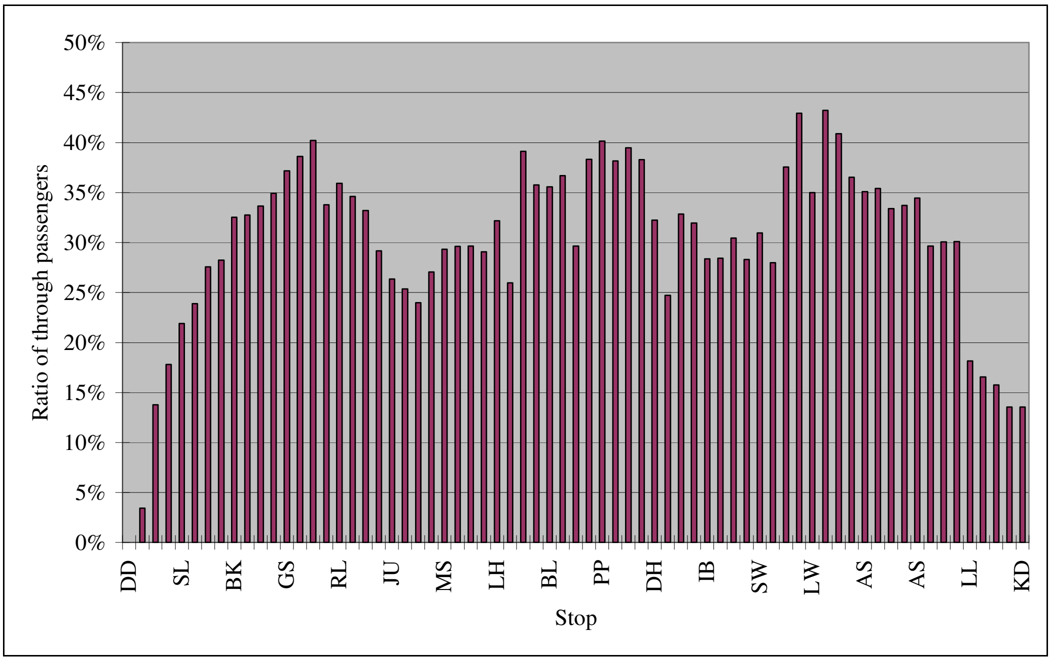


Figure 5.29: Number of passengers passing a stop as a percentage of total boardings on bus line 23

On line 23 there is no stop where enough passengers exchange. In this case, splitting the line with some overlap might be a solution, as Figure 5.30 shows. Not splitting the line at C, but at D and E, with overlap between D and E. This way fewer direct connections are removed. It is clear though that this solution leads to more expensive operations due to the overlap. This adds a new dimension to the previously mentioned dilemma, namely the additional operational costs vs. the additional reliability benefits. Additional research is needed on this topic.

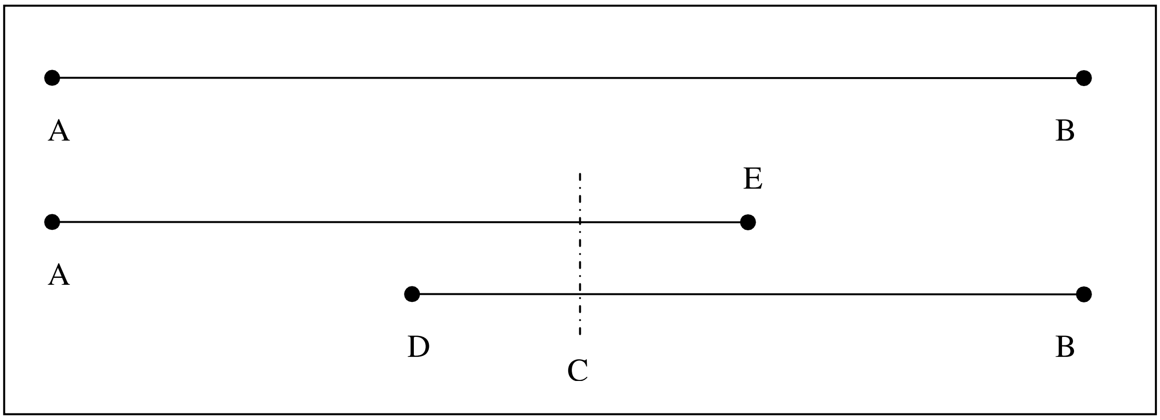


Figure 5.30: Splitting a line into two parts with an overlap

5.4.5 Conclusions

In this section we introduced an additional design dilemma, namely the length of line vs. reliability. Long lines offer many direct connections, thereby saving transfers. However, the variability is often negatively related to the length of a line, leading to poorer schedule adherence and additional waiting time for passengers. In this section we suggest taking into account both the positive and negative effects of extending or connecting lines. We applied the framework of Chapter 2 to calculate the average additional travel time per passenger due to variability and transfers based on actual trip and passenger data. A case study conducted in The Hague shows that in the case of long lines with large variability, splitting the line may result in less additional travel time due to improved service reliability. This advantage compensates for the additional time of transferring if the transfer point is well chosen. Our findings show the effects when the transfer point is chosen at a stop with many and fewer through passengers. The latter may lead to a decrease of about 30% in additional waiting time. Splitting a long line into two lines with an overlap in the central part may even result in more time saving. In that case, fewer passengers will need to transfer. However, operational costs may increase. The results of our research of the public transport in The Hague might be used in other cities as well. Our international survey (see Chapter 3) showed that traditionally, no maximum line length is applied. Similar to the lines in The Hague, being regular lines, decreasing line length might reduce additional travel time elsewhere as well.

5.5 Summary and conclusions

The objective of this chapter was to investigate a number of possibilities at the strategic level of urban public transport design to improve the level of service reliability. In Chapter 4 we selected three potential planning instruments potentially improving service reliability, namely terminal design, line coordination and line length. Applying our control framework and new indicators presented in Chapter 2, these instruments indeed demonstrate that service reliability may be positively influenced already at the strategic stage and thus that considering the dynamics of the operations in the design may lead to other design choices. Both case studies (of The Hague) and theoretical calculations of the expected passenger travel time effects proved the possible benefits of these instruments. Considering the results of the international survey, concerning design choices and line characteristics, the results are valuable for other cities as well. The first instrument deals with infrastructure design, the second and third are related to service network design. The results of the analysis of these instruments are presented below in more detail. Service reliability should be explicitly considered in cost-benefit analyses at the strategic level. Nowadays it is more common to deal with service reliability in a qualitative way at this level. In this chapter, we provide computational tools enabling a quantitative analysis as well. The next chapter will provide results of the analysis of the tactical level regarding service reliability.

In our research on terminal design we demonstrated that punctual departures may save up to 2 minutes additional travel time on average per passenger. To improve punctual departures, we showed the effects of various terminal configurations on reliability of services enabling optimized design, concerning passenger travel time and vehicle trip time. Besides terminals, the results may also be used for short turning infrastructure. A simulation tool enabled calculations of the average delay per vehicle, regarding three main types of terminals. We showed the effects of frequency on the one hand and occupancy time (determined by the distance from the switches to the platform (i.e. length of the terminal), technical turning time and scheduled layover time) on the other. The substantial effects of arrival variability and the number of lines using the terminal are illustrated as well. We showed that using stochastic variables, delays will occur, although they are not to be expected in the static case. The best performance regarding service reliability is achieved, when double crossovers are situated after the platforms. Single tail tracks facilitating the turning process are only acceptable if frequencies are low. However, they are often used in practice as short tuning facility for high frequent services. This research shows the large impacts of occupancy time on expected delays. It is recommended to minimize this time by designing short distances between switches and platform and tail tracks.

Since the impacts of line coordination on service regularity and vice versa are rarely analyzed in a quantitative way, we performed research to assess the impacts of network changes on the regularity on a public transport route using the control framework of Chapter 2. A case study on introducing coordinated services shows that considering service reliability leads to more realistic estimates than the traditional approach using a quantitative analysis. Coordination may improve service reliability, but that depends on the punctuality characteristics of the coordinated lines. A case study showed increased perceived frequencies of 5-40%. Our theoretical approach showed similar results.

Concerning the third strategic planning instrument, we introduced a new design dilemma in the service network design, namely length of line vs. service reliability. Long lines offer many direct connections, thereby saving transfers. However, the variability is often negatively related to the length of a line, leading to less schedule adherence and additional waiting time for passengers. We suggest taking into account both the positive and negative effects of extending or connecting lines. A case study in The Hague shows that in the case of long lines with large variability, splitting the line may result in less average additional travel time per passenger because of improved service reliability. We showed several lines, where total average additional waiting time per passenger has been decreased after splitting the line, even savings up to 30%. This benefit compensates for the additional transfer time, provided that the transfer point is well chosen. The results of our international survey showed similar lines in other cities, which enables such savings as well.

In this chapter we demonstrated that substantial reduction of passenger travel time may be achieved by applying strategic planning instruments. In Chapter 7, these benefits will be used to assess the cost-effectiveness of the investigated instruments. In that chapter, we also discuss the possible interaction and combination of the instrument, both at strategic and tactical level. In the next chapter we will address the impacts of tactical instruments on service reliability.

6. Service reliability improvements at tactical level

6.1 Introduction

In this chapter, we address the possibilities to improve service reliability that exist during the design of the timetable. In Chapter 4 we selected two tactical instruments enabling enhanced service reliability during operations, namely trip time determination and vehicle holding. In this chapter, we will analyze these instruments in more detail aimed at identifying opportunities to minimize the effects of unreliability for passengers in terms of travel time.

A variety of factors are important in designing a proper timetable. Given a public transport service network and frequencies per line (as described in Chapter 4), vehicle trip times have to be determined, both from terminal to terminal and in more detail from stop to stop. Frequencies and trip times enable the design of a skeleton timetable. To fix the timetable in time, the offset has to be determined. This fixation may be the result of synchronization and coordination with other lines, as addressed by Chapter 4, and thus is important as well during the timetable design. It applies to transfer options and to offering a constant interval on a corridor with multiple lines. Through this coordination, the scheduled departure times per stop are fixed. The phenomenon of coordination is strongly related to network design. Our study analyzing the impacts of line coordination on service reliability was presented in Chapter 5.

Above, the important variables of timetable construction are mentioned, focusing on the timetable for the public. However, at the tactical level, timetables for resources (vehicles and crew) are also designed. All these three types are interconnected. The fleet timetable consists of all the trips the vehicles make on a day, consisting of a connection of public trips. Deadheading from and to the depot is part of this schedule as well. A crew schedule consists of a connection of trips as well, but of course the length of the duty is shorter. Often the crew schedule and vehicle schedule are constructed simultaneously (Bodin et al. 1983, Freling et al. 1999, Haase et al. 2001 and Huisman et al. 2005).While during the design of the public timetable, the desired services and speed and capacity are main indicators, in the timetable construction of crew and fleet other issues are of main interest. In the fleet planning of rail systems, the types of vehicles are very important if trips are linked to each other. Special vehicles which are not able to operate on all tracks restrict the possibilities. This may be due to the width of the vehicles for instance, or whether a route is designed for two-directional vehicles only. For crew management, the law, union regulations and company rules are very important. They determine for example the maximum length of a shift, the number and length of breaks, etc. The knowledge of and experience with certain types of vehicles and routes may be a constraint as well.

In this chapter, we demonstrate that considering service reliability as an output quality during the design of the timetable may lead to sensible service reliability improvements. We provide insights into the relation between the tactical and operational level. First of all, trip times are determined by using operational data and secondly, during operations early vehicles may be held, thereby improving schedule adherence. We demonstrate in our research, that optimization of timetables with regard to these topics is possible concerning passenger travel times. We apply the control framework of Chapter 2 to calculate the average additional travel time per passenger as a function of timetable design. For our research, we investigated actual lines in The Hague as well as hypothetical lines using insights of the international survey (see Chapter 3). This way, results are considered useful for other cities as well.

This chapter is structured as follows: In Section 6.2 the first instrument, that is trip time determination, is presented while the second instrument to be studied, that is vehicle holding, is analyzed in Section 6.3. The chapter finishes with a summary and conclusions in 6.4.

6.2 The instrument of trip time determination[1]

6.2.1 Introduction

As mentioned in Chapter two, service reliability is a resultant of the match between schedule and operations on passengers. Hence, the actual operations are compared to a reference, which is designed and thereby may be influenced. Our first instrument presented will show the impacts of adjusting the reference (i.e. the scheduled trip time that is used in the timetable) on the travel time for passengers. It is shown that commonly used design parameters do not succeed in minimizing the average additional travel time per passenger.

The main element of a timetable, besides the number of trips, is the scheduled trip time, i.e. the time necessary to drive from stop to stop. In urban public transport, it is common practice to determine the trip time based on empirical data of the services from the previous period (Van Oort and Weeda 2007). Using this type of feedback (indicated as the long-term feedback loop in Section 4.4), attainable trip times are scheduled. An example of empirical data of trip times is illustrated by Figure 3.8 in Chapter 3.

In Chapter 3 we showed that the realized trip times have a distribution which is caused by several factors, such as weather, traffic, variation in the number of passengers, human interaction, etc. Chapter 4 provided a detailed description of possible causes, as did Cham and Wilson (2006). The challenge for the planner is to choose the best trip time from this distribution, since only one time value may be used as input for the timetable. By choosing a single trip time, knowing the real trip times are distributed, schedule adherence will not become optimal and differences will arise between the timetable and actual operations, leading to additional travel time for passengers, as demonstrated in Chapter 2.

The trip time for the schedule is normally chosen by selecting a percentile value. In urban public transport planning usually a large percentile value of this distribution (e.g. 85th percentile) is used to determine the trip time for the schedule. This way, most drivers could operate on time (that is 85% of vehicle trips are not late). However, in most conditions this method also influences service reliability. Because of high percentile values a lot of trips may operate ahead of schedule, being an important source for passenger delay. Changing the percentile value will change the number of vehicles ahead of schedule and thus the punctuality and the average additional travel time per passenger. Muller (1995) presented research, recommending the 85-percentile value, which leads to an attainable timetable. The design dilemma that arises is thus service reliability vs. schedule attainability. Also the international survey shows that mainly high percentile values are used in practice, as Figure 6.1 illustrates (Van Oort 2009). The impacts of scheduled trip time on passenger travel time apply only to long headway services. In short headway services, people tend to arrive at random at the departure stop and the trip time used in the schedule is of no relevance (when no control is applied).

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[1] This section is based on a reviewed article published in the proceedings of the 11th international conference on advanced systems for public transport (CASPT; Van Oort et al. 2009)

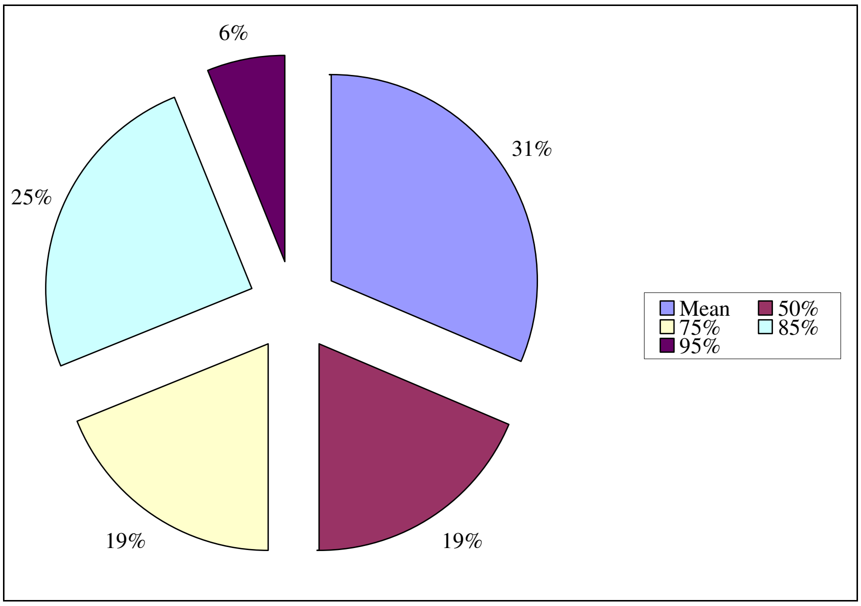


Figure 6.1 Answers in international survey to "If trip times are determined by actual data of the previous period, which percentile value is used?"

In literature so far, only limited attention has been paid to this phenomenon with respect to travel time for passengers (Muller 1995 and Fattouche 2007). In heavy railways, more attention has been paid to this topic (for instance Geraets et al. 2007 and Vromans 2005). However, in heavy railways the construction of timetables is completely different from that in urban public transport (Van Oort and Weeda 2007). No feedback loop is applied, but trip times are theoretically determined using characteristics of vehicles and infrastructure. In this section we will calculate the average additional trip time per passenger as a function of the percentile value used for the scheduled trip time in an attempt to show that scheduled time setting indeed may improve service reliability. However, first we will give an overview of the consequences of trip time determination in Section 6.2.2 and the applied modelling framework in Section 6.2.3.

6.2.2 Consequences of trip time determination

The final choice of the scheduled trip times has many consequences. Divided into supply side issues and demand side issues, the main ones are:

Supply side

- *The probability of departing on time from the first stop;*
  If many vehicles are delayed (i.e. a low percentile value is used), the probability of a punctual departure of the next trip in the opposite direction will decrease. This depends both on the delay and on the slack in the layover time at the terminal.
- *Attainability for the driver;*
  The longer the scheduled trip time (i.e. a higher percentile value is applied), the larger the probability that a driver will arrive within the scheduled time. However, the consequence might be that drivers are ahead of schedule.

- *Number of vehicles needed.*
  The number of vehicles required to operate conform the timetable is determined by the frequency and cycle time of the line. This time consists of trip time and layover time in two directions. If the scheduled trip time decreases (i.e. a lower percentile value applied), in theory, one vehicle is able to run more trips and fewer vehicles are required. However, the number of actual vehicles needed always depends on the actual trip time and not on the scheduled one.

Demand side

- *Travel time of passengers.*
  As illustrated by Figure 2.8 in Chapter 2, the total passenger journey does not only consist of in-vehicle time. Apart from in-vehicle time, waiting comprises a substantial part of the journey , especially in urban public transport. If operations do not match the planning, the passenger waiting time at the stop increases (as described in Chapter 2). If vehicles drive ahead of schedule (i.e. a high percentile for scheduled trip time has been applied), it is possible that passengers miss their vehicle and have to wait a full headway. The choice of what percentile value of the previous data is used for a new timetable determines the punctuality and therefore waiting time and travel time.

The choice of the optimal percentile value is a major topic in many public transport companies. The effects mentioned above show the large consequences of the choice of scheduled trip time. This section will perform a quantitative analysis of the choice of the percentile value. Two effects are shown, being the average additional travel time per passenger caused by the mismatch of planning and operations and the probability of departing on time at the first stop for the next trip. In analyzing these effects of scheduled trip times, the following aspects are most important:

- *The distribution of actual trip times.*
  The larger the bandwidth, the larger the effects on punctuality and probability to arrive at the last stop on time.
- *Frequency.*
  The lower the frequency, the larger the effects of driving ahead of schedule. After all, people have to wait a complete headway if they miss the vehicle.
- *Number of boardings.*
  The stops where people board and their location at the line are of great importance. Once passengers have boarded and are on their way, the departure time at the following stops are no longer relevant.
- *Layover time.*
  The time at the last stop, before departing in the other direction may be used as slack time to make up for delays. A portion of this time may also be used as a break for the drivers. This portion is not taken into account in our analysis.

The distribution of actual trip times is assumed to be fixed in the following analysis; only the scheduled trip time is changed and thereby departure times at all stops. This scheduled departure time is communicated to passengers and they adjust their moment of arrival at the departure stop, which determines their waiting time.

6.2.3 Approach of scheduled trip time determination analysis

To gain insights into the impacts of trip time determination on service reliability we performed an analysis calculating the average additional travel time per passenger as introduced in Chapter 2. To calculate the additional travel time due to trip time determination, the framework presented in Chapter 2 is applied. This will be shown in Section 6.3.3.1. In Section 6.3.3.2, the details of the analysis are presented. Both a theoretical and a practical analysis are used to illustrate the impacts of trip time determination on service reliability.

6.2.3.1 Applied modelling framework

To analyze the effects of the choice of the percentile values for scheduled trip time on punctuality, additional travel time and the probability of on-time departure, we applied our control framework presented in Chapter 2. This framework already showed the main computation and equations to calculate the average additional travel time per passenger. Below the steps for the specific instrument of trip time determination are presented as summarized in Figure 6.2.

The first step in the model is constructing the timetable. The main variable is the percentile value based on the data of actual trip times during the previous period, which is used to determine the scheduled trip time. After the percentile value has been chosen, the complete timetable is determined. The main input is actual data from the operations, i.e. vehicle trip times from stop to stop on a certain line. The next step is to compare the newly constructed timetable with the stochastic set of trip times under the assumption that trip times are not affected by the timetable. As a result the stochastic departure deviation of the timetable is calculated per stop ($\tilde{d}_{l,i,j}^{stop}$). Since trip time variability is not affected, the passenger in-vehicle is not affected neither and is not taken into account in the analysis of this instrument.

With the help of the departure deviation per stop, the average additional waiting time per passenger due to variability in trip times (see Equations 2.19-2.21 in Chapter 2) will be derived. Driving ahead leads to a waiting time equal to the headway. Particularly in the case of low frequencies, this means a large increase in waiting time. Driving late creates additional waiting time equal to the delay. The average additional waiting time is first calculated per stop ($T_{l,j}^{Add,waiting}$) and then as a weighted average for all passengers on the line (T_l^{Add}), depending on the relative number of boardings at each stop ($\alpha_{l,j}$).

In addition to the average additional travel time per passenger, the probability of on-time departure at the first stop is determined by the model ($P_{l,i,1}^{on\_time-departure}$). The model calculates the punctuality deviation at the last stop for every vehicle trip ($\tilde{d}_{l,i,last\_stop}^{arrival}$) and uses this value in combination with the scheduled layover time (i.e. the time between the scheduled arrival and departure of the vehicle at the terminal, $T_{l,i}^{layover}$) to determine the departure delay (if the arrival delay is larger than the layover time; otherwise, no delay will occur). After the departure delay for all vehicle trips has been calculated, the probability of on-time departure is determined. Equation 6.1 shows the calculation of the probability of departing on time.

$$P_{l,i,1}^{on\_time-departure} = P(T_{l,i}^{layover} - \tilde{d}_{l,i,last\_stop}^{arrival} \geq 0) \tag{6.1}$$

where:

$P_{l,i,1}^{on\_time-departure}$ = *probability of on-time departure of vehicle i at the terminal on line l*
$T_{l,i}^{layover}$ = *scheduled layover time of vehicle i at the terminal on line l*
$\tilde{d}_{l,i,last\_stop}^{arrival}$ = *arrival deviation of vehicle i on line l at the terminal*

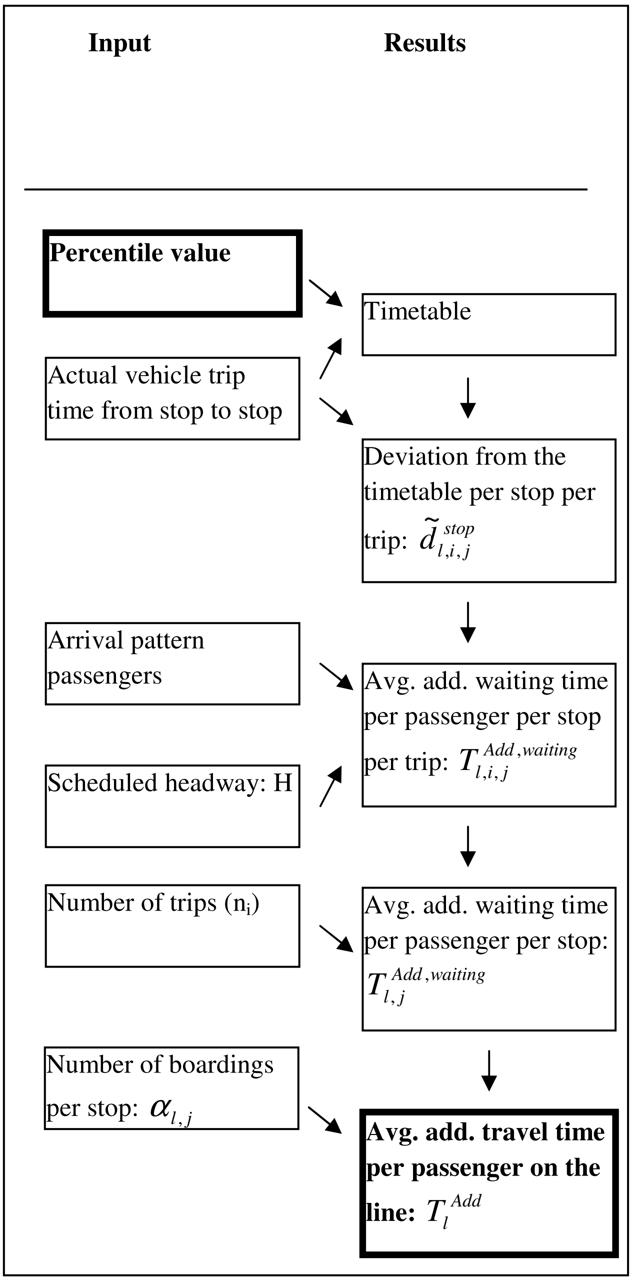


Figure 6.2: Model for calculating the impacts of trip time determination on average additional travel time per passenger (cf. Equations 2.19-2.21)

6.2.3.2 Set up of case study

The study on minimizing the average additional travel time per passenger by adjusting the timetable is set as follows. It consists of both a case study of actual lines in The Hague and a theoretical analysis. In this way, the analysis yields practical valuable results and by adding the theoretical analysis, the variables are controllable so effects of different values may be calculated.

The input for the theoretical analysis is a fictitious line with a trip time of 30 minutes, headways of 15 minutes, serving 30 stops. The boardings and alightings are distributed across the line, as Figure 6.3 shows. This service line is assumed to be a typical radial line, in which boarding mainly occur in the first part of the line and alightings in the second part.

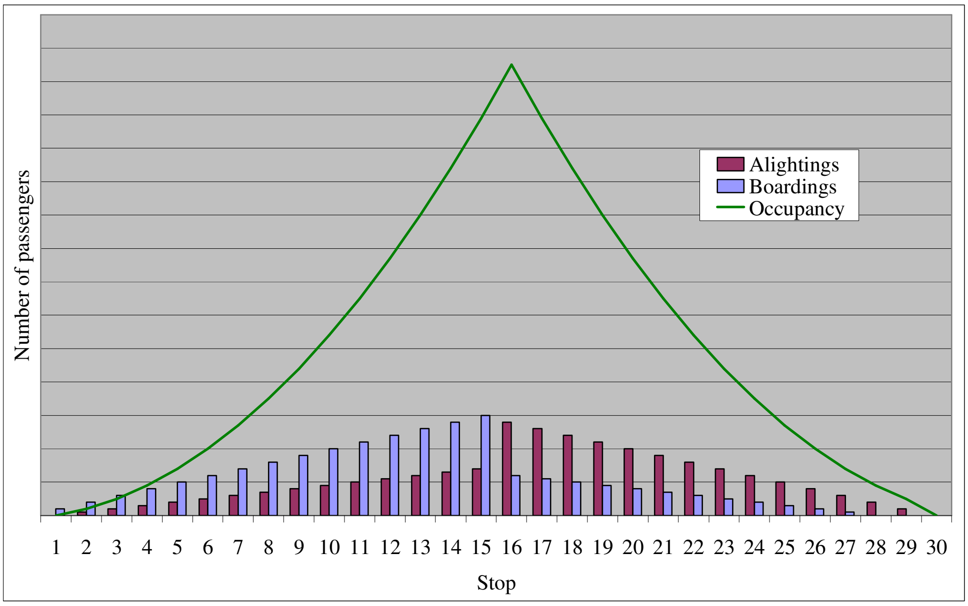


Figure 6.3: Distribution of boardings and alightings, hypothetical line

Based on actual trip time data, the trip times are assumed to be Gaussian distributed (as proposed by Abkowitz et al. 1987 and Strathman et al. 2002). Three scenarios are analyzed, namely actual trip times with 5%, 10% and 20% of the scheduled trip time as standard deviation. Using these values, a set of hypothetical "actual" trip times is randomly determined which is the input for the analysis, as described in Section 6.2.3.1.

The case study consists of different tram and bus lines (in terms of length and distribution of trip times) operated by HTM in The Hague. Actual trip times and passenger flows are used as input. Appendix B shows the main characteristics of the lines analyzed.

The next subsection shows the results of the theoretical study and the case study on the effects of trip time determination on the average additional travel time per passenger. The effects on the probability of on-time departure at the first stop are also analyzed.

6.2.4 Results of trip time determination analysis

Let us first look at the results of the theoretical case as shown in Figure 6.4. For three different trip time distributions, the average additional travel time per passenger is calculated and shown as a function of chosen percentile value for scheduled trip time. This figure illustrates that the average additional travel time increases with increasing variance of the distribution of trip times and percentile values.

The minimum average additional travel time per passenger is achieved if a 35 percentile (or lower) value is chosen. This low value prevents most vehicles to depart ahead of schedule saving many passengers much waiting time. Depending on the standard deviation of the trip time, the size of the minimized additional trip time is between 0.5 and 4 minutes. The difference between the 85 and 35 percentile value lies between 0.5 and 11 minutes.

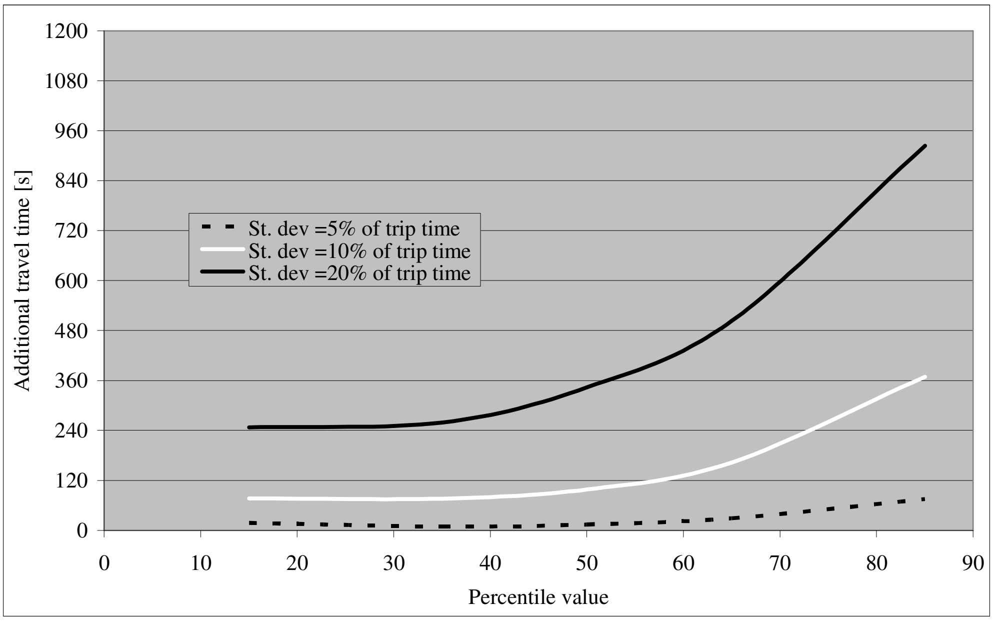


Figure 6.4: Average additional travel time per passenger as function of chosen percentile value for a hypothetical line (trip time 30 min, standard deviation 5, 10 and 20%)

Figure 6.5 shows the effects of the chosen percentile value on the probability of on-time departure at the first stop, using a hypothetical line of 30 minutes, regarding a 10% standard deviation. Both an increasing layover time and a higher percentile value lead to a higher probability of departing on time. To ensure a punctual departure, a layover time between 15% and 35% of the trip time (for a percentile value of 85 and 15% respectively) is necessary.

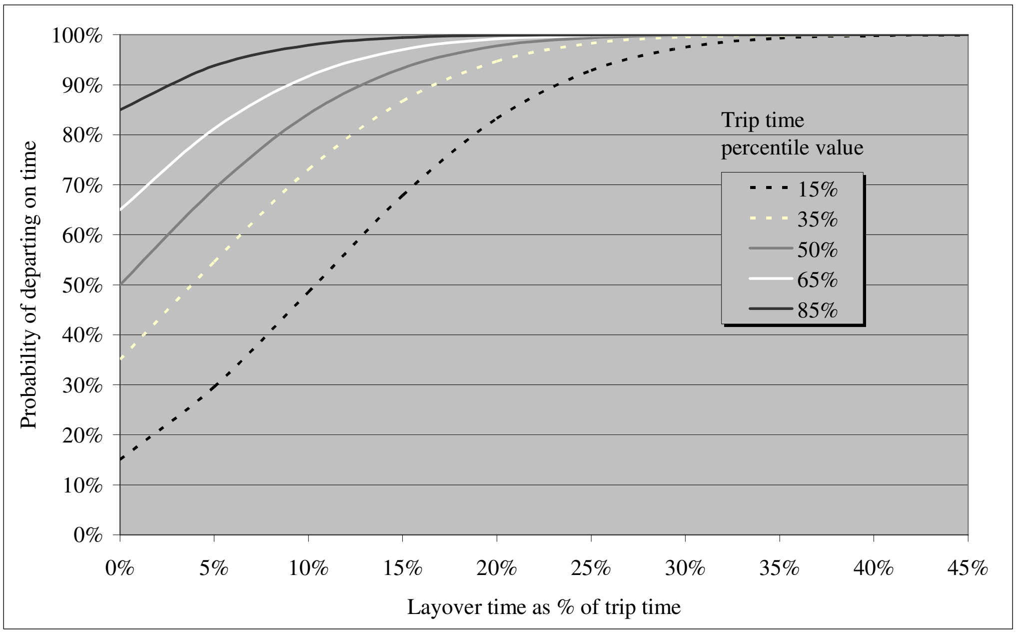


Figure 6.5: Probability of on-time departure as a function of percentile value and layover time, hypothetical line

If the percentile value decreases, more layover time is needed to ensure punctual departures in the opposite direction. Nevertheless, this additional time is saved in the trip time, using a lower percentile value. In fact, this is a redistribution of time between trip and layover time, not adjusting total cycle time at all.

In addition to a theoretical approach, a case study has been conducted in order to assess the impacts of the percentile value choice. Figure 6.6 shows the average additional travel time per passenger as a function of the chosen percentile value for 4 tram lines. This figure shows a substantial increase in additional travel time if the percentile value exceeds the level of 50. The minimum value, 0.5-1.5 minutes, is reached when the 35 percentile value is used. This supports the results from the theoretical analysis (which showed in addition to the actual lines results of a line with a standard deviation of 20%). Also shown is a large difference depending on the chosen percentile value. On average, passengers will experience 2 to 5 minutes additional travel time if the 85 percentile value is used, instead of the 35 percentile.

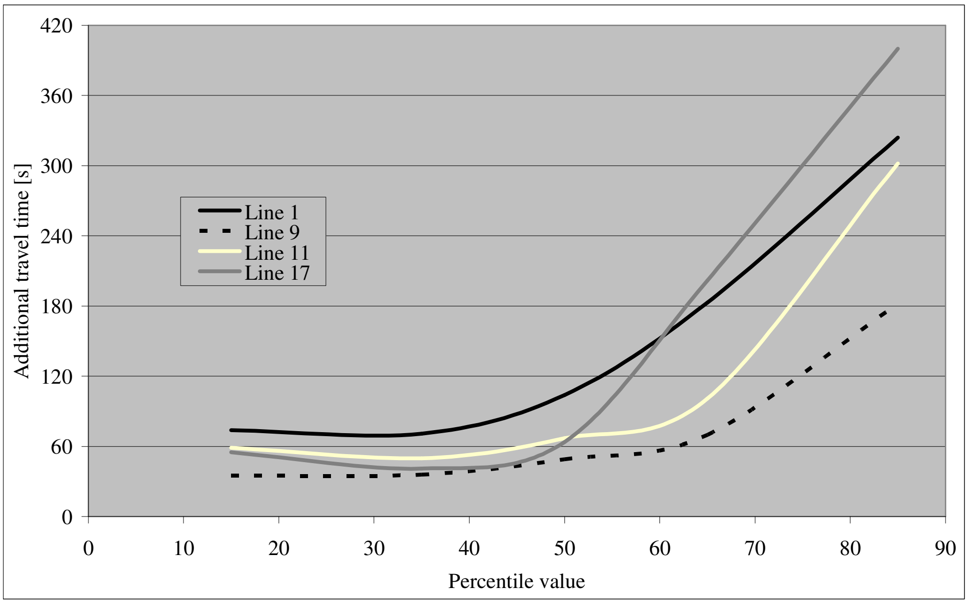


Figure 6.6: Average additional travel time per passenger as a function of chosen percentile value

Figure 6.7 shows the probability of on-time departure from the first stop of tram line 11 as a function of percentile value and layover time. The characteristics of this line are shown in Appendix B. The results match those of the theoretical analysis and the analysis of the other actual lines analyzed. This also confirms that a redistribution of total cycle time is necessary implying reducing the trip time and increasing the layover time. This ensures that passenger travel time is minimized and departure punctuality for the first stop of the next run is not affected.

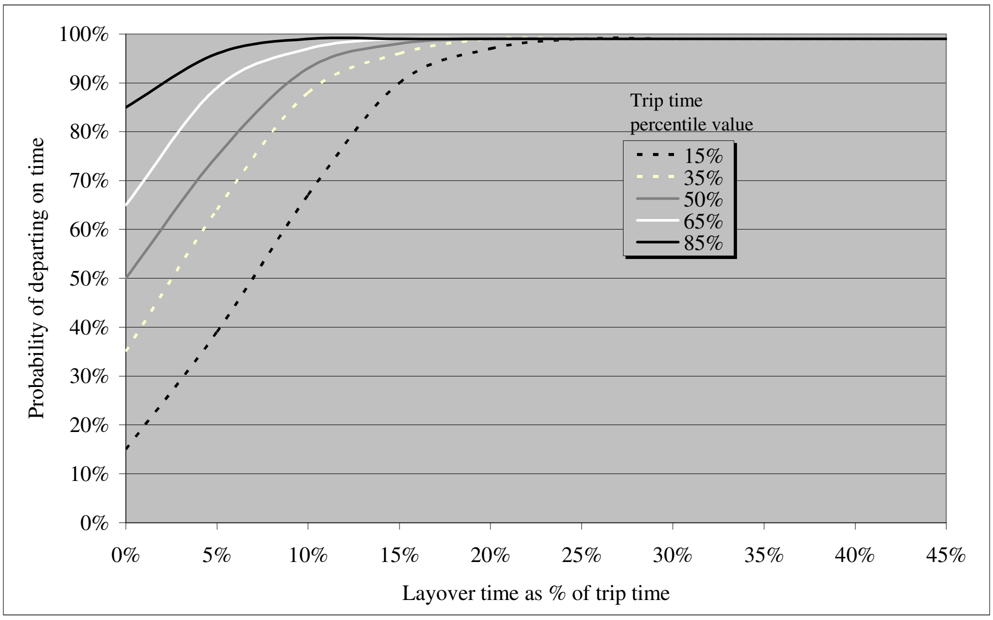


Figure 6.7: Probability of on-time departure as a function of percentile value and layover time for tram line 11

6.2.5 Conclusions

In this section we presented our research on optimizing service reliability of urban public transport by analyzing service reliability by adjusting the timetable. A theoretical approach and a study of actual lines show the effects of design choices of timetabling on service reliability. Our analysis of actual and theoretical data shows that the average total travel time per passenger is minimized if the 35-percentile value is used to determine the scheduled trip time based on historical data. To ensure punctual departure from the terminal in the opposite direction, layover time should be extended by the same amount of time, with which the trip time is decreased. This implies a fixed cycle time and constant operating costs. To optimize total cycle time, further research is recommended. Preventing vehicles to operate ahead of schedule may be achieved by vehicle holding as well, as stated in Chapter 4. In the next section we will elaborate on this instrument.

6.3 The instrument of vehicle holding [1]

6.3.1 Introduction

The first instrument we presented in this chapter, trip time determination, only requires timetable adjustments; operations were assumed not be changed otherwise. In the second study in this chapter, that is analyzing the instrument of vehicle holding, operations are adjusted on top of the timetable itself. In Chapter 4 we selected vehicle holding as a potential instrument, applied during operations, but dependent on timetable design choices. Holding implies that too early arriving vehicles have to wait until they are on schedule again. This way, service reliability will be improved downstream of the holding point. However, the passengers who are already in the vehicle during the holding process will suffer from additional travel time leading to a conflict of interest, namely between the positive impacts for passengers downstream and the negative impacts for passengers in the vehicle. The amount of holding depends on the schedule. If trip times are designed tightly, not many vehicles will operate ahead of schedule and holding will not be applied much. But if trip times are designed in such a way that the schedule is very loose, many vehicles will be held due to earliness. We analyzed these issues to find an optimal holding strategy and optimal design parameters with respect to travel time for passengers. Often, vehicle holding is handled as an operational instrument, but in this section it is shown, that timetable design plays an important role as well.

Several research papers on holding have been published during the last decades (e.g. Turnquist and Blume 1980, Levinson 1991), but the combination of holding strategies and schedule parameters is rarely analyzed. In practice, vehicle holding is a popular instrument as well, confirmed by the results of our international survey (see Chapter 3). About 78% of the operators and authorities use holding in their operations.

Our research on holding (see Boterman 2008, Van Oort et al. 2009 and Van Oort et al. 2010) for more details) is divided into a number of categories, which are shown by Table 6.1. First of all, a distinction is made between long and short headways (which leads to different arrival patterns of passengers at their departure stop, as discussed by Chapter 2). In addition, the type of holding strategy is differentiated. One strategy holds vehicles when they are ahead of schedule, the other one when the headway ahead is too short. They are referred as schedule-based and headway-based holding. The last differentiation is where the holding takes place; at all stops or at only a few main ones.

Table 6.1: Categories of vehicle holding in our research

		Long-headway services	**Short-headway services**
Holding strategy	Schedule-based	X	X
	Headway-based		X
Holding location	All stops	X	
	Few stops	X	X

[1] This section is based on a reviewed article published in the Transportation Research Records (Van Oort et al. 2010)

In long-headway services, headways are of less importance because passengers arrive depending of the schedule. Schedule adherence is thus much more important and thus schedule-based holding as well. Vehicle holding at all stops is only presented in the case of long headways, to simply indicate the impacts. In the following sections, all marked types of holding in Table 6.1 are analyzed and their impacts on passenger travel time are presented. First, we will show the impacts of vehicle holding in Section 6.3.2. After this, a literature review of vehicle holding is presented in which we demonstrate that although much research has been conducted, still some questions are not addressed yet. We will present these issues in Section 6.3.4. In Section 6.3.5 we will discuss the approach we chose to calculate the impacts of timetabling and holding, using the framework of Chapter 2. The next section presents the results of all categories of holding that we have investigated (see Table 6.1) and finally, conclusions are given in Section 6.3.9.

6.3.2 Expected impacts of vehicle holding

Holding points are stops where drivers are not allowed to leave ahead of schedule. Introducing holding points will affect service reliability and passenger travel times. Not driving before the scheduled time reduces the variability in trip times, as Figure 6.8 shows. At holding point p, vehicles that have arrived early wait until they are on time; late vehicles are unaffected. Vehicle holding decreases the distribution of the schedule deviations. This section presents the results of a research study on designing trip time and holding points. The research questions are how many points should be introduced and which percentile value should be used for driving towards the holding point to minimize average additional travel time per passenger.

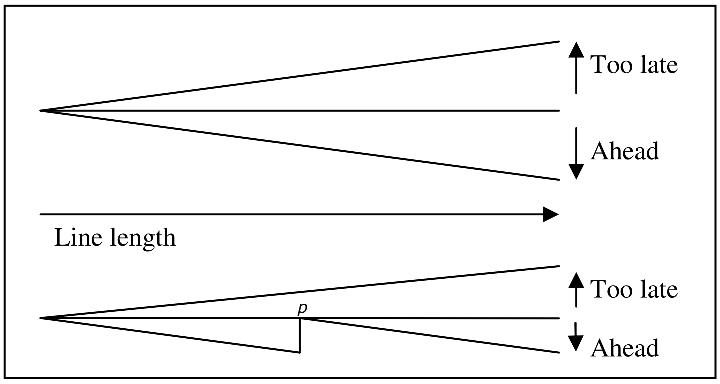


Figure 6.8: Effects of holding point p on schedule adherence

The expected impact of the application of the holding instrument is a reduction of the average additional travel time per passenger. Although holding vehicles will increase the average vehicle trip time in the first place, due to less trip time variability, bunching will be reduced, thereby decreasing the average vehicle trip time.

Not every stop is useable as a holding point. At a good holding point, the proportion of passengers who board and alight is high. Through passengers gain no advantage from waiting at the holding point. Besides, a good holding point is a stop where no other traffic or public transport is affected by a waiting vehicle.

In the same way as used in trip time determination, the scheduled trip time from holding point to holding point may also be chosen by a percentile value from a distribution of realized trip times.

6.3.3 Literature review on vehicle holding

Many research papers on holding have been published. Hickman (2004) provides an overview of some earlier research on holding. Most of the references described focus only on headway-based holding. Hickman (2001) presents research on holding using thresholds. He shows the influence of different perceptions of waiting at the stop and inside the vehicle (due to holding). When the perception of waiting at the stop (as a ratio of waiting in the vehicle) increases, holding becomes more interesting. Lin et al. (1995) compare headway-based and schedule-based holding strategies, concluding that for short headways headway-based controlling is more effective. They also mention proportional holding, i.e. holding time as a fraction of the headway or schedule deviation, but do not provide any expected results of this method. Furth and Muller (2006 and 2009) deal with the holding problem for low-frequency services. Besides average travel time, they consider the budgeted travel time as well. Uniman (2009) also deals with this phenomenon, called Reliability Buffer Time (RBT, as presented in Chapter 2). This indicator shows the effects of unreliability by taking into account the 95-percentile arrival time. People tend to want to be on time and take this additional time required into consideration when planning their trip. In addition, Furth and Muller (2007) also consider the possibility for operators to add slack time to the schedule. This ensures that service reliability will increase, although a trade-off must be found between service reliability and passenger travel time, due to additional scheduled trip time. Abkowitz and Lepofsky (1990) performed a real-life experiment, applying threshold-based holding. Their results of headway-based holding are positive and they state that the reported effects of holding may have been understated because human factors (i.e. behaviour of drivers) may greatly reduce the effectiveness of the holding strategy. Eberlein et al. (2001) focus on holding when real-time information is available, enabling better holding strategies. Fattouche (2007) did research on schedule-based holding in high-frequency systems and explicitly took the schedule design into account as well. One of the findings is that long holding times are hard to enforce in practice.

The optimal number and location of holding points has not been researched to the same degree. Lesley (1976) states that bus stops where the coefficient of variance of the headway is greater than twice the average over all bus stops may serve as holding points. Abkowitz et al. (1986) conclude that the optimal location is sensitive to the number of boardings downstream. Additionally, the optimal stop is most of time located at the stop prior to a group of stops where many people board. Hickman (2001) adds that using the stop with maximum boardings might be the best location as well. In Abkowitz and Engelstein (1984), the best holding points are defined as stops, where the product of the standard deviation of the bus travel time to the stop and the ratio of passengers that will subsequently board the bus along the route to the passenger on the bus, is maximized. The best location for a holding point thus both depends on deviation characteristics and on the distribution of passengers on a line, (i.e. the number of through passengers at the holding point and boardings downstream). Table 6.2 summarizes the references mentioned above, showing the main aspects dealt with in the specific research.

Table 6.2: References on holding and aspects taken into account

Reference	Holding type[1]	Headway type[2]	RBT	Proportional holding	Schedule parameters	Maximum holding time
Hickman (2001)	H	Short	X	X	Not applicable	X
Abkowitz and Lepofsky (1990)	H	Short	X	X	Not applicable	X
Eberlein et al. (2001)	H	Short	X	X	Not applicable	X
Lin et al. (1995)	S/H	Short	X	✓	X	X
Fattouche (2007)	S	Short	X	Not applicable	✓	X
Furth and Muller (2007)	S	Long	✓	Not applicable	✓	X

[1] S(chedule-based) or H(eadway-based)
[2] The arrival pattern of passengers at their departure stop is assumed to be dependent of the headway type. When headways are short (no specific numbers are provided) people arrive at random, while they consult the schedule when headways are long.
X = not taken into account

Table 6.2 clearly illustrates that not all main variables are taken into account yet in research on holding. The maximum holding time is relevant for both drivers and for passengers. The introduction of maximum holding takes into account the effects of holding on individual passengers. It makes it possible to optimize scheduling and holding strategies regarding a minimum quality for all passengers, i.e. a maximum additional travel time due to holding. Besides, in the case of short headway rail systems, limited capacity and shared use of tracks with other lines may force held vehicles to depart. Although leading to an optimum for all passengers on average, in the case of short headways holding strategies without a maximum holding time are not likely to be introduced if holding times exceeds 60 seconds. Experiences in The Hague show drivers do not accept large holding time for the sake of both passengers as drivers. Fattouche (2007) also states that long holding times are hard to enforce. This is only relevant in short headway service.

Due to the lack of research on the effects of introducing maximum holding time and only little focus in literature so far on the effects of schedule parameters on short- and long-headway services holding strategies, we will particularly address these variables in the following analysis.

6.3.4 Vehicle holding strategies and issues

Since we concluded in the previous section, that in existing research not all aspects of vehicle holding are considered, we conducted new research on this topic. In this section the main holding strategies and their associated key variables are explained.

Holding strategies may be designed in various forms with a major differentiating characteristic being how a holding action is triggered. As presented in the previous sections, commonly either headway or schedule deviations are used to initiate holding. The most commonly used method for holding is a threshold strategy, whereby vehicles are held only if a certain threshold is exceeded (as presented by Barnett 1974).

In this chapter, vehicle holding is presented as an instrument to reduce passenger travel time on a single line, but it may also be employed to ensure transfers, as explored by Dessautels (2004) and Wong and Wilson (2006). Holding may also be very effective in restoring service after service disruptions have occurred, as described by Wilson et al. (1992), O'Dell and Wilson (1999) and Puong and Wilson (2004). However, we only address vehicle holding in normal operations, according to our overall focus as stated in Chapter 1.

When applying holding points, it is important to determine the location(s) of holding points. However, optimizing the location of holding points is beyond the scope of this research. Rather the holding location is chosen in a pragmatic way, that is good holding points are characterized by few through passengers and many passengers boarding downstream (as described in the previous section and by Abkowitz et al. (1986) and Hickman (2001). An analysis of all stops as holding points is also performed for sake of a reference case. Figure 6.9 shows the number of holding points per line used by the participants of the international survey, illustrating several strategies used.

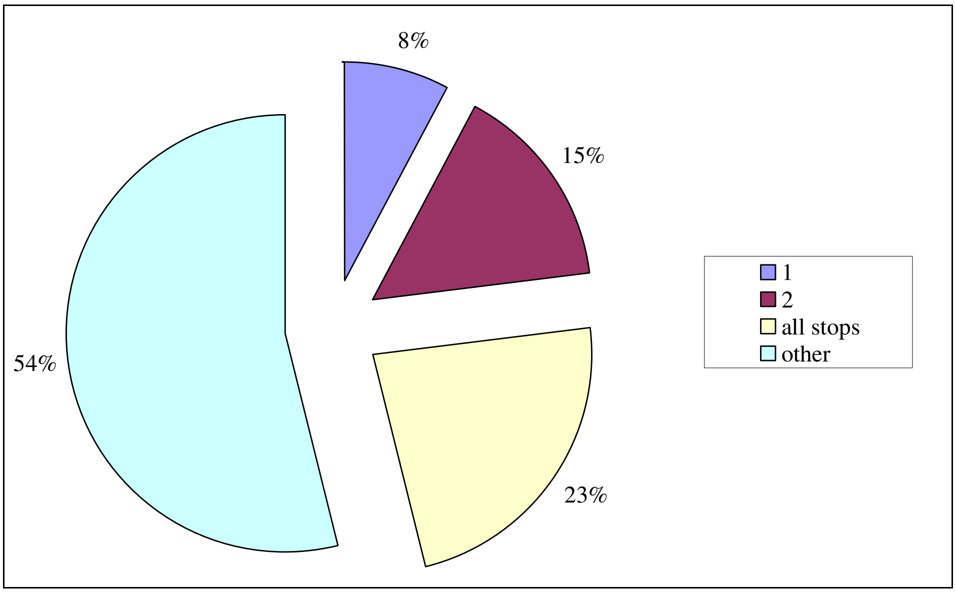


Figure 6.9: Answers international survey to "What is the number of holding points applied?"

The following subsection will present the main aspects of the holding types we will explore.

6.3.3.1 Headway-based holding

Headway-based holding means that vehicles with headways shorter than scheduled are held to restore a tight headway distribution. No action is taken for vehicles with long headways because it is assumed that vehicles cannot be sped up. When applying headway-based holding the following variables are considered:

Holding factor

This factor determines how long vehicles are held relative to the difference between the actual and scheduled headways. A holding factor of 100% means that vehicles are held the full amount of time needed to achieve the scheduled headway. This means that even if only one vehicle experiences a delay, all following vehicles will also be held. A lower holding factor will reduce this effect.

Maximum holding time

Introducing a maximum holding time affects the maximum individual travel time. Maximum holding prevents anyone from experiencing extremely long travel times in order to achieve the optimum for all passengers. Experiences of several operators have shown that in short-headway services, holding times longer than 60 seconds are generally not acceptable to either passengers or drivers.

Figure 6.10 illustrates the headway-based holding strategy. Vehicle 1 is delayed and vehicle 2 is ahead of schedule, creating a short headway between them. At stop 3, the holding point, vehicle 2 will be held by an amount of time equal to either the maximum holding time or the product of the holding factor and the headway deviation. By holding vehicle 2, the headway between vehicle 2 and 3 also decreases, which then also lead to the holding of vehicle 3 (depending on the trajectory of vehicle 3).

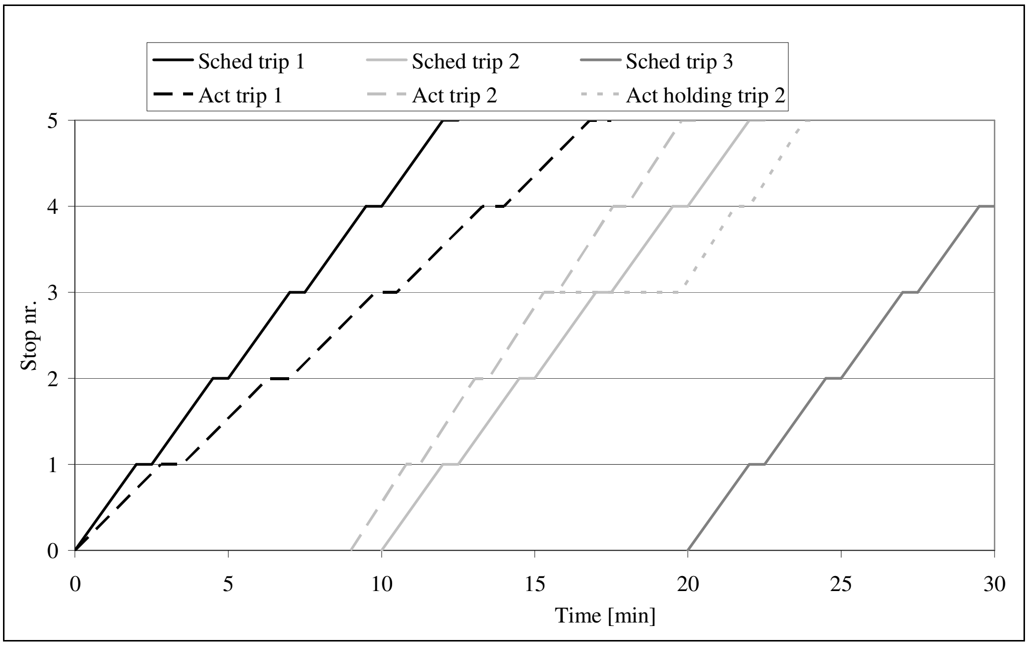


Figure 6.10: Headway-based holding

6.3.3.2 Schedule-based holding

In contrast to headway-based holding, schedule-based holding involves analyzing only one vehicle at a time. At the holding point the vehicle's schedule adherence is checked and if the vehicle is ahead of schedule, it is held for a certain time. The following variables are of importance.

Schedule percentile value

Because a comparison is made between the performance and the schedule of a specific vehicle, schedule design plays an important and direct role in this type of holding. For example, if scheduled trip times are very tight, few vehicles will operate ahead of schedule and little, if any holding is necessary. On the other hand, if the schedule is very loose, most vehicles will be ahead of schedule and will be held. To determine scheduled trip time, most public transport operators use a percentile value of the cumulative distribution of the actual trip times from the previous period, as presented in Section 6.2. Note that this is not relevant in the case of random arrivals of passengers and headway-based holding.

Maximum holding time

Similar to headway-based holding, a maximum holding time is included in the analysis of schedule-based holding to ensure that the model results are acceptable in practice. In long-headway services maximum holding time is not incorporated.

Figure 6.11 illustrates schedule-based holding, dealing with the variables mentioned above and showing both the 5- and 95-percentile values of trip 1. The actual trajectory of trip 1 is also shown. At the holding point, stop 3, a comparison is made between the scheduled and actual departure times. Depending on the percentile value, the actual trip is ahead of schedule or delayed. In this example the figure shows that the vehicle is ahead of schedule and is held for a certain time. The holding time is either the earliness or the maximum holding time. By holding the vehicle, the following headway will be shortened. However, the next vehicle is held only if its schedule adherence is negative, regardless of the value of the headway. The example shown in Figure 6.11 shows that the next vehicle is too early and it should be held as well.

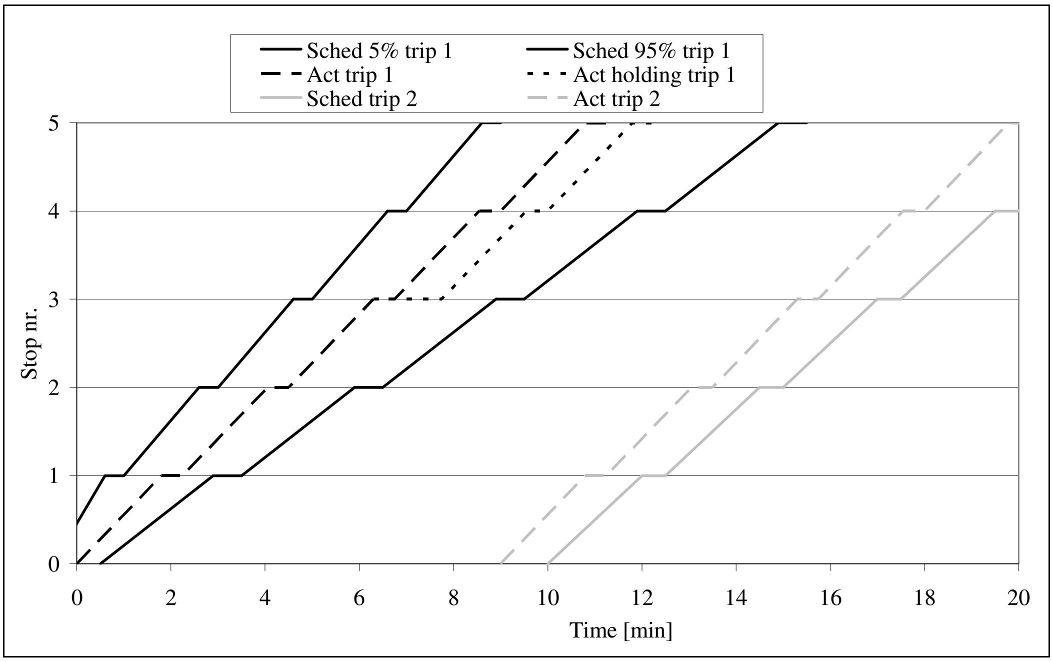


Figure 6.11: Schedule-based holding

6.3.5 Approach of vehicle holding analysis

The objective of our research of vehicle holding is to assess the impacts of the variables mentioned in Section 6.3.4 on the optimal holding strategy with regard to service reliability.

Next to headway-based holding being the main research topic in literature, this research also deals with schedule-based holding. From a practical point of view, schedule-based holding is an interesting method, even if headways are short. Due to resource planning, schedules exist anyway and dealing with schedules is easier than dealing with headways, which involves two vehicles. Another interesting phenomenon is the existence of branched networks all over the world, providing short headways on the trunk part (as described in Section 5.3), but on the branches headways may become large enough for people tending to arrive at the stop by using the schedule. In that case, schedule adherence is preferred over headway adherence. Additionally, in most Western European countries, schedule adherence is similar to headway adherence, since schedules provide constant headways. In this section, we will analyze several categories of vehicle holding, as shown by Table 6.1 in Section 6.3. The following subsections will describe the framework applied per category, which are:

- Long headways
  - Schedule-based holding;
- Short headways
  - Headway-based holding;
  - Schedule-based holding.

To calculate the effects of holding strategies on passenger travel time, the framework introduced in Chapter 2 is applied. The main objective is to compute the average additional waiting time per passenger (resulting in average additional travel time per passenger). The basic calculation of the additional travel time has been given in Chapter 2. This section shows the extensions needed to deal with holding points.

First the variables used and the main assumptions made in the model are defined. Next the equations used to calculate additional travel time are presented, separately for long and short headway services. Finally, equations are given to calculate the effects of headway and schedule-based holding on headways.

To calculate the average additional travel time per passenger we used the following variables in our research:

- Number holding points;
- Standard deviation of total trip time;
- Percentile value used to determine scheduled trip time (schedule-based holding only);
- Maximum holding time (short headway service only);
- Holding factor (headway-based holding only);

Fixed parameters that we used are:

- Passenger boarding and alighting distribution;
- Scheduled headway.

In the analysis of determining the probability of on-time terminal departure in the opposite direction, the layover time is of importance too. However, in the analysis of the average additional travel time per passenger, cycle time is assumed to be fixed, so this probability is not affected (Van Oort et al. 2009). The location(s) of the holding point(s) are selected in such a way that the effects of holding are maximized. However, we also performed a simple sensitivity analysis on this issue with an actual line.

This research considers both long and short-headway services, assuming schedule dependent and random arrival of passengers at stops respectively. Layover time is assumed to be long enough to enable punctual departures in the opposite direction. In addition, there is assumed to be no relation between headways and trip times (including dwell times), as in Fattouche (2007). Reducing complexity, no relationship between the holding time and the number of on-board passengers is assumed. Holding is applied at a stop and only the preceding headway is considered, because at the holding point, no information is assumed to be available for the driver about the following headway. This is only relevant for headway-based holding. The final assumption is that scheduled headways are constant.

Reliability Buffer Time is only considered in short-headway services, where deviations are relatively larger compared to the headway. Further research on RBT and vehicle holding is recommended for long headway services.

6.3.5.1 Applied modelling framework long headway services
When holding points are used, passenger waiting time in the vehicle must be considered in addition to passenger waiting time at the stop. Equations 6.2-6.7 show the computation of the impact of holding on waiting in the vehicle, including the calculation of the average effects for all passengers. In Chapter 2, the equations for the expected waiting time at the stop are given. Note that due to holding, the additional waiting time at the stop downstream of the holding point decreases, due to enhanced schedule adherence. Figure 6.12 shows the calculation process, as an addition to Figure 6.2. The right part is the extension considering the waiting time in the vehicle.

$$\tilde{T}_{l,i,j}^{holding} = D_{l,i,j}^{sched} - \tilde{D}_{l,i,j}^{act} \quad \text{if} \quad j = h_n \text{ and } \tilde{D}_{l,i,j}^{act} < D_{l,i,j}^{sched} \tag{6.2}$$

$$\tilde{T}_{l,i,j}^{holding} = 0 \quad \text{if} \quad j = h_n \text{ and } \tilde{D}_{l,i,j}^{act} > D_{l,i,j}^{sched}$$

$$\tilde{T}_{l,i,j}^{holding} = 0 \quad \text{if} \quad j \neq h_n$$

$$\tilde{T}_{l,i,j}^{add,in-vehicle} = \tilde{T}_{l,i,j}^{holding} \tag{6.3}$$

$$\tilde{D}_{l,i,j}^{'act} = \tilde{D}_{l,i,j}^{act} + \sum_{1}^{j} \tilde{T}_{l,i,j}^{holding} \quad j \geq h_1 \tag{6.4}$$

$$T_{l,j}^{add,in-vehicle} = \frac{\sum_{i=1}^{n_{l,i}} T_{l,i,j}^{add,in-vehicle}}{n_{l,i}} \tag{6.5}$$

$$T_{l}^{add,in-vehicle} = \sum_{j=1}^{n_{l,j}} \beta_{l,j} * T_{l,j}^{add,in-vehicle} \tag{6.6}$$

$$T_{l}^{add} = T_{l}^{add,waiting} + T_{l}^{add,in-vehicle} \tag{6.7}$$

where:

$\tilde{T}_{l,i,j}^{holding}$ = *holding time of vehicle i at stop j on line l*

$D_{l,i,j}^{sched}$ = *scheduled departure time of vehicle i at stop j on line l*

$\tilde{D}^{act}_{l,i,j}$ =*actual departure time of vehicle i at stop j on line l*

$\tilde{D}'^{act}_{l,i,j}$ = *calculated new actual departure time of vehicle i at stop j on line l (after holding)*

h_n = *stop number of holding point n*

$T^{add,in-vehicle}_{l,i,j}$ = *expected additional in-vehicle time in vehicle i at stop j on line l*

$T^{add,waiting}_{l,i,j}$ =*expected additional waiting time due to vehicle i at stop j on line l*

T^{add}_{l} = *average additional waiting time per passenger on line l*

$\beta_{l,j}$ = *proportion of passengers passing stop j on line l*

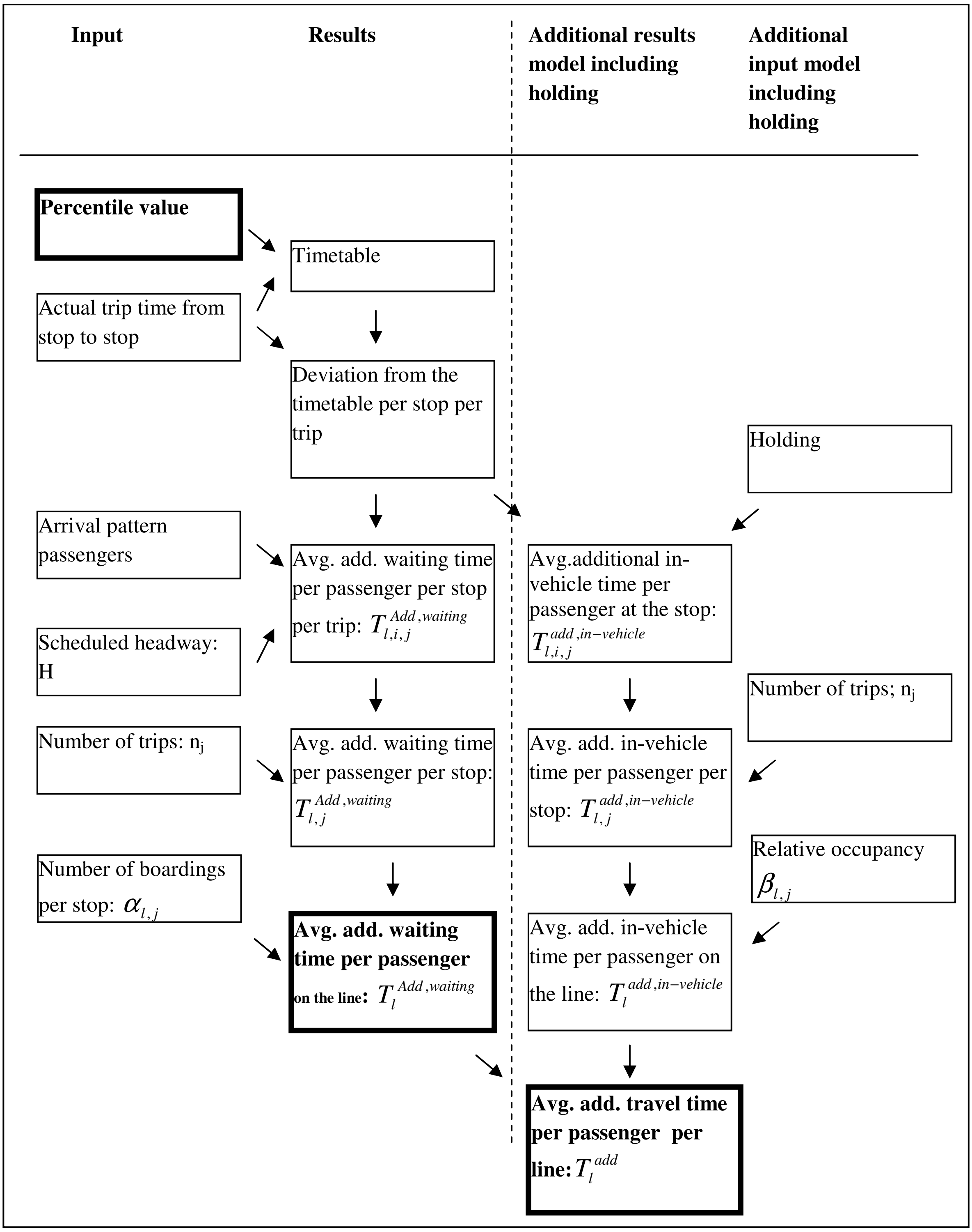


Figure 6.12: Extended model for average additional travel time per passenger in the case of holding

6.3.5.2 Applied modelling framework short headway services

Similar to the calculations above, the average additional travel time per passenger may be calculated for short headway services. Equation 2.17 gives the average additional waiting time at a stop as a function of actual headways.

To calculate the additional (average) travel time for all passengers on the line, Equation 2.18 (Chapter 2) and 6.5-6.7 (shown above) are used. Besides the average additional travel time, Furth and Muller (2006) and Uniman (2009) argue that the reliability buffer time (RBT) is also important, reflecting the effects of unreliable services on passengers travel time budget. Equations 2.16-2.20 deal with the RBT which are also weighted per stop to calculate a line total. The 95th percentile is taken out of the actual trip data set and similar to Furth and Muller (2006) and Uniman (2009) the RBT is calculated for the waiting time in the vehicle as well. Finally, Equation 2.26 assesses the total additional time using different weights for different components (compared to in-vehicle time).

a) Calculation of headway-based holding impacts

To calculate the average additional travel time per passenger, the model calculates the effects of headway-based holding (holding at stop h_n) on headways. A change in headways will lead to a change in additional travel time (as shown by Equation 2.17). Equations 6.8 and 6.9 give the holding time and the effects on expected waiting time in the vehicle ($T_{l,i,j}^{add,in-vehicle}$), while Equations 6.10 and 6.11 show the effects of departure times ($\tilde{D}_{l,i,j}^{act}$ before holding and $\tilde{D}_{l,i,j}^{'act}$ after) and headways ($\tilde{H}_{l,i,j}^{act}$) for the rest of the trip and the following trip. Note the effect of holding trip i on the holding choice process for trip i+1.

$$\tilde{T}_{l,i,j}^{holding} = Min(\gamma * (H_l^{sched} - \tilde{H}_{l,i,j}^{act}), T^{\max holding}) \quad if \quad j = h_n \text{ and } H_l^{sched} > \tilde{H}_{l,i,j}^{act} \qquad (6.8)$$

$$\tilde{T}_{l,i,j}^{holding} = 0 \quad if \quad j = h_n \text{ and } H_l^{sched} < \tilde{H}_{l,i,j}^{act}$$

$$\tilde{T}_{l,i,j}^{holding} = 0 \quad if \quad if\ j \neq h_n$$

$$\tilde{T}_{l,i,j}^{add,in-vehicle} = \tilde{T}_{l,i,j}^{holding} \qquad (6.9)$$

$$\tilde{D}_{l,i,j}^{'act} = \tilde{D}_{l,i,j}^{act} + \sum_{1}^{j} \tilde{T}_{l,i,j}^{holding} \quad j \geq h_1 \qquad (6.10)$$

$$\tilde{H}_{l,i,j}^{act} = \tilde{D}_{l,i,j}^{'act} - \tilde{D}_{l,i+1,j}^{act} \quad j \geq h_1 \qquad (6.11)$$

where:

$\tilde{T}_{l,i,j}^{holding}$	*= holding time of vehicle i at stop j on line l*
γ	*= fraction of headway deviation that vehicle is held for*
$T^{\max holding}$	*= maximum holding time*
H_l^{sched}	*= scheduled headway on line l*
$\tilde{H}_{l,i,j}^{act}$	*= actual headway of vehicle i at stop j on line l*

b) Calculation of schedule-based holding impacts

Equations 6.12 and 6.13 give the effects on passenger waiting time in the vehicle in the case of schedule-based holding being applied at stop h_n. Equations 6.14 and 6.15 calculate the effects of holding on the departure times ($\tilde{D}^{act}_{l,i,j}$ before holding and $\tilde{D}^{'act}_{l,i,j}$ after) and headways ($\tilde{H}^{act}_{l,i,j}$) for the portion of the trip downstream of the holding point. Note that Equations 6.13-6.15 are similar to the headway-based holding equations. In contrast to headway-based holding, schedule-based holding does not affect the holding decision process for the next trip. In Equation 6.8, H is used, while Equation 6.12 uses D. Regarding the next trip, the holding process only affects H.

$$\tilde{T}^{holding}_{l,i,j} = Min((D^{sched}_{l,i,j} - \tilde{D}^{act}_{l,i,j}), T^{\max holding}) \quad if \quad j = h_n \ and \ \tilde{D}^{act}_{l,i,j} < D^{sched}_{l,i,j} \tag{6.12}$$

$$\tilde{T}^{holding}_{l,i,j} = 0 \quad if \quad j = h_n \ and \ \tilde{D}^{act}_{l,i,j} > D^{sched}_{l,i,j}$$

$$\tilde{T}^{holding}_{l,i,j} = 0 \quad if \quad j \neq h_n$$

$$\tilde{T}^{add,in-vehicle}_{l,i,j} = \tilde{T}^{holding}_{l,i,j} \tag{6.13}$$

$$\tilde{D}^{'act}_{l,i,j} = \tilde{D}^{act}_{l,i,j} + \sum_{1}^{j} \tilde{T}^{holding}_{l,i,j} \quad j \geq h_1 \tag{6.14}$$

$$\tilde{H}^{act}_{l,i,j} = \tilde{D}^{'act}_{l,i,j} - \tilde{D}^{act}_{l,i+1,j} \quad j \geq h_1 \tag{6.15}$$

6.3.5.3 Set up of case study in long headway services

Similar to the research of trip time determination, the research of vehicle holding is performed using both actual and hypothetical lines. The actual lines are used to demonstrate the actual effect of vehicle holding in real-life, while the analysis of hypothetical lines gained insights into the impacts of controllable variables. The characteristics of the hypothetical lines used in the research of holding in long headway service are similar to those presented in Section 6.3.3.2. The scheduled trip time is 30 minutes, headways are 15 minutes and 30 stops are served. The boardings and alightings are distributed across the line as shown Figure 6.3. Concerning service variability, we assumed, based on actual data and literature (Abkowitz et al. 1987 and Strathman et al. 2002), a Gaussian distribution with different values for the variance.

6.3.5.4 Set up of case study in short headway services

For the analysis of short headways hypothetical lines are used as well. The trip times of the hypothetical line are assumed to be Gaussian distributed (as proposed by Abkowitz et al. 1987 and Strathman et al. 2002) and they consist of thirty stops with scheduled trip time being constant between all adjacent stops. Three different standard deviations (σ) of total trip times are considered, namely 2 minutes, 4 minutes and 6 minutes. The passenger travel pattern that is used is equal to the one that is used in the trip time determination analysis in Section 6.3.3.2, shown by Figure 6.3. Service frequency is 6 vehicles an hour. Stop number 8 is chosen as the holding point. At this point, the number of through passengers is low (18%) and the number of downstream boardings is high (82%).

To assess the effects of applying different holding strategies in short headway services, tram line 9 in The Hague, operated by HTM, is analyzed (see Appendix B for line characteristics). Figure 6.13 shows the passenger travel pattern on line 9 in one direction. Both the percentage of boardings per stop and the percentage of through passengers are shown. They are shown as a percentage of total boardings on the complete line.

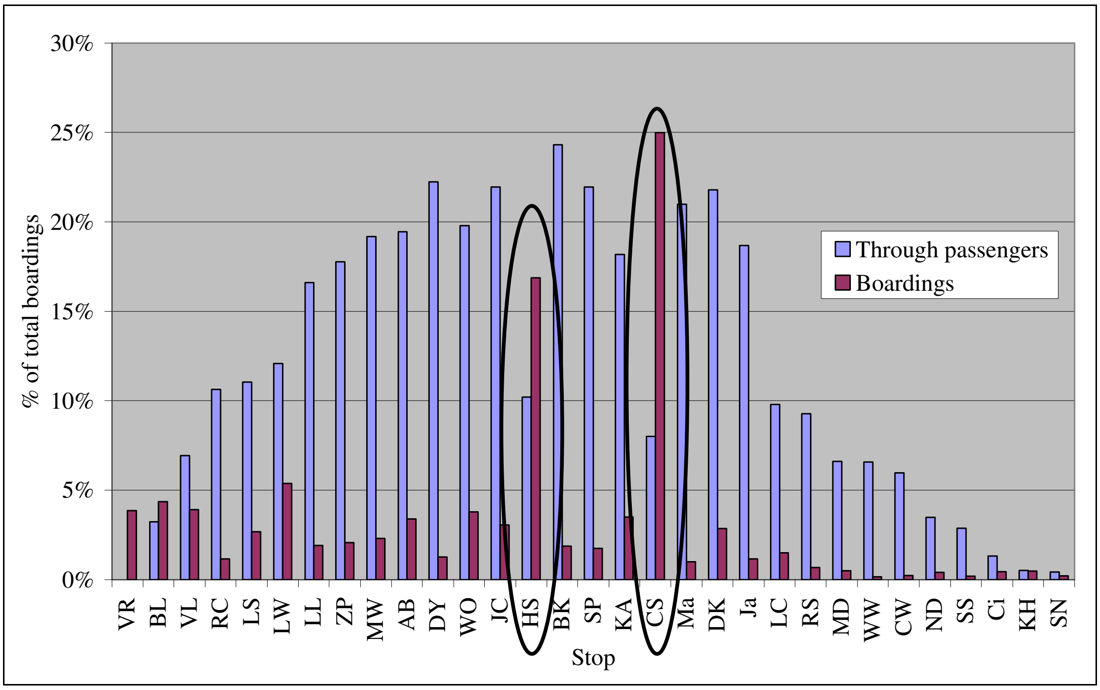


Figure 6.13: Percentage boardings and through passengers per stop (of total line boardings) on line 9

Figure 6.13 clearly illustrates that stops HS and CS are dominant. They are both major stations offering many connections to other local, regional and intercity rail services. The number of through passengers is low at these stops, which makes them interesting stops for holding. In our research, stop HS is chosen as the holding point. At this point the through passengers ratio is 10%. The number of passengers boarding downstream is 60% of total boardings and 50% of total boardings are within 5 stops, maximally benefiting from holding.

For both the actual case and the hypothetical lines, both headway-based holding and schedule-based holding strategies are analyzed with the results given below. In this research γ is set to 0.75 and the values of θ, the weights of actual time and RBT, are (according to Furth and Muller 2006):

- $\theta_{waiting}$ = 1.5
- $\theta_{in\text{-}vehicle}$ = 1.5
- $\theta_{waiting,RBT}$ = 0.75
- $\theta_{in\text{-}vehicle,RBT}$ = 0.75

6.3.6 Results of holding in long headway services, all stops as holding points

In Section 6.3 we showed the effects of the determination of scheduled trip times. The main conclusion was that early vehicle departures affect travel time very much. In the scenario presented here, we make an analysis of whether vehicles are not allowed to depart ahead of schedule because of the introduction of holding points. As mentioned earlier, the effects of driving ahead of schedule are considerable, i.e. an extension of passenger waiting time by a complete headway. Due to the fact that vehicles are not allowed to depart early at any stop, through passengers may have to wait at the stop (in the vehicle). This leads to additional travel time for through passengers, thereby increasing the average additional travel time per passenger.

We present below a case study in long-headway services about a strict holding regime at every stop, thus all vehicles are obliged to depart at scheduled instants (as for instance in The Hague at RandstadRail (Van Oort and Van Nes 2009a)). Figure 6.14 shows the theoretical results for such a control regime, namely the calculated average additional travel time per passenger. The characteristics of the hypothetical lines are presented in Section 6.3.3. The shown additional travel time is the average per passenger of total waiting time at the stop and in the vehicle. As stated in Section 6.1, no RBT is calculated. If these values are compared to the results of the trip time determination (Figure 6.4), a large decrease is shown, especially at high percentile values. For instance, if the standard deviation is 10% of the average trip time, holding reduces the average additional travel per passenger by about 5 minutes (in case of an 85-percentile value applied)). The optimum value is now about 40-60%, dependent on the standard deviation of the trip time.

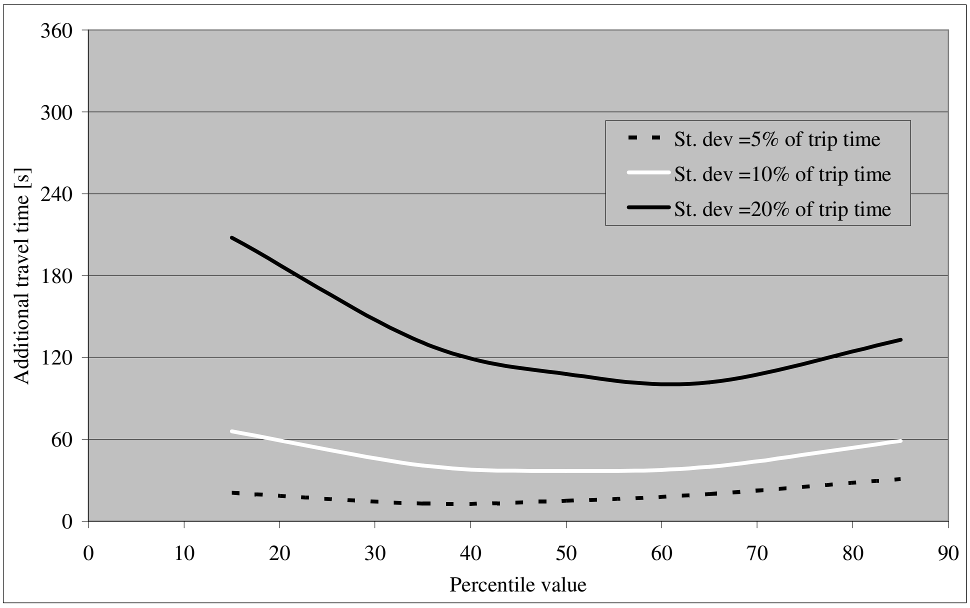


Figure 6.14: Average additional travel time per passenger in the case of holding at all stops (hypothetical line, trip time= 30 min and standard deviation = 5, 10 and 20%)

Figure 6.15 illustrates the impacts of holding at every stop for actual lines in The Hague. The average additional travel time per passenger is presented as a function of the percentile value applied for the scheduled trip time. The standard deviation of the trip time of these lines is about 5-10% of the average trip time. Other characteristics of the lines are given in Appendix B.

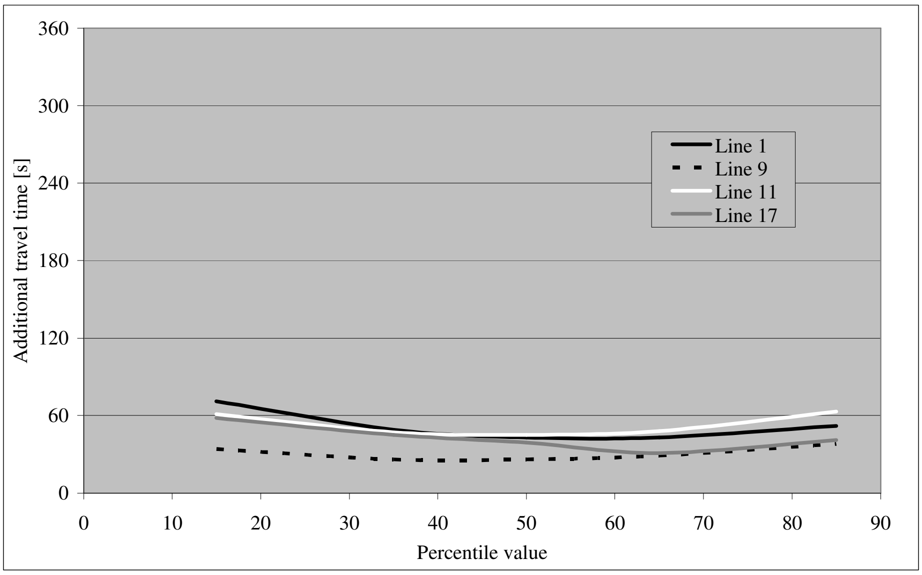


Figure 6.15: Average additional travel time per passenger in the case of holding at all stops (actual lines in The Hague)

Similar to the theoretical results, the introduction of a holding strategy reduced the average additional waiting time per passenger compared to the no-holding case (especially in the case of applying large percentile values, which shows a reduction of over 4 minutes of additional travel time on line 11 for instance), as shown by Figure 6.6. The optimum is as well around 50-65%. The differences between the results of different percentile values are small, only about 0.5 min.

Figure 6.16 shows the impacts of holding at all stops on terminal departure punctuality for the actual line 11 in The Hague. Compared to the non holding situation (Figure 6.7 in Section 6.2.4) the results differ especially when layover times are planned short. In that case, holding has a negative impact on the probability to depart on time in the other direction. With equal layover time, the probability of departing on time is lower. The time spent on holding can not being used to run back to schedule if delays occurs after the holding point and thus leads to a lower probability of departing on time again. When layover is large, the difference between the two situations is nil.

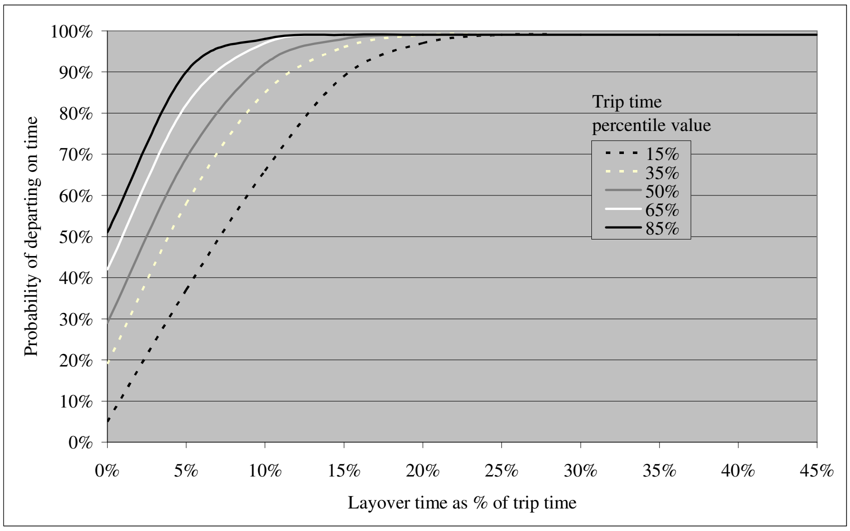


Figure 6.16: Probability of departing on time from the terminal as a function of the chosen percentile value and layover time (line 11 in The Hague)

A redistribution of vehicle trip time and layover time (with constant cycle time) will keep the probability of departing on time fixed.

6.3.7 Results of holding in long headway services, few holding points

In the following study we examined the calculated effects of introducing holding points in long-headway services on a few stops on the line only. In this case, the additional travel time consists of two parts, namely the waiting time at the stop and time spent in the vehicle. As stated in Section 6.3.5, no RBT is calculated. Figure 6.17 shows that when using higher percentile values, the additional waiting time shifts from passengers at the stop to passengers in the vehicle. This subsection shows the effects of the number and location of holding points and the percentile value, which is chosen to set the scheduled departure time at the holding point.

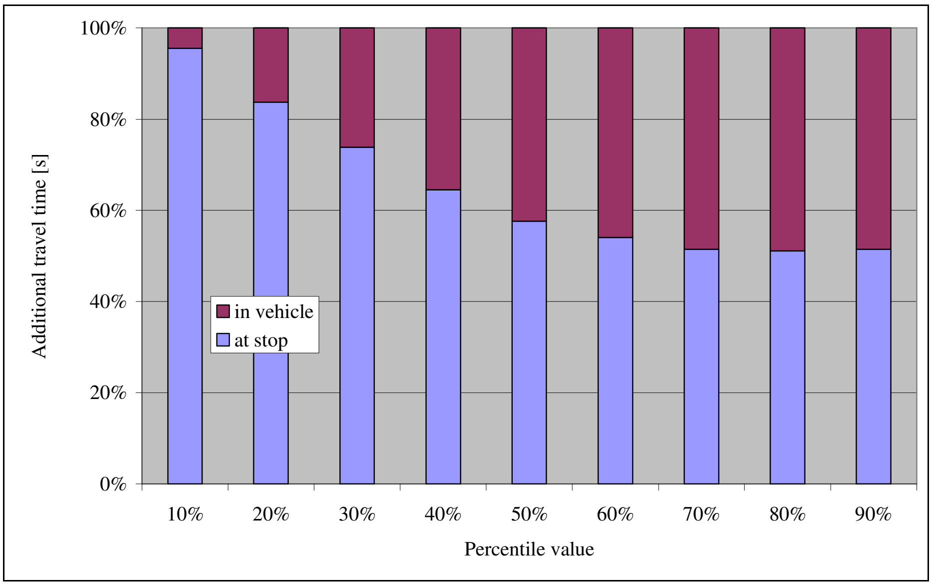


Figure 6.17: Average additional travel time per passenger on tram line 1 with four holding points divided into two parts being in the vehicle and at the stop as a function of percentile value

Figure 6.18 shows the expected effects of the number of holding points on a hypothetical line with a standard deviation of 4 minutes. It appears that introducing more than two points does not significantly reduce additional travel time. However, when more holding points are used, the reduction of additional travel time will be distributed among more passengers. The optimal percentile value with regard to passenger travel time lies between 30 and 50%. Figure 6.19 shows the effects of the chosen percentile value with which the scheduled trip time to the holding point is designed for different values for the standard deviation (when two holding points are applied). Besides the number of holding points, this optimal percentile value depends on the standard deviation of the trip time (from 30% when the standard deviation is 3 min. to 55% when the standard deviation is 10 min.). The higher this deviation is, the higher the optimal value of the percentile value for scheduled trip time is.

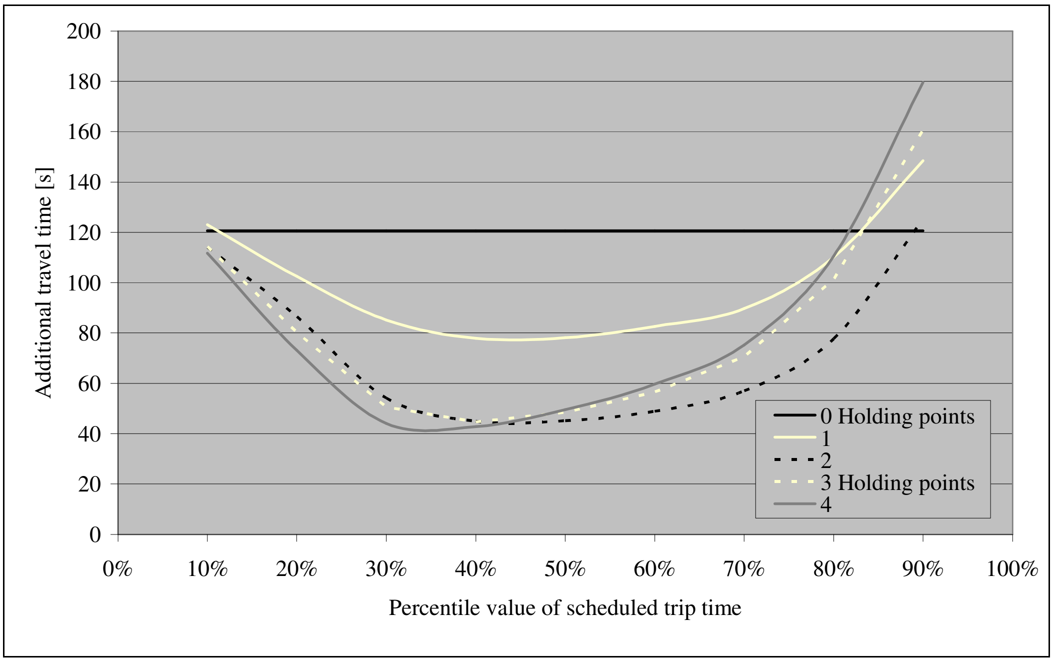


Figure 6.18: Average additional travel time per passenger hypothetical line (st. dev.=4 min) as a function of percentile value and number of holding points

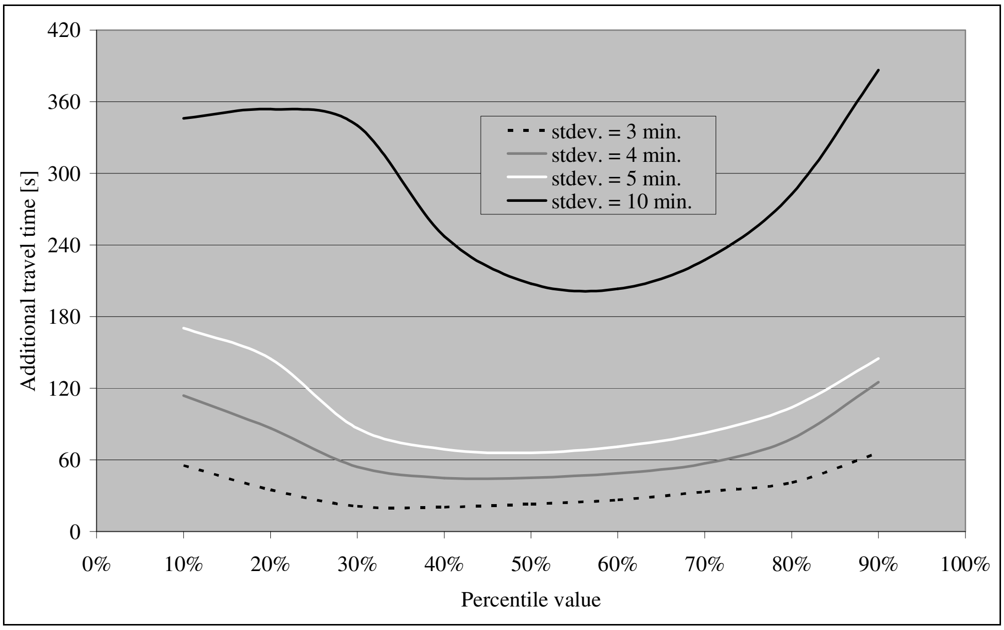


Figure 6.19: Average additional travel time per passenger hypothetical line as a function of percentile value and standard deviation of trip time (2 holding points)

In addition to our analysis of hypothetical lines, we also investigated actual lines in The Hague concerning the expected effect of holding on passenger travel times. These lines represent different values of characteristics of for instance line length and trip time variability. See Appendix B for characteristics of the analyzed lines. Figure 6.20 shows the average additional travel time per passenger of tram line 2 in the direction of Leidschendam. In the period analyzed, the trip time was designed loosely, creating many vehicles operating too early. The relative standard deviation was 6.3%. The figure shows that a medium-high percentile value minimizes the average additional travel time per passenger (50% when 4 holding points are applied and 80% in the case of only one). A reduction of 60% average waiting time is possible. Another conclusion of this figure is that the application of only one holding point already causes a large positive impact. Adding more holding points still decreases the additional waiting time but not with a similar effect. Although the average effect of additional holding points on average additional travel time is limited, the main advantage is that both the negative consequences and the positive ones are more spread along all passengers (Van Oort et al. 2009).

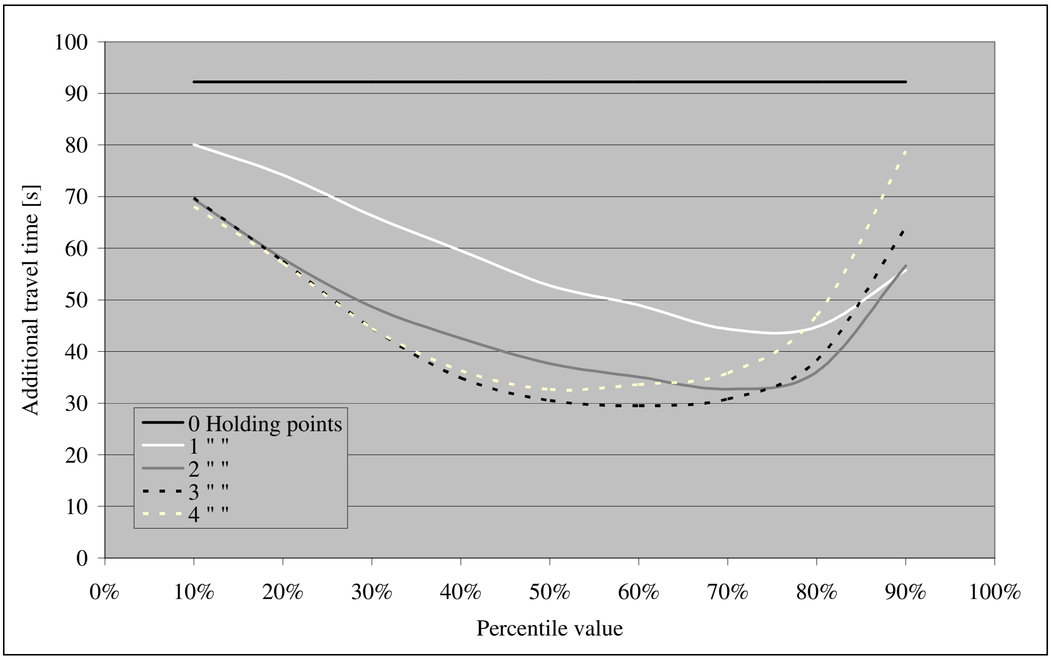


Figure 6.20: Average additional travel time per passenger on line 2 as a function of percentile value and number of holding points

Figure 6.21 shows the calculated additional travel time by applying two holding points on three tram lines and one bus line. Tram lines 2 and 15 had excessive scheduled trip time and a small distribution of actual trip times. The optimal percentile value is high (60-80-percentile). For tram line 1 the scheduled trip time was short and the realized trip times had a relatively low standard deviation. The optimal percentile value concerning passenger travel time (both in the vehicle and at the stop) is about 20%. Similar to tram line 1, on bus line 18 the scheduled trip time was tight, but realized trip times are heavily distributed. The optimal percentile value is about 40%. These numbers show a larger bandwidth of optimal values than our theoretical research, due to more differences between lines. The main reasons are the availability of proper locations for holding points (concerning the ratio of through passengers and passengers downstream) and an expected impact of the type of schedule applied (tight or loose) that may have affected driving behaviour on these specific lines.

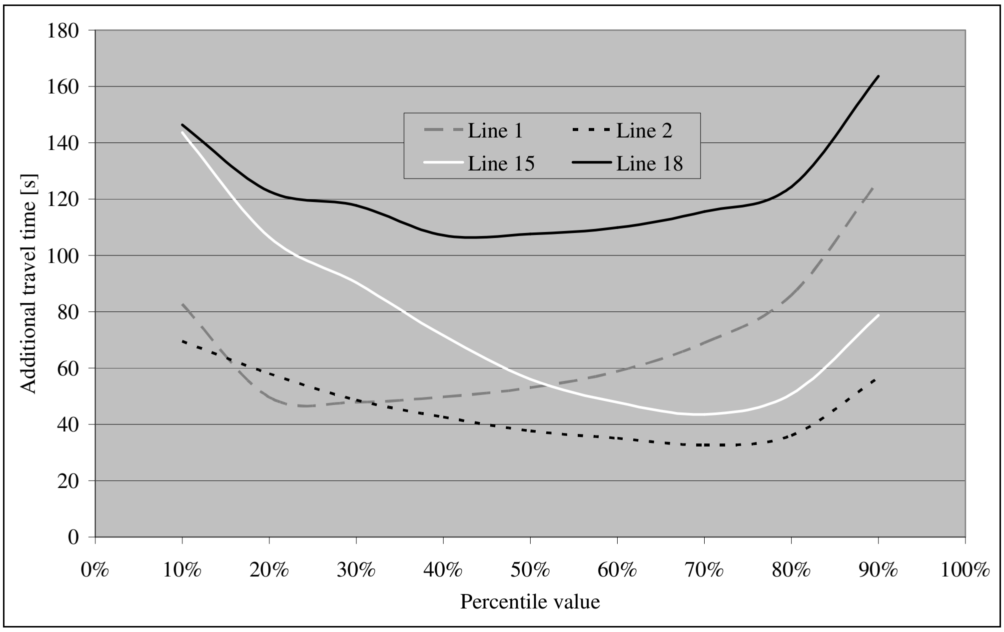


Figure 6.21: Average additional travel time per passenger as a function of percentile value (2 holding points)

As noted earlier, it is important to choose a good location for a holding point. In the analysis presented above, the holding points are chosen with regard to a good ratio of through passengers and passengers boarding downstream, if possible, thereby optimizing the effect of holding.

In order to gain insights into the effects of different holding point locations, Figure 6.22 shows the average additional travel time per passenger by scheduling a holding point at the beginning, middle or end of tram line 1. Figure 6.23 shows the number of through going passengers at this line in one direction as a percentage of total boardings. The chosen holding points are indicated.

In general, a holding point at the beginning of a line is desirable (there will still be many boardings ahead), but not yet necessary (the line is not yet greatly deviated). A holding point at the end of a line is necessary because of the higher standard deviation, although only few passengers will benefit. The best location for a holding point thus depends on the distribution of passengers on a line. The case of line 1 shows that a holding point at the beginning of that line (at ¼ of the length) is the optimal location.

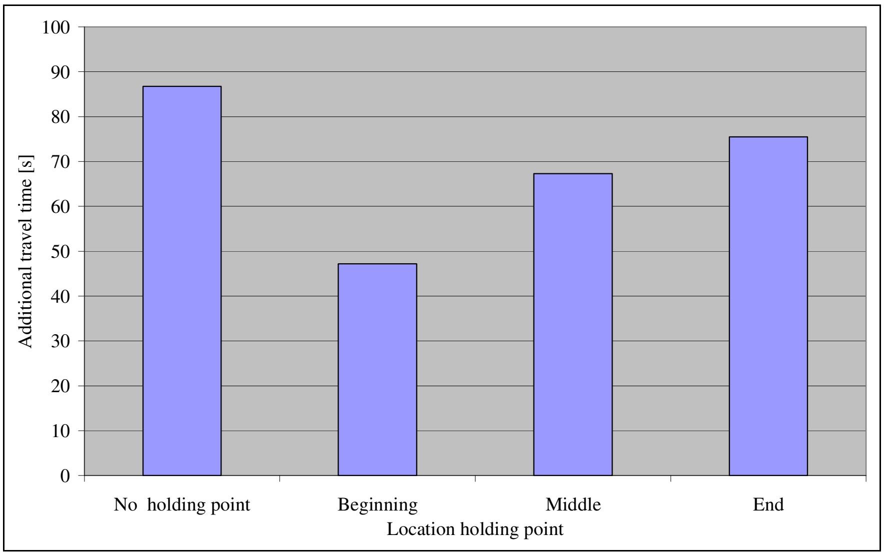


Figure 6.22: Average additional travel time per passenger by using one holding point at the beginning, middle and end of tram line 1

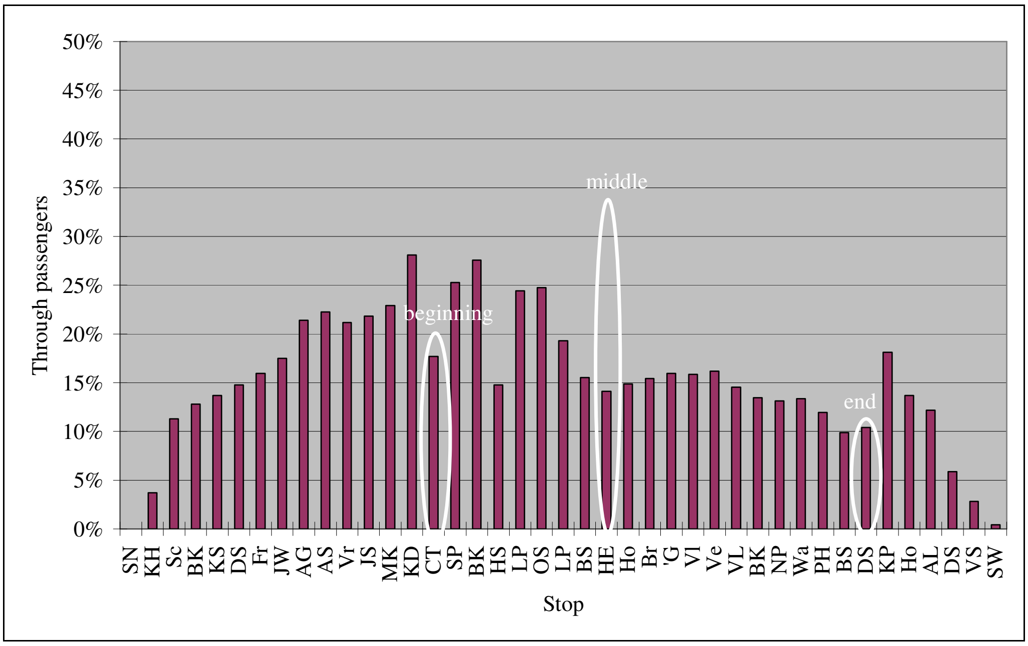


Figure 6.23: Percentage through passengers (of total line boardings) at line 1

6.3.8 Results of holding in short headway services

To analyze the importance of the key variables and their effects on service reliability and passenger waiting time in short-headway services, the developed framework is applied with actual data for both hypothetical lines as well as a real line. In the average additional travel time per passenger, the RBT is also included (calculated as shown by Section 2.5).

6.3.8.1 Headway-based holding results

For the three hypothetical lines and tram line 9 introduced in Section 6.3.5, Figure 6.24 shows the results of headway-based holding compared to the reference case without holding (i.e. maximum holding time is zero). Analysis is conducted for both one and two holding points. To put the results in a relative perspective, the average additional travel time per passenger is shown as a percentage of the waiting time in the case where perfect service is provided (i.e. average waiting time is half the scheduled headway).

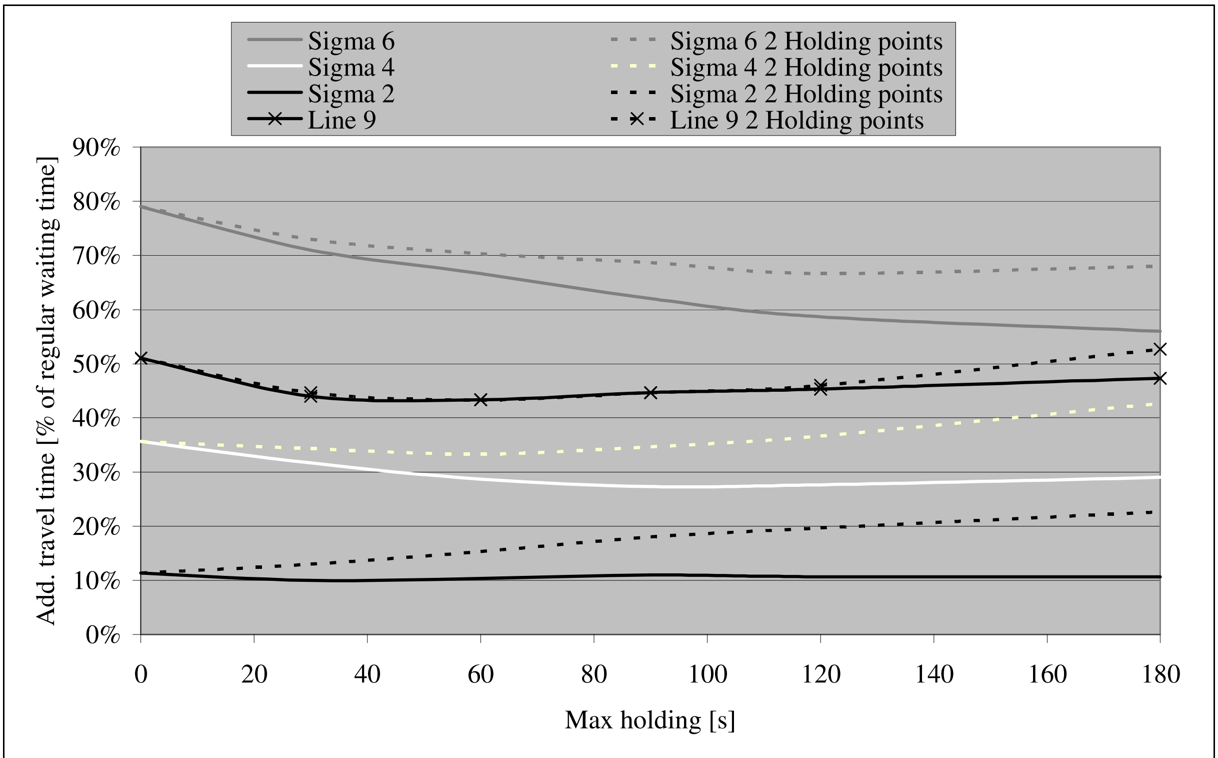


Figure 6.24: Effects of headway-based holding on average additional travel time per passenger (both actual and hypothetical lines)

Figure 6.24 shows that headway-based holding has a positive effect on the average additional travel time per passenger and its effect increases with sigma (the reference case is indicated as max. holding = 0s.). The optimal maximum holding time decreases with a decrease in sigma. The optimal value for the maximum holding time is about180 s. for σ=6, 100 s. for σ = 4, 40 s. for σ=2 and about 60 s. for line 9. The effects of introducing a maximum holding time of 60 s. are also shown in the figure. Actual holding times (σ = 4, 1 holding point) are shown in Figure 6.25 for both unlimited holding as well as a maximum of 60 s. Unlimited holding involves holding about 10% of the vehicles longer than 2 minutes.

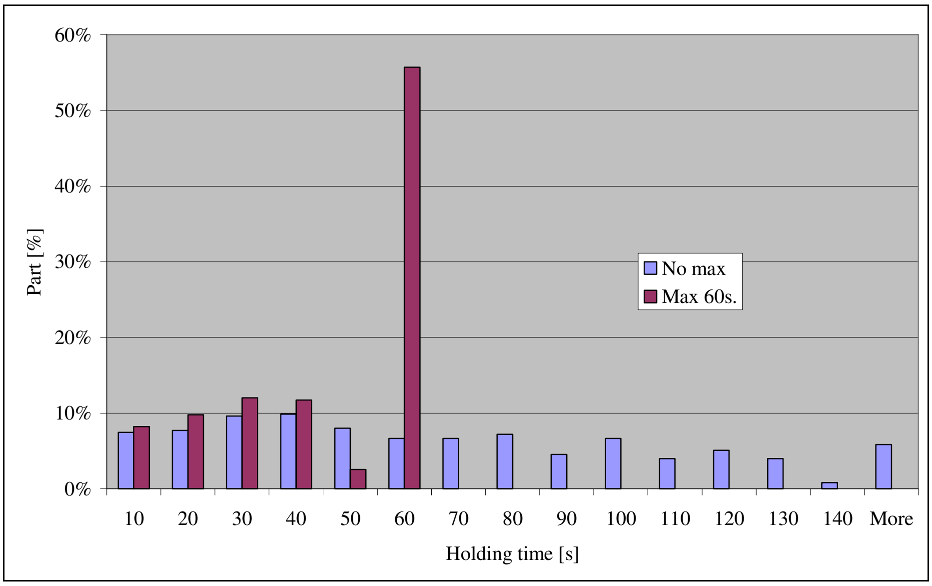
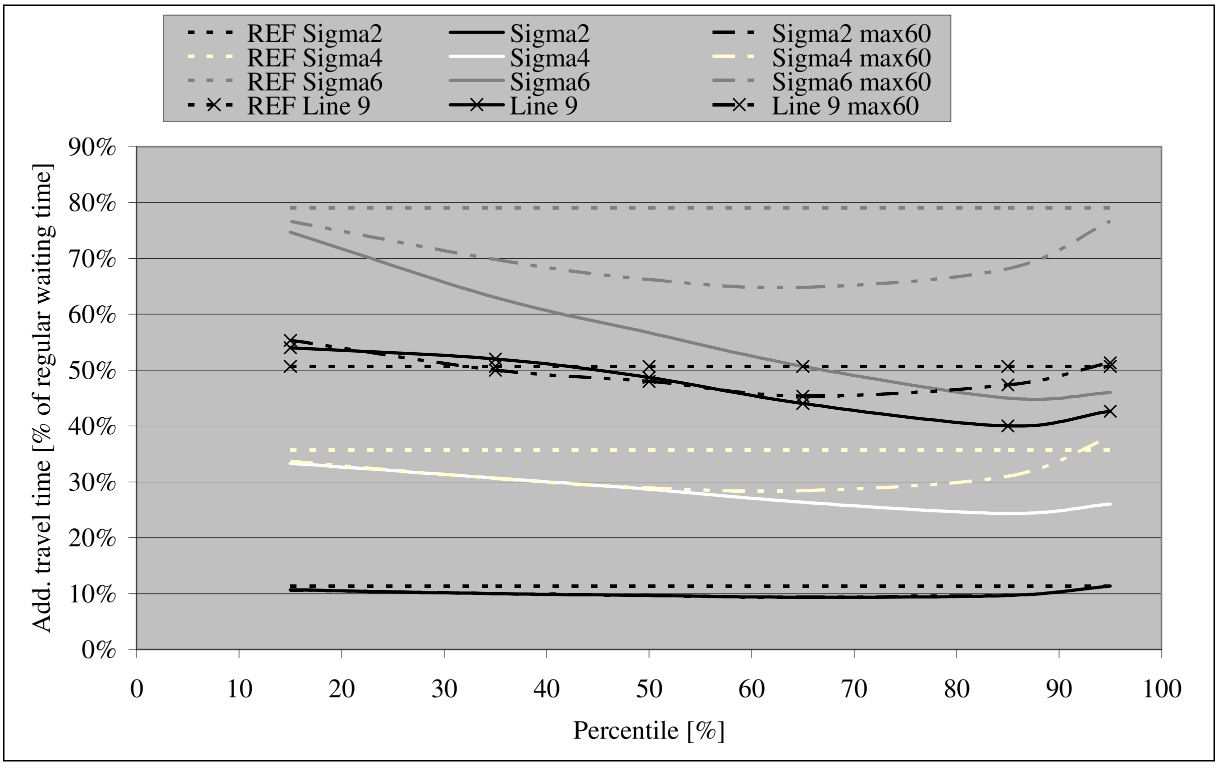


Figure 6.25: Actual holding times, headway-based holding (σ=4min)

As Figure 6.24 shows, an analysis of adding a second holding point was also conducted. For line 9, the other main station on the line, CS (stop 18), is used, while for the hypothetical lines, stop 23 is chosen (see Figures 6.18 and 6.19). Both stops have a relatively small number of through passengers (8% and 18%). The results in Figure 6.24 show that in the hypothetical case the effects of adding a second holding point is negative. This is because there is no good second holding point on this line given the passengers travel patterns. No other point exists with both low numbers of through passengers and high numbers of downstream boardings. On line 9, however, such a point does exist, although the results in Figure 6.24 show no significant benefit over a single holding point in terms of the average additional travel time per passenger. However, more holding points spread the positive effects of reduced average additional travel time per passenger over more passengers. In addition, the negative effects for through passengers are divided over two stops and thus more passengers as well.

6.3.8.2 Schedule-based holding results

Figure 6.26 shows the effects of schedule-based holding on the average additional travel time per passenger as a function of the chosen percentile value for scheduled trip time. Only one holding point is investigated, since the analysis of headway-based holding did not show benefits. The average additional waiting time is again shown as a percentage of the average waiting time when service is perfectly on time and headways are equal. Results are shown for both the hypothetical lines and line 9 for different percentile values chosen for scheduling and different maximum holding times (unlimited and 60 seconds).



Ref= no holding applied, max60=maximum time of 60 s. applied

Figure 6.26: Effects of schedule-based holding on average additional travel time per passenger as a function of percentile value

Figure 6.26 shows that holding has a positive effect which increases with trip time variance. It also shows that the optimal percentile value decreases with smaller variance. The optimal value, in the unlimited holding case, is between 70% (σ =2) and 90% (σ = 6). But when a maximum of 60 s. holding time is applied, the optimal value becomes about 65% for all lines. Figure 6.27 shows an example of applied holding times (σ = 4) for both the unlimited holding strategy as well as a maximum holding time of 60 s. In each case the schedule percentiles values are set to their optimal values. Unlimited holding involves holding about 20% of the vehicles longer than 2 minutes.

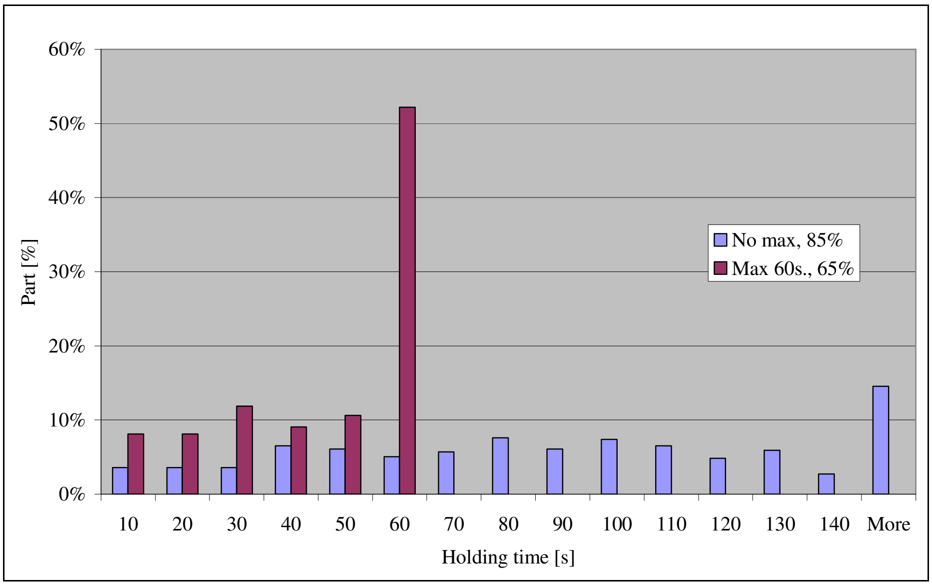
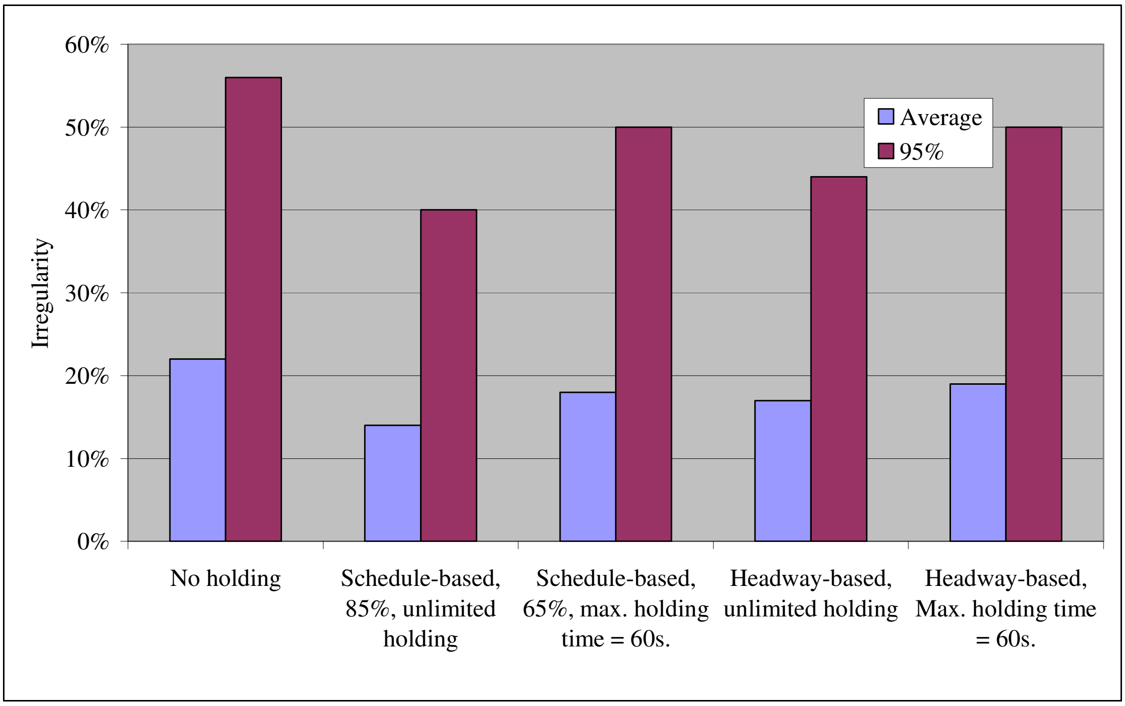


Figure 6.27: Actual holding times, schedule-based holding (σ=4min)

6.3.8.3 Effect of holding on the level of crowding

All research on vehicle holding referred to in this chapter focuses on the passenger travel time effects of holding. However, improving service reliability may also affect the level of crowding. To indicate this effect, Figure 6.28 shows the level of irregularity (actual headway deviation as a percentage of the scheduled headway) for the reference case as well as two schedule-based and two headway-based holding cases (with and without a applied maximum holding time). The cases are based on assumed actual trip times with σ= 4 and for schedule-based holding, two different percentile values are used to determine scheduled trip time, namely 65 and 85. Both the average irregularity and the 95th percentile value are shown. The results differ per case, but in general the introduction of vehicle holding reduced the average irregularity from 20% to 15% and in the case of the 95th percentile from 55% to 40-45%. If uniform arrivals are assumed, this number is similar to the excess level of crowding for 50% of the vehicles (representing over 50% of the passengers). The other 50% of the vehicles will experience a lower level of crowding than the average value. Normally, during the process of determination of the number of vehicles, slack is included with respect to the passenger capacity per vehicle. The results presented here illustrate that either this slack may be decreased (implying that fewer vehicles are needed) or the level of crowding may be decreased.



% indicates percentile value used for scheduled trip time determination

Figure 6.28: Irregularity (average and 95th-percentile value) for different scenarios

6.3.8.4 Headway-based holding vs. schedule-based holding

The previous sections showed results of both headway-based and schedule-based holding in short-headway services. Comparing the effects of these two methods of holding on the average additional travel time per passenger, it is clear that the schedule-based method might be more effective. The reason for this is that in that case, it is possible to set a loose schedule, which might be very reliable. Normally this implies a slow schedule as well, but when a small number of passengers passing the holding point this effect is minimal. However, when maximum holding time of 60 s. is introduced, the effects of headway-based and schedule-based holding are similar.

6.3.9 Conclusions

This section dealt with holding of early vehicles. If vehicle holding is applied (and departing ahead of schedule is not allowed), the average additional travel time per passenger proves to be reduced substantially. Considering short journeys in urban public transport and a negative perception of waiting by passengers, reducing waiting time may lead to additional passengers and higher appreciation. Since the arrival pattern of passengers is of influence on the results, as is the number of holding, we have analyzed three scenarios:

- Long headways, all stops are holding points;
- Long headways, some stops are holding points;
- Short headways, some stops are holding points.

Since both actual and hypothetical lines are investigated, yielding valuable insights that may be applied in other cities as well.

Both a hypothetical and a practical approach of holding in long-headway services, in which all stops are holding points, show that holding vehicles at every stop if they are too early have significant positive effects on additional travel time per passenger. This analysis showed that higher percentile values are beneficial for trip time design if the deviation of the trip time is higher. Four actual tram lines in The Hague showed a difference of 0.5 min between the maximum and minimum additional travel time per passenger. A theoretical analysis with larger deviations showed larger differences. Optimal percentile values are found to be 50-65%.

Looking at long-headway service, with only a few stop as a holding point, a theoretical and a practical study show that designing 2 holding points, using a 30-60 percentile value minimizes travel time (additional travel times are reduced up to 60%) in terms of both the waiting time at the stops and in the vehicle.

The optimal percentile value by using holding points depends on the following variables:

- The value of the relative standard deviation. The higher the standard deviation, the higher the optimal percentile value.
- The number of holding points. The impact of two holding points on the additional travel time is greater than when only one is used, but almost equal to three or four.
- The best location for a holding point depends on the distribution of passengers on a line.

Concerning short-headway services we investigated both schedule-based and headway-based holding strategies. Despite a significant focus on holding in current literature, some important aspects have not been researched previously. The main, new, aspects are the use of maximum holding time, the calculation of reliability buffer time and, in the case of schedule-based holding, the percentile value used to design the schedule. Both a real line in The Hague (tram line 9) and hypothetical lines are analyzed with various levels of running time variability. Both headway-based and schedule-based holding have the largest effect if deviations are high. When holding is headway-based, the optimal value for the maximum holding time is about 180 s. for σ =6 min., 100 s. for σ= 4 min., 40 s. for σ= 2 min and about 60 s. for line 9. Introducing an additional holding point on these lines does not result in further improvements in travel times. When applying schedule-based holding and a maximum of 60 s. holding time is applied, the optimal value of the percentile value becomes about 65% for all lines analyzed. When no maximum holding time is applied, schedule-based holding is more effective, while there is no difference when the maximum holding time is set to 60s. This research also shows the effect of holding on crowding. An average level of irregularity of 20% may decrease to 15%, enabling either smaller capacity slack or less crowding.

The short-headway scenarios showed that the effect of additional holding points does not increase the reduction of the average additional travel time per passenger anymore. Besides, in most short headway services, capacity at stops is lacking to maintain a holding strategy. That is why no research is done considering short headways and all stops as a holding point.

This section demonstrated that vehicle holding is a successful instrument to increase service reliability. Although it is in fact an operational instrument, we showed that, the design of the timetable and type of strategy is of main influence and should be considered when holding will be applied during operations.

6.4 Summary and conclusions

In this chapter, we have analyzed instruments, supporting our hypothesis that promising opportunities exist to improve service reliability not only during operations, but also during the timetable design. In Chapter 4, we selected two potential tactical planning instruments for deeper analysis, which proved to be able to reduce the average additional travel time per passenger. The presented instruments are trip time determination and vehicle holding. The results demonstrate that consideration of service reliability should be incorporated more in the scheduling process as a design criterion. If the objective is to optimize travel time and to decrease unreliability, different choices and parameters may be made and used at the tactical design stage than commonly used in most companies or authorities. Service reliability should be treated as a part of the objective, which may be partly influenced instead of a result of a non-controllable process.

In this chapter, a theoretical approach and a case study of tram lines in The Hague show the effects of design choices of timetabling on service reliability. We applied the control framework of Chapter 2 to calculate the expected passenger travel time effects as a function of scheduled trip time. Our analysis of actual and theoretical data shows that the total passenger travel time is minimized if the 35-percentile value is used to determine the trip time out of historical data. High percentile values cause much additional travel time due to early departures. Passengers who miss their vehicle have to wait a full headway then. To maintain the equal probability of departing on time after the layover at the terminal, it is recommended to redistribute the “saved” trip time (by decreasing the percentile value) to the layover time, maintaining a fixed cycle time.

Besides adjusting trip time design, one common operational strategy to prevent vehicles to operate ahead of schedule is holding. Holding too early vehicles may improve service reliability, resulting in both shorter passenger travel times and less crowding. Although holding is an operational instrument, the main impact is determined in the schedule design phase. In this chapter, we analyzed vehicle holding for both long and short-headway services. One of the main issues regarding holding we investigated is the trade-off between passengers in the vehicles (suffering from holding) and passengers downstream (benefiting from holding).

When dealing with vehicle holding, it is important to distinguish two types of arrival patterns of passengers at their departure stop, namely scheduled arrival and arriving at random. We calculated the expected travel time effects by applying the control framework of Chapter 2 for both situations. If passengers arrive consulting the schedule (mainly when headways are long) our research (both a theoretical approach and a practical case) showed that designing 2 holding points is adequate and the optimal percentile value lies between 30 and 60. This depends on the characteristics of the line. The optimal percentile value mainly depends on the following variables:

- The value of the relative standard deviation. The higher the standard deviation, the higher the optimal percentile value.
- The number of holding points. The impact of two holding points on the additional travel time is greater than when only one is used, but almost equal to three or four.
- The best location for a holding point depends on the distribution of passengers on a line.

Vehicle holding at all stops also reduces the average additional travel time per passenger, but our analysis showed that more than 2 or 3 holding points does not reduce the additional travel time anymore. However, that way, holding time is spread more over the stops and passengers. But again, it depends on the distribution of passengers on the line how effective this is.

We also investigated the impacts of vehicle holding when the arrival pattern of passengers is at random. In that case, we explored two types of holding, that are schedule-based holding and headway-based holding. Despite a significant focus on holding in current literature, some important aspects have not been researched previously. In our research we explicitly considered the maximum holding time, the reliability buffer time and, in the case of schedule-based holding, the percentile value used to design the schedule. Both an actual line in The Hague (tram line 9) and hypothetical lines are analyzed with various levels of trip time variability. Both headway-based and schedule-based holding have the largest effect if deviations are high. When applying schedule-based holding and a maximum of 60 s. holding time is applied, the optimal value of the percentile value becomes about 65% for all lines analyzed. When no maximum holding time is applied, schedule-based holding is more effective, while there is no difference when the maximum holding time is set to 60s. This research also shows the effect of holding on crowding. An average level of irregularity of 20% may decrease to 15%, enabling either smaller vehicle capacity slack or less crowding.

When comparing the results of our analysis of trip time determination and vehicle holding, we should note that the possibilities to apply these instruments differ. Using a low percentile value for scheduled trip time yields positive results in the case of long-headway services. If a break point exists in the passenger pattern on the line, vehicle holding may be applied, in both short and long-headway services. In contrary to trip time determination, vehicle holding affects both passengers in the vehicle and passengers at the stops. We proved that the trade-off between these two groups requires higher percentile values that the ones we found in our trip time research.

In this chapter we demonstrated the interaction between the tactical design and operations. To reduce the average additional travel time per passenger, we showed that lower percentile values to determine the scheduled trip time than traditionally used are beneficial. This prevents many vehicles to depart early. In addition, we have analyzed vehicle holding. We showed that this instrument reduces early vehicle departure as well, but should not be treated only as an operational instrument. We demonstrated the impacts of timetable parameters on the average additional travel time per passenger. The results shown are based on research of both actual and hypothetical lines, supported by our international survey presented in Section 3.2.3. This way, the results may be used for public transport research in other cities as well.

In Chapter 5, the impacts of the strategic design on reliability were shown. Together with the results of the tactical design in this chapter, the next chapter will provide a synthesis of the results. We will present a tentative cost-effectiveness assessment of the instruments and the possibilities of combining planning instruments are discussed.

7. Synthesis of research findings

7.1 Introduction

In Chapters 5 and 6 we have explored strategic and tactical instruments for service planning and we assessed their impacts on service reliability. We demonstrated that these instruments incorporate the dynamic character of operations into the planning process and that they are able to set conditions to achieve a higher level of service reliability. Although we showed one of the main passenger benefits of these instruments, being less average additional travel time per passenger due to service variability, a more comprehensive approach will provide more insights into the wider range of impacts of these instruments. In this chapter, we provide a synthesis of our research findings, including a tentative cost-effectiveness assessment, an analysis of possible combinations of instruments and a reflection on our main research assumptions. This way, we will demonstrate the value of the investigated instruments with regard to practical implementation and further research.

In this chapter we will tentatively assess the cost-effectiveness of the instruments presented in the previous two chapters. We present general cost indications of all instruments introduced in our research, along with the expected (welfare) benefits, based on accepted methods of a cost-benefit analysis (CBA), as described by for instance CPB/NEI (2000), Annema et al. (2007), Rietveld (2000) and Johansen (1991). In the past, service reliability has proved to be hard to quantify in terms of costs and (welfare) benefits (Husdal 2004, OECD/ITF 2009 and Snelder 2010). Our new indicator introduced in Chapter 2, that is the average additional travel time per passenger, however helps to quantify the benefits much better, since we demonstrated how to translate service variability of vehicles into additional travel time for passengers. Literature on the value of travel time reduction and value of travel time uncertainty is available (Wardman 2001, Rietveld et al. 2001, Ministry of Transport and Ministry of Economics 2004), although knowledge of the latter aspect is limited.

In addition to the cost-effectiveness assessment, we have investigated the combined application of the instruments presented in our research. In Chapter 4 we presented several instruments separately while in this chapter we will elaborate on the potential mix of strategic, tactical and operational instruments to achieve the highest possible level of service reliability, considering the economics of the instruments. Specific measures may be derived from all instruments, differing in type, intensity, location, moment of application, etc. The optimal set of measures depends on several of such variables. Every city, every system will have its own specific set of optimal measures. This chapter will include a methodology that helps planners in practice to construct this set.

In the introduction of this thesis, the scope of our research was set. In our control framework presented in Chapter 2, we assumed a number of conditions and constraints for our subject. This chapter will reflect on the scope and the assumptions and on their expected impacts on the resulted findings. In our research, we only considered recurrent delays being the “normal” daily delays in public transport, when no blocking of the infrastructure occurs. The infrastructure is assumed to be fully available. In contrast, Tahmasseby (2009) presents extensive research on non-recurrent delays in urban public transport. This chapter demonstrates that some instruments aiming at reducing or preventing recurrent delays are also beneficial in dealing with both non-recurrent delays, thereby increasing the benefits of such instruments.

The first section (7.2) deals with the cost-effectiveness assessment, while Section 7.3 presents synergy effects of combining instruments. In Section 7.4, our instruments are compared to instruments reducing the impacts of non-recurrent delays. Section 7.5 reflects on the main assumptions and constraints of our research, providing insights into the sensitivity of the presented results. The last part of the chapter presents a summary and conclusions (Section 7.6).

7.2 Cost-effectiveness assessment of design instruments

In Chapters 5 and 6, we have determined impacts of strategic and tactical design instruments on the level of service reliability. In these chapters, we presented the reduction of additional passenger travel time from departure to arrival stop due to less service variability while equally the parallel reduction of travel time uncertainty was indicated in some cases by the reliability buffer time (RBT) introduced by Furth and Muller (2006). The main contribution of our research is showing the impacts of improving service reliability on passengers, by calculating the reduction of the average additional travel time per passenger. Both passengers and operators/public transport authorities benefit by these improvements due to welfare gains and additional revenues respectively. However, we think it is important to assess the costs of the instruments as well, next to the welfare gains. This way, we may illustrate the cost-effectiveness of all presented instruments. The following assessment has been based on a regular cost-benefit analysis (CBA, see for instance Johansen 1991, CPB/NEI 2000, Rietveld 2000 , Annema et al. 2007 and Ministry of Transport 2008b). In this assessment we compare the effects of the application of our instruments to the situation without these instruments.

To assess the related costs and benefits, all main stakeholders involved in public transportation need to be considered. For each instrument, we will identify and assess the main components of the costs and benefits for each main actor. Finally, this section concludes with an indicative cost-effectiveness assessment of the individual instruments.

7.2.1 Stakeholders of public transport planning

Before presenting the assessment of costs and benefits of involved actors per instrument, it is important to identify the main actors involved and their (financial) role. In public transport, costs and benefits are divided over several actors, each having their own perspective. The main actors are:

- Passengers;
- Operators;
- Public transport authorities;
- Infrastructure providers.

We do not consider all parties involved, such as the legislator and drivers and unions, but focus on the main ones mentioned above. Society in general is an actor as well and is relevant if the total effects of mobility (of all modes) are considered. Accessibility, safety and land use are examples of societal issues with regard to mobility. Sections 4.3.2 and 4.4.2 gave a detailed description of the stakeholders at the planning and operational levels of public transport. Due to the different actors and roles, costs and benefits of instruments may affect different parties in different ways. In dealing with the introduction of instruments this requires attention. For instance, extra revenues from growing ridership may result in higher income for operators and/or authorities, while the extra costs may affect the infrastructure providers as well. The distribution of costs and revenues depends on the contracts between authorities and operators. The passengers are the users of the system and they pay for the service, although in most cities in the world, this revenue is not enough to cover the total costs of the system. In that case, public transport authorities provide subsidies to the operators to cover some of the costs. In the end, they are responsible for total mobility and accessibility of the area. The public transport authority also represents society and has an interest in safe and sustainable transport, besides financial issues. The role of the operator is to provide the service as agreed on with the public transport authority. Several possibilities exist concerning the ownership of vehicles and infrastructure in relation with the public transport authority. The last main actor is the infrastructure provider. In some cases, the operators or public transport authorities have this role. In the Netherlands, the local municipalities are often responsible for the infrastructure and the maintenance. In the analysis below, we will give a reflection on the cost-effectiveness of service control instruments. Further research on local organization and agreements is recommended when considering the proposed instruments, since costs and revenues may be allocated differently.

7.2.2 Costs of public transport supply

As we argued above, we compare in our cost-effectiveness analysis the effects of our instruments with the situation when no instruments are applied. The potential costs components of public transport supply, that are relevant in that case are illustrated per actor in Table 7.1 (based on Rietveld 2002) and will be described below. For simplicity sake, we have taken the change in travel time costs of passengers as benefits, see Table 7.2.

Table 7.1: Potential cost components of public transport supply

Actor	Cost component
Operator	Additional operating costs[1,3]
Public transport authority	Additional operating costs[1,3]
Infrastructure provider	Infrastructure investments Infrastructure maintenance
Society	Decreased traffic safety[2,3] Additional noise emissions[2,3] Additional carbon dioxide and nitrous oxides emissions[2,3]

[1] exact distribution between operator and public transport authority depends on local financial agreements
[2] in the case of additional public transport vehicles are required
[3] depending on the investigated alternative, "additional" or "decreased" may also be negative

The cost component of public transport may be divided into two main categories (Ministry of Transport 2005). The costs of infrastructure (both construction and maintenance) are the first part. The second part consists of operating costs. This last part may be divided into three subcategories:

- Capacity costs, determined by the number and type of vehicles needed for operations;
- Hourly costs, indicating that every hour of operations will cost a certain amount of money. The main element of this type are the costs of the crew;
- Kilometre costs, which depend on the distance driven. An example of these costs are the costs of energy.

Some costs belong to more than one category. Maintenance costs for example are partly based on the distance driven and partly on the hours of operations. The hourly costs consist of productive and unproductive elements. The productive part is the time in the schedule which is open for passengers. Layover time, deadheading and interlining is considered unproductive.

However, increasing the unproductive hours may increase the level of quality for passengers. We demonstrated in Chapter 6 that scheduling less vehicle trip time (i.e. using lower percentile values) and more layover time results in reduced passenger travel time. The most complex part of the operating costs are the capacity costs. Due to the discrete character (the number of vehicles is an integer) there is no linear relation in determining these costs. The number of vehicles is determined as shown by Equation 4.1 (presented in Chapter 4). If total cycle time is 1 minute more than a multiple value of the headway, a minute less trip or layover time may decrease the needed number of vehicles by one. On the other hand, an increase in trip or layover time of an amount of time less than the headway minus 1 does not increase the number of vehicles needed. In the case of total cycle time being exactly a multiple of the headway, this mechanism works the other way around. This integer character limits proper comparisons and analyses of costs on a general level. In our research, it is only indicated that additional vehicles may be needed.

In our cost-effectiveness analysis, we will focus on the cost components mentioned above. Table 7.1 also shows societal cost components as a result of additional vehicles that might be required for some of our instruments. These effects, such as decreased traffic safety, noise and emissions are limited and since the additional number of vehicles needed is assumed to be limited as well, these effects are not considered.

7.2.3 Benefits in public transport

Concerning the possible benefits of public transport, Table 7.2 summarizes the main potential benefit components (based on Rietveld 2002), related to our instruments, differentiated per actor. We will elaborate on these components below in more detail. Note that we mainly focus on service reliability improvements and reduction of additional travel time. This additional travel time is the result of service variability (and determines the total travel time when added to the scheduled travel time) and will be reduced when service variability is reduced. Pure travel time reductions may be incorporated in the schedule and do not affect additional travel time. However, these reductions are beneficial for passengers (travel time) and operators (operating costs).

Table 7.2: Potential benefit components of public transport

Actor	Benefit component
Passenger	Reduced scheduled travel time Service reliability improvement - Reduction of additional travel time due to service variability - Reduction of additional travel time variability - Reduction of crowding and increased probability of finding a seat
Operator	Additional ticket revenues[1]
Public transport authority	Additional ticket revenues[1]
Society	Improved accessibility Improved traffic safety[2] Decrease of noise emissions[2] Decrease of carbon dioxide and nitrous oxides emissions[2] Increase of spatial quality[2]

[1] *exact distribution between operator and public transport authority depends on local financial agreements*
[2] *due to reduced car mobility*

As mentioned before, the main benefits of enhanced service reliability we investigated are the reduction of additional travel time per passenger and its variability. Instruments do not necessarily improve both the average additional travel time and variability of additional travel time. In some cases total cycle time and scheduled time will be affected by instruments as well (affecting operating costs and passenger travel time respectively). The main component of travel time that is reduced by increased service reliability appeared to be waiting time. Chapter 3 demonstrated that in urban areas waiting constitutes a substantial part of the total travel time, due to short journeys. Section 2.3 elaborated on the perception of waiting showing the relative weights for waiting that implies it is perceived 1.5 times longer than in-vehicle time. When passenger travel times in public transport are reduced, two main effects occur. The first one is that existing passengers will benefit from the reduced (additional) travel time and that thus their consumer surplus will increase. Figure 7.1 shows the relation between price (or travel time) and quantity (the usage of public transport expressed by number of passenger, trips or travelled kilometres) to illustrate this (Rietveld 2002). A reduced price due to reduced (additional) travel time of P^2 (with an original price of P^1) will result into an increase of the consumer surplus for the existing passengers of area A. The second effect is that the competition position compared to other modes will be improved due to reduced (additional) travel time. This will lead to a higher public transport usage (Bovy and Van Goeverden 1994) of $Q^2 - Q^1$ and thus higher revenues for the operator and/or public transport authority. We will indicate the potential additional revenues by the expected growth of ridership. The travel time benefits of the new passengers are illustrated by area B in Figure 7.1. Empirical research is available enabling the calculation of the travel time benefits of passengers and the new ridership due to reduced travel time (Balcombe et al. 2004).

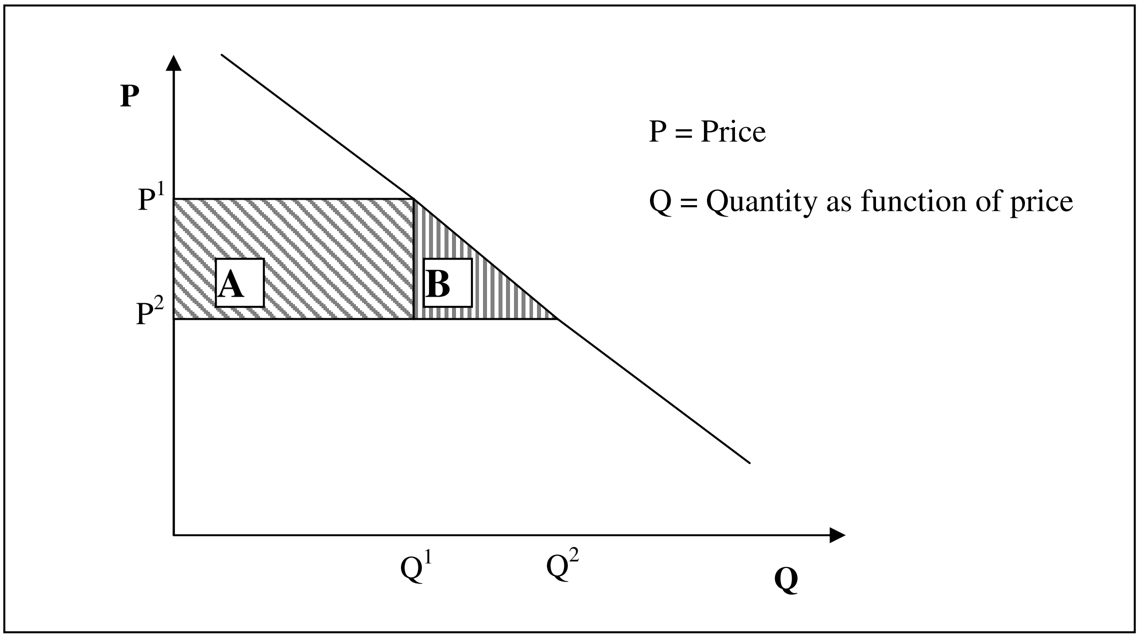


Figure 7.1: Relationship of quantity (number of passengers) and price (travel time) and consumer surplus

Concerning the effects of reduced variability on consumer surplus exactly the same reasoning holds. In our cost-effectiveness assessment, the increased level of service reliability is translated into shorter perceived average additional passenger travel times for both existing and new passengers. Secondly, the variability of the average additional travel time per passenger will be reduced due to service reliability instruments, leading to additional welfare gains for both existing and new passengers. However, in the following we will focus on the average additional travel time and will only indicate the effects of less variability of this additional time. Rand and AVV (2005) showed that passengers value one minute standard deviation of travel time 40% higher than a minute of regular travel time. In our research we used the RBT (Furth and Muller 2006) to indicate this effect. However, more research is recommended on this topic, since not much attention has been paid to this issue so far, especially to the relation between vehicle trip time variability and passenger travel time variability. In road traffic, Snelder and Tavasszy (2010) discussed this issue as well and they state that the method to deal with this in road traffic projects in the Netherlands (i.e. travel time variability gains are assumed to be 25% of the travel time gains (Besseling et al. 2004) is an underestimation and is very project specific.

In Section 2.4, we showed that improved service reliability also may lead to less crowding and an increased probability of finding a seat. Especially in short-headway services this effect is relevant, but since we only tentatively assess the cost-effectiveness of the instruments we do not incorporate this issue. We recommend more research on this topic.

As Table 7.2 shows, societal benefits arise as well due to our instruments. The quality of public transport increases, a modal shift may be achieved and car mobility may be reduced. This will lead to increased traffic safety and accessibility, less emissions and noise and more spatial quality. However, since we expect these effects to be limited due to our instruments we only focus on the effects discusses above.

Since we calculated the reduction of the average additional travel time per passenger per instrument in Chapters 5 and 6, we are able to estimate the benefits using existing techniques to assess travel time benefits and increased ridership. The analysis presented is on an aggregated level, in which the total effects for all passengers are estimated. The following relationships and assumptions are used in this assessment:

- We focus on passengers travelling from stop to stop on a single line (including waiting). Transferring is not incorporated explicitly, but is assumed to be the start of a new journey. Access and egress time are assumed not to be affected. The average passenger journey (in a 100% reliable situation) consists of 9 minutes in-vehicle time and 2 minutes of waiting time at the stop. The access and egress time sum up to 5 minutes. These numbers are based on characteristics of the urban public transport in The Hague;
- A decrease in passenger travel time (stop to stop, including waiting) of 1% will lead to a ridership increase of 0.5% (Bureau Goudappel Coffeng 1987, Balcombe et al. 2004) (i.e. a demand elasticity of travel time of -0.5);
- To incorporate passenger perception of travel time components, the weights as shown in Section 2.3 are used (Van Der Waard 1988).

7.2.4 Cost-effectiveness assessment of reliability management instruments

In this section, we confront the benefits of the individual instruments with their costs to assess the added value of each of the instruments. In the assessment we focus on the difference between the situations with and without the instrument applied. The costs consist of the elements presented above; the benefits are expressed as the reduced (additional) travel time due to reduced service variability. We translated these into welfare gains for both new and existing passengers. The expected increase of ridership is presented as well as an indication of additional revenues. To get an impression of these benefits, an estimate has been made of how beneficial the instruments in The Hague area, based on an assessment of how many lines and which time periods (e.g. peak vs. non-peak hours) may be improved. The instruments are analyzed separately and summarized in Table 7.8.

7.2.4.1 Terminal design

In Section 5.2 we introduced service reliability as an objective in infrastructure design, namely the design of terminals. The type of terminal and the number and location of switches proved to be main variables determining the delay that is experienced by vehicles using the terminal. Table 7.3 shows the main costs and benefits of this instrument per actor, which are explained and estimated below.

Table 7.3: Potential costs and benefits of terminal design instrument

Actor	**Costs**	**Benefits**
Passengers		- Reduction average travel time - Reduction additional travel time - Reduction variability additional travel time
Operator/ Public transport authority	- Reduced operating costs (vehicle and hours)	- Increased ridership - Additional revenues
Infrastructure provider	- Additional or different located tracks and/or switches - Infrastructure maintenance	

The number of switches and lengths of tracks mainly determine the infrastructure (maintenance) costs. Besides, the location of switches may influence the costs if constructing conditions differ per potential location. Concerning these costs, we roughly estimate that the additional costs in the case of adding switches and tracks to a terminal are € 50,000 - €100,000 per year (Ministry of Transport 2005). Operating costs are affected by the size of the delays in the terminal, since structural delays caused by suboptimal design may lead to an extension of cycle time. This instrument may thus result in decreased costs of operations and fewer vehicles may be necessary to fulfil the schedule. Saving a rail vehicle (and unproductive hours over the complete day accordingly (i.e. extended layover time)) by decreasing cycle time saves about € 1 million per year (based on Ministry of Transport 2005).

Optimal design of terminals, considering the level of service reliability, leads to shorter passenger travel times than currently is the case. The variability of passenger travel times will also decrease, since punctual departure will reduce the variability of vehicle trip times. Our study in Chapter 5 showed that optimal terminals may prevent up to 1.5 minutes of additional travel time per average passenger. In the city of The Hague, the travel time benefits may be about € 2 million per year, when the number of potential lines and time periods are taken into account. This quality improvement may result in a maximum increase in ridership of 5% per line (and revenues accordingly) considering the general journey characteristics presented in the beginning of this section.

7.2.4.2 Line coordination

The relevant costs and benefits for the line coordination instrument, as described by Section 5.2, are shown by Table 7.4.

Table 7.4: Potential costs and benefits of line coordination instrument

Actor	Costs	Benefits
Passengers		- Reduction additional travel time - Reduction variability additional travel time
Operator/ Public transport authority	- Increased operating costs (vehicle and hours)	- Increased ridership - Additional revenues
Infrastructure provider		

For the line coordination instrument, no additional infrastructure is necessary, so no additional infrastructure costs (construction and maintenance) arise. The operating costs however may increase, because introducing coordination in a schedule may require additional vehicles to be run in order to fulfil the schedule. Normally, the schedule of one line is fixed on one time point and cycle time may be optimized for layover time and trip time. When coordination is applied, schedules of two or more lines will be connected and fixation is forced. This may lead to suboptimal layover time (for the number of vehicles) which may result in more required vehicles than in the case of two separate or uncoordinated lines. We estimate the costs of this additional vehicle (and unproductive hours over the complete day accordingly) to be € 1 million per year for tram operations and € 500,000 for bus operations.

The benefits of coordination are that two coordinated lines on a shared route offer higher frequencies and in addition, many direct connections are enabled. To assess the benefits of coordination, we conducted an analysis, calculating the decrease of total additional passenger travel time due to service reliability. It is shown that the impacts of coordination greatly depend on the schedule adherence characteristic of the coordinated lines. The instrument of coordination is not beneficial in all cases. Only if schedule adherence is high, or schedule deviations of both lines are similar, this instrument reduces (variability of) passenger additional travel. Our analysis in Section 5.3 showed a possible increase of perceived frequency of 5-40%. We estimate the welfare gains due to travel time reduction for existing and new passenger to be € 1.5 million per year in The Hague, considering potential lines and moments of coordination. Ridership and revenues of coordinated lines are expected to increase by 5-15%.

7.2.4.3 Line length

In Section 5.4, we introduced the new design dilemma of line length vs. service reliability. Table 7.5 presents the potential costs and benefits of the line length instrument. These elements will be explained below.

Table 7.5: Potential costs and benefits of line length instrument

Actor	**Costs**	**Benefits**
Passengers		- Increased travel time due to more transfers - Reduction additional travel time - Reduction variability additional travel time
Operator/ Public transport authority	- Increased operating costs (vehicle and hours)	- Increased ridership - Additional revenues
Infrastructure provider	- Additional terminals	

Regarding the infrastructure costs, shorter lines may require additional infrastructure facilities, namely terminals. In the case of bus operations, existing road facilities may be used most of the time. However, crew facilities may be needed. In the case of rail bound operations, turning facilities are more complicated. If the service is operated by one-directional vehicles a turning loop is necessary. In the case of bi-directional vehicles, no loops are required and crossovers may be used to save space. However, capacity may become an issue then, as we have demonstrated in Chapter 5. These facilities need to be constructed and maintained. Sometimes, adequate rail infrastructure is already available and may be used (as for instance shown by Van Eck 2008). The yearly costs of a rail terminal (construction and maintenance) are estimated to be € 150,000 per year (REF).

Considering the operating costs, two short lines are typically more expensive than one long one, since the total amount of layover time probably will be longer. This additional time may require an additional vehicle as well to operate two shorter lines. As presented above, we estimate these costs to be € 500,000 (bus) to € 1 million (tram) per year, including both capacity and operating costs (i.e. longer layover times). On the other hand, costs may be reduced as frequencies on both lines may be adjusted to the demand on both parts separately instead of equal frequencies on the whole line. Van Oort and Drost (2008) present how to deal with this, including possible coordination issues.

Section 5.4 presented the trade-off between the positive and negative impacts for passengers of reducing line lengths. Shorter lines imply more reliable services and less passenger travel time on the one hand and additional transfers on the other hand. Depending on the passenger pattern and the departure punctuality characteristics, shorter lines may result in overall shorter passenger travel times and less unreliability. Section 5.4 demonstrated cases in The Hague where shorter lines lead to overall shorter passenger travel times. The welfare gains for existing and new passengers are roughly estimated to be € 2.5 million per year. Considering the general characteristics of a passenger journey, as presented in Section 7.2.2, the decrease of total travel time of about 10% may result in about 5% more passengers and revenues per line.

7.2.4.4 Trip time determination

The determination of scheduled trip time was one of the two schedule design issues that we dealt with in Chapter 6. Section 6.2 showed an analysis of the design of scheduled trip time in long-headway services and the impacts on additional passenger travel time. Table 7.6 shows the potential costs and benefits of this instrument.

Table 7.6: Potential costs and benefits of trip time determination instrument

Actor	**Costs**	**Benefits**
Passengers		- Reduction additional travel time - Reduction variability additional travel time
Operator/ Public transport authority		- Increased ridership - Additional revenues
Infrastructure provider		

No infrastructure is involved in this design issue, which means no infrastructure costs are involved neither. Cycle time was considered fixed, implying that the operating costs were not affected. Only the ratio between direct and indirect hours is adjusted, when the scheduled trip time is changed. Actual passenger in-vehicle times are not affected, since vehicle trip variability is not changed. This instrument thus mainly yields benefits, being less (variability of) average additional travel time per passenger. After having assessed the number of lines and periods of time for which this instrument is beneficial, we estimated the travel time benefits to be € 5 million per year in The Hague. Ridership growth of 5-15% per line (and additional revenues accordingly) is possible by applying the optimal percentile value, calculated by using reduced passenger travel times of both the cases and theoretical studies in Section 6.2.

7.2.4.5 Vehicle holding

In Section 6.3, we analyzed the instrument of vehicle holding. Table 7.7 presents the potential costs and benefits of this instrument.

Table 7.7: Potential costs and benefits of vehicle holding instrument

Actor	Costs	Benefits
Passengers		- Reduction additional travel time - Reduction variability additional travel time
Operator/ Public transport authority		- Increased ridership - Additional revenues
Infrastructure provider		

Similar to trip time determination, the instrument of vehicle holding does not affect the infrastructure design. However, attention must be paid to the capacity of the holding point. The vehicles held may block vehicles of other lines. Costs of operations are unaffected, as cycle time is considered to be fixed. The benefits of vehicle holding are reduced average additional travel time per passenger (for both existing and new passengers), a higher service reliability and the related growth of ridership and revenues. In the case of The Hague we estimated the welfare gains due to travel time reductions to be € 4 million per year. We performed a study indicating the level of ridership increase that is to be expected when holding is applied (see Section 6.3). Using empirical research, as mentioned in Section 7.2.2, we calculated that the lines investigated in the case study will facilitate 5-10% more passenger journeys due to enhanced service reliability. The analyzed hypothetical lines showed similar results.

7.2.5 Conclusions

Table 7.8 summarizes the indicative conclusions of the tentative cost-effectiveness assessment of the five instruments given above. The costs are divided into infrastructure costs and operating costs. Travel time costs of passengers are considered as benefits, since all our instruments reduce passenger travel time. While infrastructure costs mainly arise at the start of the project, operating costs occur during the complete period of operations. The benefits consist of additional travel time and time variability savings for passengers and additional revenues for the operators and public transport authority. In the table, it is only indicated whether costs occurs (much (--) or less (-) extra costs), savings are possible (much (++) or less (+) savings) or no impacts arise (0). Since local characteristics are very important, a bandwidth is provided. Since all instruments may yield reduced additional travel time (variability) and increased ridership and revenues, the benefits are indicated correspondingly by a + or ++.

In the cases of vehicle holding, coordination and line length, the impacts of the instrument depend on other variables as well and therefore these instruments do not always yield positive results. In that case a “0” is indicated. To get a general view on the economics of the instrument, the result of costs and revenues are generally indicated, taking the bandwidth and probability of both into account.

Table 7.8: Tentative cost-effectiveness assessment

Instrument	Infrastructure costs	Operating costs	Passenger benefits	Operator revenues	Total
Terminal design	0/-/--	+/0	+	+	+/0
Coordination	0	0/-	+/0	+/0	+/0
Line length	0/-/--	+/0/-	+/0	+/0	+/0
Trip time determination	0	0	++	++	++
Vehicle holding	0	0	++/+/0	++/+/0	++/+/0

Table 7.8 shows that both tactical instruments have a clear positive balance whereas the strategic instruments show a more scattered result. Whether these latter instruments are cost beneficial strongly depends on other factors as well. Optimizing terminal design is beneficial for passengers, but may require higher costs compared to traditional design. However, we showed that the costs per year are much less than the benefits. Coordination and shorter lines may be effective, but the effects depend on for instance deviations' and passengers' characteristics.

In Chapter 3, we roughly estimated the costs of unreliability at € 12 million per year in The Hague. In this section we assessed the effectiveness of the planning instruments for The Hague and we estimated a possible reduction of these costs of € 8 million per year when the instruments are applied on the potential lines and during the time in which they may be beneficial. The combination of effects of all instruments applied together has been assessed as well. The costs are expected to be maximum € 3 million per year. This demonstrates the added value of implementing the planning instruments we propose in our research. In addition, it is important to note that the impacts generally are underestimated, since the reduction of the variability of the additional travel time has not yet been estimated explicitly. However, all instruments we introduced will reduce this variability to some extent and since passengers consider this variability 40% more valuable than travel time (Rand and AVV 2005), we made a rough estimate that the actual costs of service unreliability and the potential savings are at least twice as high.

In all cases, detailed research on costs and benefits should be conducted in order to gain more insights into local and financial details. In Chapters 5 and 6 we provided tools and methods we developed for such applied research. Independent of the exact results, it is clear that service reliability should be considered explicitly during public transport planning, as it is quite likely that these instruments not only lead to more reliable transport services but to a better overall performance as well and thus have substantial consequences for the cost-benefit ratio of public transport projects.

7.3 Synergy effects of combined instruments

This section deals with possible combinations of the instruments described in Chapters 5 and 6. We expect synergetic effects of joint implementation of several instruments. In Chapter 4 we already concluded that a combination of operational instruments is powerful in dealing with unreliability. This chapter extends this statement by investigating the power of jointly implementing a set of instruments from all three levels of planning. Different measures may be derived from the presented instruments, varying in for instance the location, the moment and intensity of application. We have developed a methodology that helps designers and planners to choose the best set of measures when aiming at a high level of service reliability.

In Table 7.9, instruments are summarized at the two planning levels. These instruments are described in detail in Chapter 4. The instruments investigated in our research are indicated. In this section we address possible synergetic effects of our instruments, both on the horizontal and the vertical direction. This implies both a combination of instruments at the same level and a combination of instrument from different levels.

Table 7.9: Available instruments, including the scope of our research

Level		**Instruments**			
Strategic	*Infrastructure Network*	Terminal design	Stop design	Exclusive lanes	Traffic light priority
	Service Network	Line coordination	Line length	Line synchronization	Stopping distance
Tactical		Trip time determination	Vehicle holding		

Our investigation does not focus on all possible strategic instruments. For example line synchronization, exclusive lanes, traffic light priority and stopping distance are not analyzed, as much literature is already available on these subjects (see for instance Ceder 2007, Vuchic 2005 and Van Nes 2002). Further research should be performed on the combination of these instruments, since we focus here only on the five instruments we introduced in Chapters 5 and 6. Further research is recommended on capacity in urban rail bound systems as well. In our research, only terminals were analyzed in detail, whereas dealing with service variability and unreliability related to stop design is important as well. Further research is recommended on this topic, since a dilemma of investment costs vs. service reliability arises.

When selecting the best set of instruments for reliability management, some characteristics of the system that will be (re)designed are of importance. First of all, it is important to consider whether a new system is designed or an existing system is adjusted and optimized. In the case of an existing system, the infrastructure is harder to optimize, since infrastructure is already available and is expensive to adapt. In general, the higher the level where the instruments are applied, the better. Strategic instruments are more sustainable and their existence is better guaranteed over years, especially if they are related to infrastructure. Infrastructure is constructed for decades and will not be adjusted easily. Although the infrastructure costs are high, the effort needed over the total life cycle is limited, while revenues will be continuous during this time frame. Considering the cost-effectiveness presented in the previous section, it is recommendable to apply the trip time instrument in all cases. The vehicle holding instrument is interesting too, but it only has a positive impact if a clear break point exists in the passengers' pattern along the line.

If several instruments are used in combination, the combined result on service reliability generally will be more than the result of the single instruments alone. However, due to the application of the first instrument, the input for the second instrument will be less disturbed and similarly, the results will be less. In that case, the combined results of both instruments will be less than the sum of individual results. The amount of overlap in resolving potential greatly depends on local characteristics and detailed research is always necessary.

Above, a first indication has been provided how to create the optimal set of instruments leading to an optimal level of service reliability. To help with constructing this set, a general methodology is shown by Figure 7.2.

It is important to note that this methodology mainly focuses on service reliability and should be used as one of many parts in the regular design process. This process has a cyclic character. The first, indicative network proposal is considered the starting point after the desired level of service reliability is set, among other public transport quality objectives such as speed, comfort, etc. These objectives are based on the main goals of the project, for instance enhanced accessibility, modal shift or more sustainable transport. Resources and constraints are relevant in this stage as well. The main ones are budget, available space and acceptance of inhabitants. After setting the preferred, indicative network concerning these objectives, service reliability is considered. During a cyclic process the optimal network will be found, concerning all objectives.

When the indicative network has been set, the next step is to check whether the line length is optimal. For this analysis, knowledge of the prevailing passengers' pattern (i.e. the characteristics of boarding, alighting locations and occupancy along the line) is required, which may be provided by ridership or network modelling studies. If a break point (i.e. many boardings and alightings) exists in this pattern, our research, as presented in Section 5.4 enables proper decision making with regard to the design of one long line or multiple shorter ones. This leads to the next step being the check whether coordination might be beneficially applied. When the line is part of a branched network and a strong corridor exists, coordination should be investigated. In Section 5.3 we provided a method to assess the benefits of coordination.

After these steps, the service network appears established. The infrastructure supports the service network and has to be designed accordingly. Capacity of terminals requires special attention. In Section 5.2 we presented a method we developed enabling this analysis. If the expected delays are considered to be too large, terminals may be adjusted or the service line network should be adjusted, being an iterative process. The research described may be of a high level of detail or a quick scan might be possible, enabled by graphs that are provided in our research.

At the tactical level, the proposed service network and infrastructure are used as input. The main first question before starting the design of the schedule is whether the frequency is considered yielding at random or scheduled passenger arrivals at their departure stop. In our research, we assumed this to be related to short- or long-headway services. In the case of long headways, the determination of scheduled trip time is relevant. Driving ahead of schedule should be prevented, minimizing the average additional travel time per passenger. In Section 6.2 we presented our research findings enabling to set the optimal scheduled trip time. In both short- and long-headway services, vehicle holding might be applied. An indicator for a beneficial introduction of holding is when the passengers' pattern has a clear break point. Break points of passengers also indicate the possibility of designing shorter lines, as described above. Breakpoints indicating possibilities for vehicle holding may show a larger amount of through passengers than breakpoints interesting for shorter lines. The negative effects on passengers are less by applying vehicle holding, affecting the trade-off between passengers downstream the break point and in the vehicle. If vehicle holding is proposed, it must be checked whether the capacity of the holding point is sufficient. This element requires attention, especially at holding points that facilitate multiple lines. Either a detailed analysis or a quick scan helps to select the best set of measures at the tactical level.

As the instruments and derived measures chosen at both strategic and tactical levels will not reduce the service variability and unreliability completely and non-recurrent delays will occur as well (which will be the topic of the next section), it is recommended to plan and train a full set of operational instruments as well. The optimal set of operational measures is not investigated in this research study, although our planning instruments will reduce the need for operational measures. In Chapter 4, we addressed the possibilities found in literature and practice. With our methodology, a total set of measures may be constructed, consisting of strategic, tactical as well as operational measures. This will enable public transport operations with a high level of service reliability. Due to the application of planning instruments, operations will be less complicated as well.

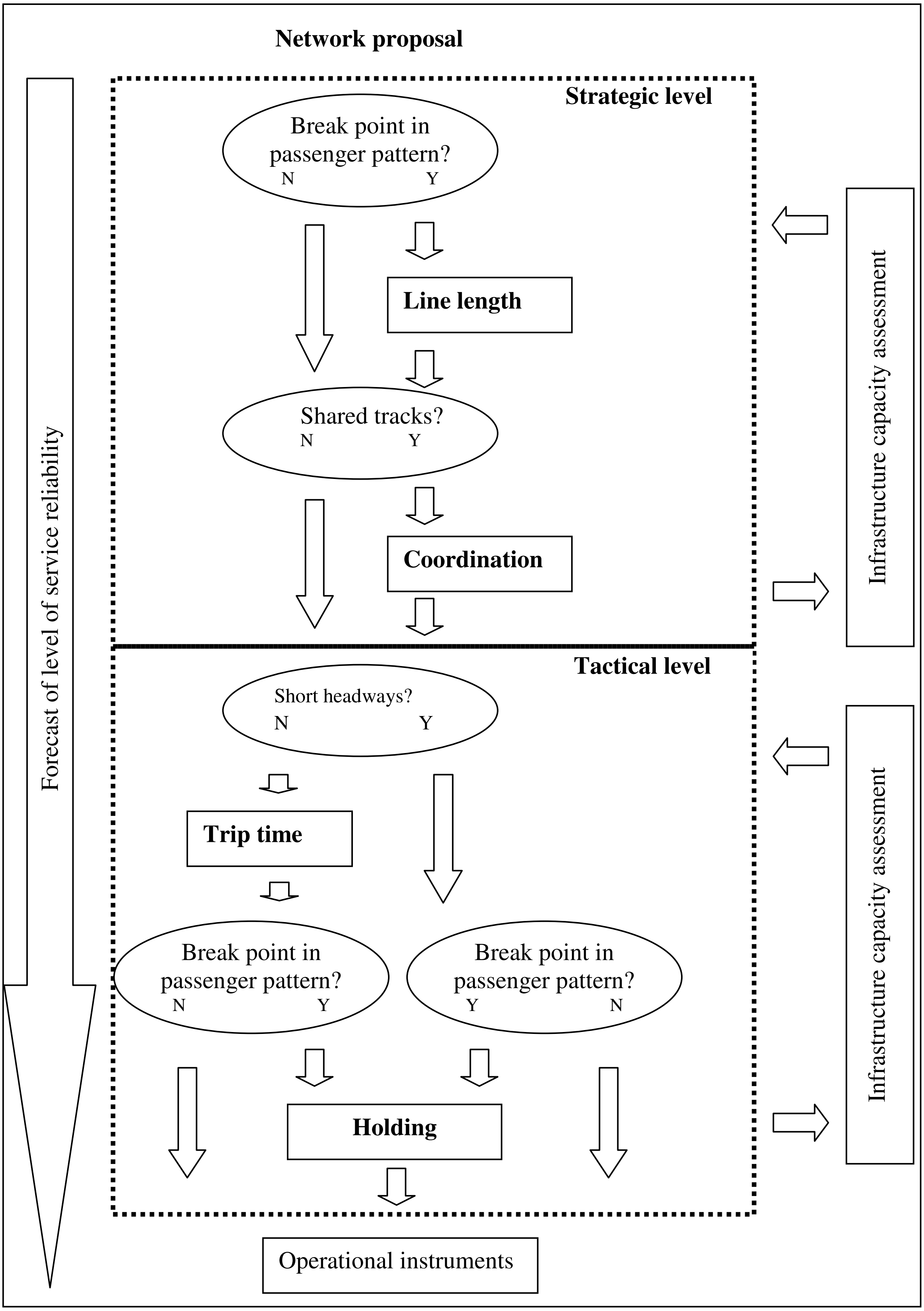


Figure 7.2: Methodology for constructing an optimal set of instruments and measures improving service reliability

7.4 Impacts on non-recurrent delays

In our research, we analyzed recurrent delays only, being common delays that arise when all infrastructure is still available. Several possibilities are described to improve service reliability in case that passenger travel time is negatively affected by recurrent delays. In Tahmasseby (2009), several infrastructure and service network design choices are introduced enhancing the robustness of public transport networks and reducing the impacts of non-recurrent delays, being delays that occur due to unavailability of (parts of) the infrastructure. The design issues and their general expected impacts are presented in Table 7.10. All instruments concern design choices at the strategic level, no timetable issues are considered.

Table 7.10: Instruments preventing or decreasing impacts of non-recurrent delays

Instrument	Impact
Shorter lines	Less geographical impacts of blockings
Bypasses	End to end line operations is still possible
Short cut infrastructure	End to end line operations is still possible
Turning facilities	Reduced line length without service

The design issues included in Table 7.10 proved to be proper ways to reduce or prevent the impacts of non-recurrent delays on passengers. Regarding our research on recurrent delays presented in this thesis, we have compared the design choices and instruments to gain insights into the possible synergy effects of instruments. If synergy exists, this positively affects the design process with regard to applying our planning instruments. Below, the instruments of Table 7.10 are described and the impacts on recurrent delays are mentioned as well.

The first instrument is the design of shorter lines. This way, vulnerability is reduced, since a blocking of the infrastructure only affects one of the two shorter lines, instead of one long line. Reducing line length may also be beneficial in dealing with recurrent delays, as demonstrated by Section 5.4. The trade-off between the passengers experiencing less unreliability due to shorter lines and the passengers having an additional transfer is important. Dealing with this trade-off, the additional positive effects in the case of non-recurrent delays should be considered during the network design as well, as this instrument is both beneficial for dealing with recurrent and non-recurrent delays.

The next proposed instrument by Tahmasseby (2009) is introducing bypasses. Infrastructure networks with multiple routes from and to main nodes are less vulnerable. In the case of disturbances, rerouting of vehicles is possible and end-to-end line operations may still continue. However, longer trip times may result in longer travel times and even in decreased frequencies. Still, this impact is less than no service at all. Compared to recurrent delays, bypasses are not very beneficial, since infrastructure is still available and the bypass is considered not to be faster. In that case, it is considered to be a shortcut which will be analyzed below.

Designing and constructing shortcuts is beneficial for both recurrent and non-recurrent delays. Shortcuts enable alternative rerouting when the original route is blocked. This way, operations may still continue, although a part of the route will not be served. By rerouting, the negative impacts will be limited to a local area, as the other parts of the line and the network are not affected. Shortcuts may be beneficial for recurrent delays as well. Chapter 4 mentioned operational instruments to deal with service variability and unreliability. One of them was speeding up, after experiencing delays. Shortcuts may help to speed up vehicles to increase their schedule adherence. This instrument is thus beneficial in reducing impacts of both recurrent and non-recurrent delays as well.

The last instrument presented by Tahmasseby (2009) is the introduction of turning facilities in rail-bound traffic. They limit the length of tracks that are unusable due to blocked infrastructure. When turning facilities are available at both sides of the blocked part, the larger part of the line may still be in operation. Important, however, is the number of vehicles available at both sides of the blocking. Resolving recurrent delays may also benefit from short-turning facilities. Chapter 4 presented the instrument of short turning to improve the regularity on the line or improve schedule adherence. In the case of rail bound services, this is only possible if short-turning facilities are available. This instrument is thus beneficial for both kinds of delays. Some attention is needed, however. Section 5.2 dealt with the capacity of terminals. Short-turning facilities may be considered as terminal, but of a temporary kind. If frequencies are high and/or the capacity of the short-turning facility is limited, delays may arise. We presented a quantitative analysis of this in Section 5.2. If capacity of the terminal is limited, it is important to consider whether the expected delays are acceptable or whether they are larger than the original problem. One solution may be to decrease the frequency of vehicles by removing vehicles (partly) from service or by coupling them. The latter is preferable regarding the seat capacity on the line.

Above, an analysis is made of the usability of instruments presented in Tahmasseby (2009) to deal with recurrent delays as well. Whereas the mentioned research only deals with non-recurrent delays, this section showed that some presented instruments are useable when dealing with recurrent delays as well. Table 7.11 summarizes the instruments of Tahmasseby (2009) and the possible application for reducing recurrent delays.

Table 7.11: Opportunities to combine instruments dealing with recurrent and non-recurrent delays simultaneously

Instrument	Useable reducing recurrent delays?
Shorter lines	Yes
Bypasses	No
Short cut infrastructure	Yes
Turning facilities	Yes

Table 7.11 shows that three of the presented instruments in Tahmasseby (2009) are beneficial in reducing (the effects of) recurrent delays as well. In addition to the impacts on recurrent delays, these effects should be considered as well, when instruments are selected. One of these instruments, shorter lines, is investigated in our research too. The presented effects in our thesis are thus an underestimation, since the effects on non-recurrent delays are not incorporated yet.

7.5 Reflections on research assumptions and constraints

In our research, several assumptions are made and several constraints are inserted to reduce the level of complexity of our study. Chapter 1 introduced the scope of our research, namely recurrent delays in urban public transport, thereby analyzing empirical data from The Hague. Other main assumptions are the focus on single lines and the use of non-weighted actual travel time in our calculations. The assumed arrival pattern of passengers is of importance on the results as well, as presented in Chapters 2 and 3. The previous chapters yielded valuable results, even considering the limitations of our approach. In this section, the main assumptions and constraints are discussed, the main objective of which is to assess the impacts of these assumptions and constraints on our findings, providing a sensitivity analysis of the chosen approach and results.

7.5.1 Actual time vs. perceived time

Chapter 2 discussed the role of waiting in the total travel time of passengers while in Section 2.3, perceived travel time is discussed. Research shows that passengers perceive one minute of actual driving differently from, for instance, one minute of waiting. In literature, values for these weights are available (Van Der Waard 1988 and Wardman 2001) and Section 2.3 showed a relative weight of 1.5 for waiting time. Although this perceived travel time is considered valuable, in the analyses in Chapters 5 and 6 only actual time is calculated. No relative weights are used for waiting time. The reason for this is that in this way, the discussion is clearer, since it is about real time that may be saved by applying planning instruments. Besides, in literature, several different time values are found, creating a very sensitive result. Bakker and Zwaneveld (2009) for instance show used values between 0.9 and 2.5. Only when introducing the reliability buffer time, weights are introduced. The main reason is that this aspect is still in development and researchers (Furth and Muller 2006) agree that this time shouldn't be fully accounted for. In the cost-effectiveness assessment (Section 7.2), the weighting of travel time components is applied as well in the calculation of the ridership growth due to travel time reductions, since this analysis is on an abstract and aggregated level. When actual time is used instead of weighted time, in most cases an underestimation of the actual effects in real life is to be expected, since we only focus on changes in waiting time. Only when waiting time is compared to in-vehicle time, which is the case in the analysis of the vehicle holding instrument, the results may be an overestimation due to lack of weighting. In the results of Chapters 5 and 6, we thus mainly have a small underestimation of the potential benefits of instruments, since passenger perception of waiting is not included.

7.5.2 Scheduled arrival vs. random arrival

One of the main input variables in our research is the arrival pattern of passengers at their departure stop. In literature it is recognized that in short-headway services, this pattern is at random and in long-headway service passengers consult the schedule to plan their arrival (Furth and Muller 2007). Little literature is available on the boundary between these two different patterns and therefore we performed a survey in The Hague to gain more insights. However, the survey also showed that no exact boundaries exist. The choice for a certain arrival pattern is very complex and depends on personal characteristics as well. Probably, in every situation mixed arrival pattern will appear. In this area, more research is recommended. Knowing that the arrival pattern is complex, the choice in our research is made by using the best available data, which is our survey. The main impact of the boundary of arrival pattern is when departing ahead of schedule becomes an issue. If people tend to arrive according to the schedule, it is important to reduce early departures, since in the case of random arrival the focus should be on the headways between vehicles. Regularity should be optimized in that case. The exact boundary of the two arrival patterns thus determines whether a long-headways or short-headways analysis should be applied. Chapter 6 showed that trip time determination is not relevant in the second scenario and the impacts of the vehicle holding instrument differs as well.

In the case of scheduled arrival, the time frame in which passengers arrive at their departure stop is of importance too. In our research, we assume this frame to be within 2 minutes ahead of scheduled vehicle departure and 1 minute after. These numbers are derived from the survey in The Hague, mentioned above. When passengers tend to arrive earlier than this time frame at their departure stop, the impacts of early vehicle departures will be reduced and the impacts of late or on-time departures will increase. This implies that the optimal percentile value used for determining trip times will become higher than presented in our research. If people tend to arrive later than our chosen time frame, this will be the other way around. Since little is known about these patterns, further research is recommended with regard to this subject.

7.5.3 Line effects vs. network effects

Our findings presented in this thesis are results of line-based research. However, most public transport is network oriented. This is not explicitly taken into account into this thesis. A limitation of this is that transferring is not explicitly considered. Many passengers in urban public transport do not transfer and much literature is already available. In our research, a transfer is only implicitly analyzed, since we consider the journey after transferring as a new one, affected by service variability as well. However, it is interesting what the impacts of transfers on the instruments presented in this thesis are. Concerning the arrival pattern of passengers, transferring is also important, since transferring passenger will (almost) arrive simultaneously at the stop of the second vehicle, while we assumed only a more linear arrival.

As mentioned in Section 7.3, capacity should be considered when planning services. Similar attention is needed to stops and intersections with multiple lines. To assess the network impacts it is recommended to develop network models, for instance microscopic simulation tools, enabling ex-ante analyses of total network service reliability. In heavy railways, it is already common use to predict network effects (e.g. Goverde and Hansen 2001, Carey and Carville 2002, Middelkoop and Bouwman 2002, Radtke and Hauptmann 2004 and Nash and Hürlimann 2004). Recently, new developments regarding this topic in urban public transport are arising, for instance by Kanacilo and Verbraeck (2006) and Kanacilo and Van Oort (2008). Since service reliability affects ridership substantially, we recommend incorporating this quality aspect in demand models as well.

7.5.4 Local vs. general results

The results of our research in Chapters 5 and 6 are partly based on empirical data from public transport in The Hague, the Netherlands. We used and analyzed substantial and unique sets of empirical data, which enabled us to understand the mechanisms concerning service variability and service reliability. Although this fundament of our research is based on typical data for The Hague, the research results are valuable and useful for other cities and continents as well because the following reasons. We used the typical data of The Hague to illustrate and recognize general mechanisms. Most cases are extended using theoretical data. The analyses of hypothetical lines showed similar results as the analyses did in which actual data was used. Especially literature and research using empirical data was reviewed to check whether comparisons were possible (for instance Levinson 1983, Strathman et al. 2002, Csikos and Currie 2007, Delgado et al. 2009). In most comparisons, service variability in The Hague proved to be smaller, indicating that in other areas even more benefits are achievable by improving service reliability. To gain more insights into the planning methods and ways of dealing with service reliability, we performed an international survey (see Section 3.2.3). All main areas are represented and the results showed that while differences exist, the results are transferable.

Our research provided general approaches and instruments dealing with service reliability. We described most relevant processes on a detailed level. Nevertheless, in specific projects detailed analysis is still necessary. Local characteristics, as objectives, budgets, passengers' patterns, deviations' distributions always require specific research, based on the principles presented in our thesis. Local empirical data provides substantial support for this and our tools presented in this thesis are able to incorporate this data.

7.5.5 Primary vs. secondary delays

The focus in our research is on delays caused by one vehicle. In Chapter 4, the tendency of vehicles to bunch in short-headway services is discussed and delay propagation is described. This effect is not explicitly incorporated into the analysis, thereby reducing the level of complexity. However, due to bunching an initial delay may increase which has negative impacts on the travel time of passengers. The presented short-headway results in this thesis thus represent an underestimation. Further research is recommended to insert the bunching effects in predictions of service reliability.

In long-headway services, bunching is not very relevant, but secondary delays may occur as well. Due to the long headways it is more common to apply transfer protection, implying vehicles to wait for their feeder at a transfer point (Knoppers and Muller 1995, Chung and Shalaby 2009). This prevents transferring passengers from waiting a long time if they miss their connection. However, due to waiting of the connecting vehicle, passengers already in the vehicle and waiting downstream suffer a delay as well. This secondary delay is a result of a primary delay of the feeder vehicle and is not incorporated into our research. This may lead to underestimation of the impacts of instruments to improve the service reliability.

Another type of secondary delay that is not explicitly incorporated in our research is the departure delay at the terminal caused by late terminal arrival. This assumption may lead to underestimation of the impacts. The use of new tools incorporating the layover process and departure in the opposite direction is recommendable. Network models in which all processes with regard to operations are considered will provide valuable insights into passenger impacts.

7.5.6 First order effects vs. second order effects

In Section 7.2, we assessed the cost-effectiveness of the investigated planning instruments. We calculated the reduction of additional travel time due to service reliability improvement leading to welfare gains and increased ridership. In the ridership calculation, only first order effects are taken into account. Due to ridership adjustment, the level of service will change as well, influencing the ridership again. Additionally, a change in passenger travel time may change the distribution of journeys over the network. This is not incorporated in the calculation models, since only relative small changes are investigated. In that case, second order effects may be neglected.

7.5.7 Conclusions

This section reflected on the main assumptions and constraints, adopted in our research approach. In order to gain insights into the complex mechanisms concerning service variability and service reliability several assumptions had to be made. In this section, the main issues are described and a sensitivity assessment is made as well. In general, the conclusion is that the presented results in Chapters 5 and 6 are an underestimation of the actual results that may be expected in real life. We distinguish three main reasons for this underestimation. The first reason for this is that delay propagation is not explicitly taken into account in our research. In Section 2.3.2 is described what the impacts of delay propagation are, namely the self-enforcing loop of delay extension. Secondly, an assumption in our research is that the focus is only on the journey from departure stop to the arrival stop without any transfers. In fact, transferring may be considered as the start of a new journey suffering from additional travel time as well. The third reason for underestimation is that no relative weighting is used in the calculation of additional travel time. This weighting is only used afterwards in the cost-effectiveness assessment.

Regarding the assumptions, it is important that further research will be performed on the network effects of service reliability. The analysis of effects at the line level is the first step in improving service reliability. The used tools should be extended or new tools should be developed to incorporate network effects. Additional research on the arrival pattern of passengers is also recommended. Little is known about the boundary between random arrival and schedule-based arrival, although this is of main importance concerning the impacts of service variability. About the arrival pattern in the case of long-headway services is not very much literature available neither. In our research, we used a survey in The Hague enabling to determine the boundary and arrival pattern.

Our research only focuses on first-order effects. Although second order effects are to be expected, the impacts are limited, as only relatively small changes are analyzed.

7.6 Summary and conclusions

In previous analyses we focused on the assessment of individual instruments for individual lines while considering the impacts on travel time only. In this chapter, we presented a cost-effectiveness assessment we performed to gain more insights into the potential of our introduced instruments. In addition to the individual research of the instruments, we argued the possibilities of combining instruments and their derived measures. This helps to construct the optimal set of measures achieving the highest level of service reliability, in a cost-effective way. Whereas we analyzed in this thesis a number of instruments regarding the impacts on recurrent delays, a similar study (Tahmasseby 2009) was focusing on the impacts on non-recurrent delays. In this chapter we investigated to what extent such instruments are complementary to deal with both kinds of delays. The last subject of this chapter was to provide a reflection on the main assumptions of this research, for example the focus on single lines and the arrival pattern of passengers. We conducted a sensitivity assessment showing the impacts of the assumptions on the results, showing that our presented results may be an underestimation.

In Chapters 5 and 6 we analyzed instruments improving the level of service reliability. This quality increase was indicated by the reduction of the average additional travel time per passenger. In this chapter, we analyzed these figures in a more economical perspective. We estimated what the costs and (welfare) benefits of the instruments are. A tentative cost-effectiveness assessment showed that the tactical instruments, trip determination and vehicle holding, are cost-effective in almost every case. Their benefits are substantial and the costs are nil. These instruments should be considered in the design of every public transport system. However, the vehicle holding instrument is only beneficial if the passenger pattern has a clear break point and trip time determination only is relevant in long-headway services. It is presented that strategic instruments are very effective as well. Optimized terminal design enables enhanced service reliability. Coordination and shorter lines may result in reduced passenger travel times as well. However, these instruments may look costly due to necessary additional infrastructure and or (occasionally) additional vehicles. We demonstrated that the costs are limited compared to the potential welfare benefits. In Chapter 3 we roughly estimated the costs of unreliability at € 12 million per year in The Hague and in this chapter we estimated the potential savings at € 8 million per year by applying the five planning instruments we analyzed in our research. The estimated costs of these instruments are assessed to be only a part of the benefits with a maximum of € 3 million per year, showing the added value of the instruments. The results of our international survey (see Section 3.2.3) show that similar results are achievable in other cities as well.

Although our cost-effectiveness assessment contributes very much, the cost-benefit ratio of the instruments very much depends on local characteristics. In practical cases, additional detailed research is always necessary. More research is necessary as well on the exact benefits of the reduction of variability in the additional travel time, since we only addressed the effects of service variability on the average additional travel time in detail.

We developed a methodology that enables to construct the optimal set of instruments dealing with service reliability. In general, a combination of strategic, tactical as well as operational instruments is necessary to improve the level of service reliability. As concluded in the cost-effectiveness assessment, the tactical instruments, being trip time determination and vehicle holding, are very cost-effective in most situations and thus valuable in the complete set of instruments. Whether the strategic instruments may be used, depends strongly on local characteristics, such as passenger flows. However, the advantage of strategic instruments is the time period they cover. Once the strategic level is well designed, the infrastructure and service networks will be beneficial for years or even decades. During the strategic and tactical design, explicit attention has to be paid to capacity of infrastructure, such as terminals. Concerning the operational instruments, it is useful to have several instruments trained and available. With a combination of strategic, tactical and operational instruments a high level of service reliability is achievable.

Our research focuses on structural delays, when the complete infrastructure is available (i.e. recurrent delays). Tahmasseby (2009) studied the impacts of design choices on situations when parts of the infrastructure are not available (non-recurrent delays). In this chapter, we made a comparison between both studies. Our research proved that one instrument shown in Chapter 5 has a positive impact on non-recurrent delays too. The line length instrument is beneficial in the case of non-recurrent delays as well. In our research, the presented positive impacts of this instrument are thus an underestimation of the total impacts. In the total analysis of that instrument, the impacts on non-recurrent delays should be considered as well.

Concerning the impacts of the main assumptions, this chapter showed that the results are probably an underestimation of the actual impacts. Issues as network effects and secondary delays are not incorporated and probably will increase the positive effects of the instruments shown. The arrival pattern of passengers at their departure stop proved to be important too. More research is recommended on all the variables determining passenger behaviour. It is recommended to enhance the used models and approaches to consider the issues for which main assumptions are made. In addition, network models should be developed incorporating all operational process of all lines in the network thereby considering interaction between lines and directions. We recommend incorporating service reliability in demand models as well, since we showed the substantial impacts of this quality aspect to the level of ridership.

8. Conclusions and recommendations

8.1 Research summary

In this thesis we presented our research on service reliability in urban public transport and our analysis of planning instruments aimed at improving it. In this chapter we present the main findings of our research. We will answer our main and sub research questions we introduced in Chapter 1. Our main research questions were how to improve service reliability through enhanced strategic (i.e. infrastructure and service network) and tactical (i.e. timetable) design and how operational data may be incorporated into these designs to improve (forecasts of) operations. Service reliability is one of the main quality aspects of public transport and is often is at a poor level. Improved service reliability increases the overall quality of public transport, thereby ensuring accessible and liveable cities for future generations and reducing the growth of car mobility. In this thesis, we have investigated how service reliability of urban public transport may be improved by enhanced strategic and tactical design. Nowadays, much attention is paid at the operational level to increase the level of service reliability. At this level, service variability and its effects on passengers become noticeable, so it seems logical to act at this level concerning this topic. However, the public transport product is a result of a process, consisting of both strategic and tactical planning. These designs of networks and timetable affect the possibilities at the operational level to perform conform the preset requirements. Although many instruments exist at the operational level to reduce the level of service variability and impacts on passengers, they are not sufficient since they only partly reduce the effects of service variability and since they are not capable of dealing with suboptimal design of network and timetable.

In this thesis we showed the impacts of unreliable services on passengers, being average travel time extension, increased travel time variability and a lower probability of finding a seat in the vehicle. We demonstrated how actual vehicle trip time variability (i.e. service variability) affects service reliability and passenger travel time. Several traditional quantifications of service reliability are presented, such as punctuality and regularity. We demonstrated the shortcomings of these traditional indicators, namely a lack of attention for passenger impacts. Traditional indicators focus too much on the supply side of public transport, which does not enable a proper analysis of passenger effects. To deal with the shortcomings of traditional indicators, we developed a new indicator, being the average additional travel time per passenger. This indicator translates the supply side indicators, for instance punctuality, into the additional travel time that a passenger on average needs to travel from the origin to the destination stop due to service variability. The average additional travel time may be calculated per stop or per line and enables explicit consideration of service reliability in cost-benefit calculations, since the level of service reliability may be translated into regular travel time. In our research we demonstrate that our indicator enables optimization of network and timetable planning and that the use of traditional indicators may lead to conflicting conclusions, concerning service reliability. We also demonstrated the benefits of using reliability buffer time (RBT, as described by Furth and Muller 2006) as an indication of the effects of uncertain arrivals for passengers (i.e. the variability of the average additional travel time per passenger).

To improve service reliability through enhanced network and timetable design, we selected five planning instruments by analyzing the causes of service variability. External causes are the weather, other traffic, irregular loads and passengers' behaviour. We presented that other public transport, driver behaviour, schedule quality and network and vehicle design are the main internal causes of unreliability. Applying instruments during the planning stages will reduce the impacts of these causes.

At the strategic level, these instruments are:

- Terminal design;
  The configuration and number of tracks and switches at the terminal determines the expected vehicle delay and thus service reliability.
- Line length;
  The length of a line is often related to the level of service variability and thus service reliability.
- Line coordination.
  Multiple lines on a shared track may offer a higher level of service reliability than one line (assuming equal frequencies).

The following instruments may be applied at the tactical level:

- Trip time determination;
  In long-headway services, scheduled vehicle departure times at the stop, derived from scheduled trip times, determine the arrival pattern of passengers at their departure stop. Adjusting the scheduled trip time may affect the level of service reliability and passenger waiting time.
- Vehicle holding.
  Holding early vehicles reduces driving ahead of schedule and increases the level of service reliability.

In our research, we extended design dilemmas and introduced new ones by taking service reliability explicitly into account. We proposed a new feedforward loop in public transport planning, which is illustrated by Figure 8.1. We recommend that the design processes at both the strategic and tactical level will be adjusted by applying the presented instruments (regulators) to optimize the level of service reliability, considering the operational disturbances.

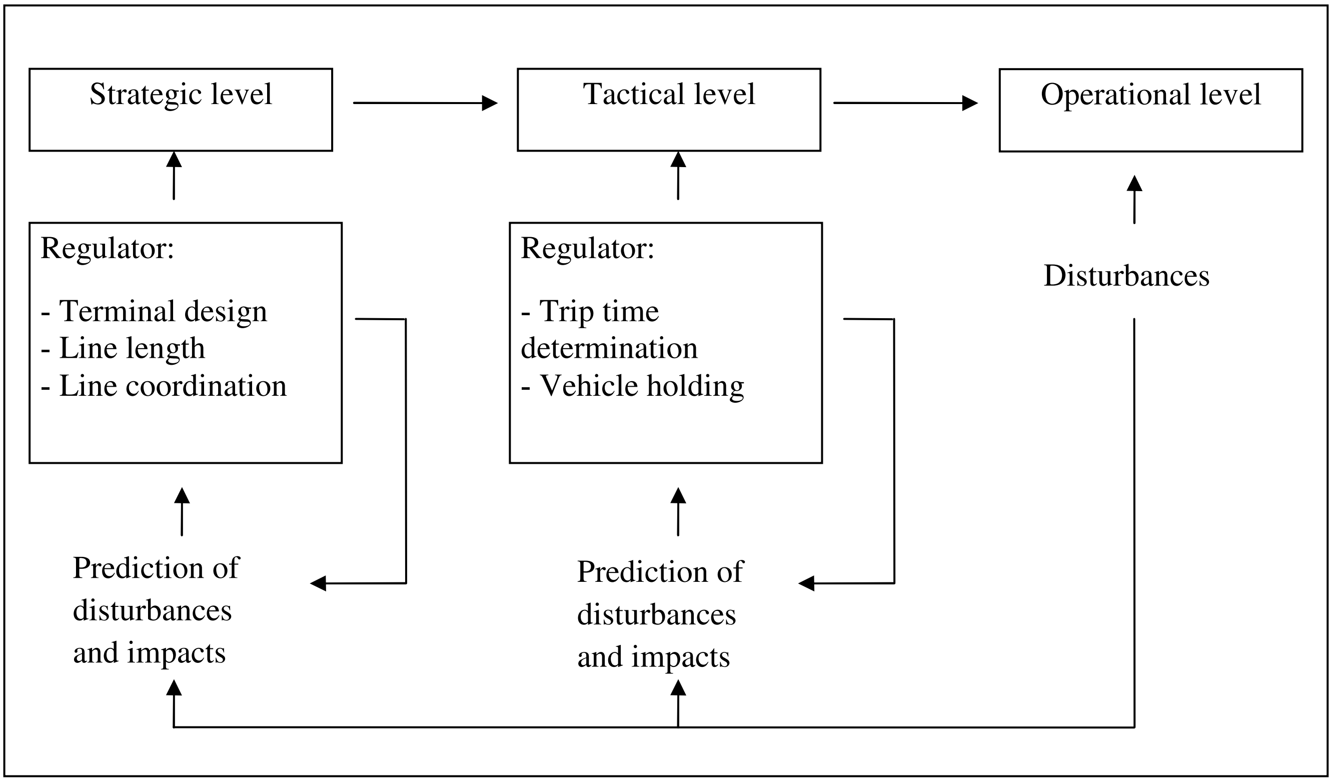


Figure 8.1 Feedforward loops in public transport planning, including our investigated instruments at strategic and tactical level

In the feedforward loop in Figure 8.1, it is necessary to predict the operational output of the planning process. To achieve this objective, we developed tools enabling an analysis of instruments and design choices on service reliability. We used these tools to illustrate the expected passenger travel time impacts of the five planning instruments. The tools simulate public transport operations based on actual data of vehicle trip times, departure times and schedule deviations. We have used actual passenger data (boardings, occupancy and arrival pattern at the departure stop) to calculate the average additional travel time per passenger with and without the application of the instruments (considering several values of design variables of the instruments). We used actual data of public transport lines in The Hague, the Netherlands to gain insights into the mechanisms and effectiveness of the instruments. In addition we performed analyses of hypothetical lines, with variables based on literature and our international survey on service reliability. This way, the results are transferrable to other cities as well.

8.2 Findings and conclusions

In our research, we estimated that in terms of passenger travel time costs about € 12 million per year was lost in The Hague (2004) due to unreliability of buses and trams. By analyzing the public transport of The Hague and by conducting an international survey we found out that all components of vehicle trip time, being driving, stopping and dwelling are substantially deviated, next to a serious variability of terminal departure times. We presented a new look on the size of this variability and showed the impacts on passengers. We demonstrated that passenger waiting time may possibly be extended up to 600% due to service variability.

We demonstrated in this thesis that the planning instruments mentioned in the previous section are beneficial with regard to service reliability, leading to substantial travel time (variability) reductions for passengers. We estimated the effectiveness of planning instruments that reduce the impacts of service variability and unreliability and demonstrated their cost-effectiveness. A rough estimate showed that in The Hague € 8 million of the costs per year mentioned above may be saved by applying these instruments. This is the result of a reduction in additional travel time for both existing and new passengers. We showed that by applying (a combination of) the planning instruments an increase of ridership of 5-15% per line (and revenues accordingly) is possible. The additional costs to achieve this in The Hague are estimated to be maximum € 3 million per year. Considering the international survey we performed, we expect that this kind of savings is possible in other cities all over the world as well. Important to note is that when the (reduction of) variability of the additional travel time due to service variability is considered, these numbers may be twice as high. More research is recommended on that topic.

As discussed in the previous section, we have investigated five planning instruments. Using the framework and tools described above we calculated the effects of the instruments on passenger travel times and demonstrated that considering service reliability during the planning of public transport results in shorter average passenger travel times. Considering that the presented travel time reductions are an average over all passengers on the line (and thus some passenger will experience more and less delays) and that urban journeys take approximately about 10 minutes, the extra travel time is substantial. The conclusions per instrument are presented below.

The instrument of terminal design
Our research illustrated the effects of various stub-end terminal configurations (single and double tracks and double cross-overs before or after the platform) on vehicle departure delays that result in additional passenger travel time. We demonstrated that punctual departures may save up to 2 minutes additional travel time on average per passenger. Our results show that in the case of using stochastic values of vehicle arrival times to assess terminal performance, delays will occur, although they are not to be expected in the static case. The higher the vehicle arrival time variability is, the more capacity should be accounted for. In addition, two lines will create more delays than one line with the same (total) frequency. The best performance regarding service reliability is achieved, when a compact design is used with double crossovers directly situated after the platforms. Single tail tracks facilitating the

turning process are only acceptable if frequencies are low. However, they are often used in practice as short-turning facility for high frequent services, thus leading to unreliable services. Supported by these findings, we recommend to explicitly consider service reliability during terminal design and to take (expected) service dynamics into account. Our tentative cost-effectiveness assessment showed that the additional welfare and revenue benefits, added to possible savings on operating costs, may be much higher than the costs of additional tracks and switches.

The instrument of line coordination
We showed in this thesis the impacts of line coordination on passenger travel time. In addition we also demonstrated the passenger travel time effects of considering service dynamics during the network design. Public transport network planners often propose network structures that either assume a certain level of regularity or that are even especially focused on improving service reliability, such as networks in which part of lines share a common route or the introduction of short-turn services. Concerning this topic, we conducted two types of research methodology, namely both theoretical and practical. A case study on introducing coordinated services shows that applying our control framework leads to more realistic estimates of service reliability and passenger travel time than the traditional approach using a quantitative analysis. We calculated that line coordination may increase passenger perceived frequency by 5-40%, leading to welfare gains and additional revenues (due to 5-15% growth in ridership). Secondly, we used general variables such as standard deviations of vehicle trip times to assess the effects of coordinating the schedules and of improving the punctuality on passengers waiting and travel time. The results of this theoretical analysis supported the case study results. We demonstrated that line coordination is a beneficial instrument to improve the level of service reliability and reduce passenger travel time and travel time uncertainty. However, we also demonstrated that operational service variability should be explicitly taken into account when calculating the expected effects of this instrument. We recommend applying our control framework during the network design when multiple lines use the same route, to maximize the passenger impacts.

The instrument of line length
We introduced a new design dilemma in the service network design namely length of line vs. service reliability. Long lines offer many direct connections, thereby saving transfers. However, we showed that the variability is often related to the length of a line, leading to less schedule adherence and more average additional travel time for passengers. We suggested taking into account both the positive and negative effects of extending or connecting lines. We applied our control framework to calculate the average additional travel time per passenger due to variability and transfers based on actual vehicle trip and passenger data. A case study in The Hague shows that in the case of long lines with large trip time variability, splitting the line may result in less average additional travel time per passenger because of improved service reliability. This benefit compensates for the additional transfer time, provided that the transfer point is well chosen. A case study shows a decrease of about 30% in average additional waiting time per passenger. Splitting a long line (for instance a diametric line) into two lines with an overlap in the central part may even result in higher travel time savings. In that case, fewer passengers have to transfer. We estimated that the benefits of this instrument may be two to four times higher than the costs, in the case of long, distributed lines. We recommend considering both the positive and negative aspects of long lines during network design, achieving an optimal design, with regard to passenger travel time.

The instrument of trip time determination
One of the main design choices of the timetable is the time value used as scheduled trip time. In urban public transport it is common use to have a feedback loop from operations to timetable design. Actual trip times are input for the new schedule. However, the actual trip times are distributed while only a single value can be used as scheduled time. Normally, a high percentile value is used to set the new scheduled trip time. This way, an attainable timetable is constructed, since most of time drivers are able to arrive without a delay at the terminal. But this implies early vehicle departures at stops along the line as well. We analyzed the impacts of the chosen percentile value on service reliability and travel time in the case of long-headway services. A theoretical approach and a case study of tram lines in The Hague show the effects of design choices of timetabling on service reliability. By analysis of actual and hypothetical trip time and passenger data we demonstrated that the total passenger travel time is minimized if the 35-percentile value is used to determine the scheduled trip time out of historical data, which is much lower than currently adopted. High percentile values cause much average additional travel time per passenger due to early vehicle departures. Passengers who miss their vehicle have to wait a full headway then. To maintain the equal probability of departing on-time after the layover at the terminal, it is recommended to redistribute the "saved" trip time (by decreasing the percentile value) to the layover time, maintaining a fixed cycle time.

Since we proved that lower percentile values of scheduled trip time yield less average additional travel time per passenger in long-headways services and since the costs are nil and the benefits are substantial (i.e. a reduction of additional travel time of 3-7 minutes per average passenger) we recommend adjusting traditional timetables that still use high percentile values.

The instrument of vehicle holding
Besides adjusting trip time design, one common operational instrument to prevent vehicles to operate ahead of schedule is holding. Holding too early vehicles may improve service reliability, resulting in both shorter average passenger travel times and less crowding. Although holding is an operational instrument, the main impacts are determined in the schedule design phase. In our research, we analyzed holding for both long (more than 10 minutes) and short-headway (10 minutes and less) services, which is presented separately below. One of the main issues regarding holding is the trade-off between passengers in the vehicles (suffering from holding) and passengers at the stops downstream (benefiting from holding). In our research, we provided insights into this trade-off.

Vehicle holding with long headways
We performed a theoretical and a practical study of tram and bus lines in The Hague to gain insights into the optimal value of scheduled trip times and the number of holding points in long-headway services. The results are that designing 2 holding points is adequate and the optimal percentile value lies between 30 and 60 percent. This depends on the characteristics of the line. The optimal percentile value mainly depends on the following variables:

- The value of the relative standard deviation of the actual trip time.
  The higher the standard deviation, the higher the optimal percentile value.
- The number of holding points.
  The impacts of two holding points on the average additional travel time per passenger are greater than when only one is used, but almost equal to three or four.
- The holding point location.

> The best location for a holding point depends on the distribution of passengers on a line. The ratio of the number of through passengers versus the boarding passengers downstream determines the effectiveness of a holding point.

Holding at all stops also reduces the average additional travel time per passenger, but the analysis showed that more than 2 or 3 holding points does not reduce the average additional travel time per passenger anymore. However, that way, the effects (both positive and negative) are spread more over the stops and passengers. It depends on the distribution of passengers on the line how effective this is.

Our research shows that the schedule is of main importance when holding is applied. With high percentile values used for scheduled trip times, service reliability will get high, but (scheduled) passenger travel times will become very long, due to much holding. Using the average additional travel time per passenger as an indicator for service reliability, this effect is clearly visible.

Vehicle holding with short headways
In addition to long-headway services, we also investigated the effects of holding in short-headway services. Despite significant attention to holding in current literature, some important aspects have not been researched yet, such as the maximum holding time, the reliability buffer time and, in the case of schedule-based holding, the percentile time value used to design the schedule. We incorporated these aspects in our holding research. Both an actual line in The Hague (tram line 9) and hypothetical lines are analyzed with various levels of trip time variability. Both headway-based and schedule-based holding yield the largest effects if deviations are high. When applying schedule-based holding and a maximum of 60 s. holding time is applied, the optimal value of the percentile value becomes about 65% for all lines analyzed. When no maximum holding time is applied, schedule-based holding is more effective, while there is no difference when the maximum holding time is set to 60s. We also showed the effects of holding on crowding in this thesis. An average level of irregularity of 20% may decrease to 15%, enabling either smaller capacity slack of vehicles or less crowding.

In the analysis of vehicle holding we demonstrated that although vehicle holding is an operational instrument, timetable design plays a main role. The benefits for passengers of vehicle holding are maximized if the timetable is designed considering future holding strategies. We recommend investigating the possibilities of vehicle holding already during the tactical design, so timetables may be designed accordingly and passenger travel time will be minimized. The costs of vehicle holding are nil and travel time may be reduced substantially (1-2.5 minutes per average passenger), if a break point of passenger pattern is available on the line.

The instrument of vehicle holding and trip time determination both prevent early vehicle departures. These two instruments differ with their possibilities to apply. Trip time determination is only relevant in long-headway services. Vehicle holding only yields positive effects if a clear break point in passenger pattern exists, since this instrument creates a trade-off between passengers in the vehicle and passengers at the stops downstream of the holding point. If such break point does not exist, no holding should be applied and lower percentile values should be used for scheduled trip times. If they do exist, larger percentile values and holding points should be applied.

The instruments presented above support our hypothesis that at the planning stages of public transport, possibilities exist to improve service reliability. Our research shows that service reliability is not only a result of an operational process, but it is also the results of a certain design. By applying a feedforward loop, service reliability will be improved by enhanced service planning. If this feedforward loop is applied next to operational feedback instruments, a substantial leap in the level of service reliability will be achieved. We dealt in this research with recurrent delays, but also demonstrated that some instruments that are introduced are also beneficial when dealing with non-recurrent delays that occur when parts of the infrastructure are blocked. Since service reliability is one of the most important quality aspects of public transport, a substantial quality improvement is possible resulting in an increased position compared to other modalities. Finally, this will lead to welfare gains for existing and additional passengers, increased passenger satisfaction and additional revenues for operators.

8.3 Recommendations for further research

Concerning our presented research, we have some recommendations for further research. In our research we mainly focus on the benefits of the instruments. A cost-benefit analysis of all the instruments may be helpful to convince stakeholders. In our research we only presented a tentative assessment of costs and benefits. Detailed research incorporating local agreements and financial contracts must always be performed when instruments are analyzed. Our developed indicator, the average additional travel time per passenger, is valuable in such an analysis to translate service variability effects into average passenger travel time effects. We showed that the reliability buffer time (Furth and Muller 2006) is a helpful indicator to address the variability of this additional travel time. More research on this aspect is recommended, with special regard to passenger behaviour and monetary impacts. We used this aspect in parts of our research since we are convinced that this is an important aspect for passengers. However, more detailed research is required to understand the exact impacts on passengers and their behaviour accordingly. The welfare effects of the changed probability of finding a seat in the vehicle and overcrowding due to improved service reliability may be further investigated as well, since less literature on this topic is available.

The focus of our research was mainly on line level, while research on network level is recommended as well. In that way, transfers may be explicitly taken into account, next to line synchronization and bunching effects. The arrival pattern of passengers at their departure stop may also be a future research topic. This pattern is of main influence on the impacts of service variability on passengers and on the methods to reduce additional travel time due to unreliability. We performed a survey in The Hague to understand the passenger arrival pattern and with the results of this survey we were able to analyze passenger effects of service variability and instruments affecting them. However, we found that the arrival pattern is a complex function of several factors and we recommend more research on this, especially in long-headway services.

With regard to the specific instruments, recommendations are presented below.

- Terminal design
  The presented model calculates the average delay per vehicle indicating the impacts on passengers, but an extension of the model is necessary to illustrate the average additional travel time per passenger on the line.

- Line coordination
  To assess the impacts of line coordination on passengers, we applied our control framework. The framework focuses on the impacts on regularity and the level of

demand. Changes in the regularity also influence the capacity efficiency, which might influence the operational costs. Therefore, the framework might be extended in the future to incorporate operational costs.

- Line length
  As presented in Chapter 5, splitting lines into multiple parts may require more vehicles. On the other hand, splitting lines enables to fit the supplied number of trips with the expected demand on both new lines instead of one single frequency on the complete line. This way, a high efficiency level may be achieved. More research is recommended concerning this issue. Another research aspect to further explore concerning an alternative for long diametric lines, are the impacts of overlapping lines (i.e. semi-diametric lines) on service reliability and operational costs.

- Trip time determination
  In the presentation of the results of our trip time determination analysis, it was stated that when scheduled vehicle trip time was decreased, the layover time should be increased, thereby enabling a punctual departure. To optimize the timetable, further research is necessary to show the effects if the total cycle time is not fixed. In this way, it is possible to calculate the trade-off between shorter cycle times (implying lower costs) and higher quality (due to higher service reliability).

- Vehicle holding
  Chapter 6 presented several important variables when dealing with vehicle holding. One that we did not consider explicitly is the location of holding points. More research is recommended to determine what the optimal holding point is, concerning service reliability, as a function of for instance punctuality, number of through passengers and passengers boarding downstream the holding point. Another recommendation concerning vehicle holding is to investigate the impacts of reliability buffer time on holding strategies and passengers in long-headway services, since we only analyzed this aspect in short-headway services.

In general, our presented instruments may be incorporated in research of complete networks, thereby analyzing all processes of a complete public transport network, considering all interaction between lines and vehicles (including deviation propagation or bunching). Other planning instruments (for instance traffic light priority) should be incorporated in such research as well, to assess the effects of combination of instruments. As we demonstrated that service reliability affects the level of demand substantially, this quality aspect may be incorporated in passenger demand models in the near future.

We demonstrated in our research that a substantial leap in level of service reliability is possible by applying planning instruments. We introduced several instruments and we developed tools to create a feedforward loop in public transport planning. The potential of these instruments is great, but we are convinced more instruments are available to improve service reliability, as presented by Chapter 4. Therefore we recommend more research on the capacity of tracks and stops in urban public transport and the impacts on service reliability. Furthermore, we recommend that researchers and planners of bus and tram systems cooperate more with metro and train researchers and planners and vice versa to gain insights into the methods of each other and to combine the best of both worlds. In our research we focus on urban public transport, but we also reviewed and discussed literature of railways, finding interesting methods and tools. Generally speaking, the systems are developing towards each other in an attempt to combine the advantages of both systems (for instance light rail and high frequent train systems). Looking from a different angle at traditional planning processes helps to optimize them.

Another recommendation we give is to put more effort in combining the practical and scientific world. This thesis shows that combining practical data and experience with scientific knowledge and instruments, leads to valuable insights into the mechanisms of service reliability and results in directly applicable tools and instruments. Both the scientific and the practical world should look for more cooperation. Trying to understand the other one and adjusting towards the other one's language and interests is a necessary prerequisite to achieve a fruitful cooperation.

8.4 Practical applications of our research

In this thesis we presented planning instruments enabling enhanced service reliability. To achieve a higher level of service reliability in practice, we recommend considering service reliability explicitly in the design of infrastructure networks, service networks and timetables using our developed control framework and tools. Service reliability effects should be incorporated in a sophisticated way into cost-benefit analyses of public transport projects as well, using the average additional travel time per passenger we introduced. This way, welfare gains and additional revenues may be calculated.

Nowadays, little attention is paid to service reliability during network and timetable design. Investment costs, scheduled travel time and schedule attainability for drivers get more attention. Since we illustrated by the case of The Hague that the five planning instruments we introduced are cost-effective, we recommend applying them on potential lines. The terminal design instrument concerns (new) lines with tail tracks as terminal or short-turning facilities. For high frequent, distributed lines, we recommend compact tail tracks with double crossovers directly after the stop. Concerning (new) lines with a clear break point in passenger pattern, we recommend to split the line or to apply holding points. For long-headway services we propose to use the 35-percentile value for scheduled trip time. And if parts of lines are very crowded, we suggest investigating the effects of coordination. Optimized strategic and tactical design improves service reliability and also simplifies the operational process with regard to service reliability. Enhanced service planning will allow passengers to benefit from improved service reliability tomorrow!

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Appendix A: List of symbols

The ~ symbol indicates a stochastic variable

Symbol	Unit	Explanation
$\tilde{C}$	€	Generalized passenger costs for public transport
CoV		Coefficient of variation
$\tilde{D}_{l,i,j}^{act}$	Hour:Min:s.	Measured actual departure time of vehicle i on stop j on line l
$\tilde{D}'^{act}_{l,i,j}$	Hour:Min:s.	Calculated new actual departure time of vehicle i on stop j on line l (after holding)
$\tilde{D}_{l,i,j}^{act,new}$	Hour:Min:s.	Calculated actual departure time of vehicle i on stop j on line l (in the case of punctual departure at the terminal)
$D_{l,i,j}^{sched}$	Hour:Min:s.	Scheduled departure time of vehicle i on stop j on line l
F^{sched}	Vehicles/hour	Scheduled service frequency
F_l^p	Vehicles/hour	Perceived service frequency at line l
H	s.	Scheduled headway
$\tilde{H}_{l,j}^{act}$	s.	Actual headway of line l at stop j
$\tilde{H}_{l,i,j}^{act}$	s.	Actual headway for vehicle i on line l at stop j
H_l^p	s.	Perceived headway at line l
$H_{l,i}^{sched}$	s.	Scheduled headway for vehicle i on line l
O^{static}		Static occupancy
$P_{l,i,,j}$	%	Relative frequency of vehicle i on line l having a schedule deviation between $\delta^{\min}$ and $\delta^{\max}$ at stop j
$P_{l,i,1}^{on\_time-departure}$	%	Probability of on-time departure of vehicle i at the terminal on line l
$PRDM_{l,j}$	%	Relative regularity for line l at stop j
$RBT_{l,j}^{in-vehicle}$	s.	Reliability Buffer Time at stop j on line l due to variability in in-vehicle time
$RBT_{l,j}^{waiting}$	s.	Reliability Buffer Time at stop j on line l due to variability in waiting time
$T_{1,1}$	s.	Dwell time, vehicle 1 at stop 1
T^{cycle}	s.	Vehicle cycle time
$\tilde{T}_{l,j}^{access}$	s.	Passenger access time at stop j on line l
T_l^{Add}	s.	Average additional travel time per passenger on line l

$\tilde{T}_{l,j-k}^{add,in-vehicle}$	s.	Additional in-vehicle time due to service variability between stop j and k on line l
$T_{l,i,j}^{add,in-vehicle}$	s.	Expected additional in-vehicle time due to service variability in vehicle i at stop j on line l
$T_{l}^{Add,transfer}$	s.	Average additional travel time per passenger on line l due to transferring
$T_{l\_passenger}^{Add,transfer}$	s.	Average additional waiting time on line l due to transferring at transfer point per transferring passenger
$T_{l,j}^{Add,waiting}$	s.	Expected additional waiting time per passenger at stop j on line l due to service variability
T^{budget}	s.	Travel time budget per passenger due to service variability
$\tilde{T}_{l,k}^{egress}$	s.	Passengers egress time at stop k on line l
$\tilde{T}_{l,i,j}^{holding}$	s.	Holding time of vehicle i at stop j on line l
$\tilde{T}_{l,j-k}^{in-vehicle}$	s.	Passenger in-vehicle time between stop j and k
$\tilde{T}_{l,j}^{in-vehicle}$	s.	Passenger in-vehicle time at stop j on line l
$T_{l,j}^{in-vehicle,95\%}$	s.	95th percentile value of in-vehicle time due to vehicle i between stop j and j+1 on line l
$\tilde{T}_{l,j-k}^{journey}$	s.	Passenger travel time from stop j to stop k
$\tilde{T}_{l,j-k}^{journey,\exp}$	s.	Experienced passenger travel time from stop j to stop k
$\tilde{T}_{l,j-k}^{journey,perc}$	s.	Perceived passenger travel time from stop j to stop k (including weights for travel time components)
$\tilde{T}_{l,j-k}^{journey,tot}$	s.	Passenger travel time from origin to destination (on line l departing at stop j and arriving at stop k)
$\tilde{T}_{l,j-k}^{journey,sched}$	s.	Total passenger travel time according to schedule (on line l departing at stop j and arriving at stop k)
$T^{layoverA}$	s.	Vehicle layover time at terminal A
$T^{\max holding}$	s.	Maximum holding time
T^{occ}	s.	Vehicle occupancy time
$T_{l,j-k}^{sched,in-vehicle}$	s.	In-vehicle time (stop j-k) per passenger according to the schedule
$\tilde{T}_{l,j}^{sched,waiting}$	s.	Waiting time according to the schedule per passenger at stop j on line l
$\tilde{T}_{l,m}^{transer}$	s.	Passenger transfer time at stop m on line l
T^{tripAB}	s.	Scheduled vehicle trip time one direction (A to B)

$\tilde{T}_{l,j}^{waiting}$	s.	Passenger waiting time at stop j on line l
$\tilde{T}_{l,j}^{waiting\_origin}$	s.	Passenger waiting time at origin (hidden waiting time) (corresponding to stop j at line l)
$T_{l,j}^{waiting,95\%}$	s.	95th percentile value of waiting time due to vehicle i at stop j on line l
TP	€	Ticket price
ϕ	€	Public transport mode preference constant
V	Veh.	Number of vehicles
VOT	€ /s	Average value of time for public transport passengers

The ~ symbol indicates a stochastic variable

Symbol	**Unit**	**Explanation**
$\alpha_{l,j}$		Proportion of passengers of line l boarding at stop j
$\beta_{l,j}$		Proportion of passengers of line l travelling between stop j and j+1
γ		Fraction of headway deviation that vehicle is held for
d	s.	Initial delay
$\tilde{d}_{l,i,last\_stop}^{arrival}$	s.	Arrival deviation of vehicle i on line l at the terminal
$\tilde{d}_{l,i,j}^{departure}$	s.	Measured departure deviation of vehicle i at stop j on line l
$\tilde{d}_{l,i,j}^{departure,new}$	s.	Calculated departure deviation of vehicle i at stop j on line l (in the case of punctual departure at the terminal)
$\delta^{\max}$	min.	Upper bound bandwidth schedule deviation
$\delta^{\min}$	min.	Lower bound bandwidth schedule deviation
θ_X		Subjective weight of travel time component x
h_n		Stop number of holding point n
$n_{l,i}$		Number of trips on line l
$n_{l,j}$		Number of stops on line l
n_{tracks}		Number of tracks for turning
p_l	min.	Average punctuality on line l
τ_{early}	s.	Lower bound of arrival bandwidth of passengers at departure stop
τ_{late}	s.	Upper bound of arrival bandwidth of passengers at departure stop

Index	**Explanation**
i	Vehicle
j	Stop (departure)
k	Stop (arrival)
l	Line

Appendix B: Line characteristics of case study The Hague, the Netherlands

Line	From	To (and vv.)	Length [km]	Number of stops	Trip time [min]	Standard deviation [min]	Scheduled headway peak [min]	Scheduled headway off peak [min]
1	Scheveningen	Delft	20	43	60	3	10	15
2	Kraayenstein	Leidschendam	13	32	43	3	7	15
3	Loosduinen	Den Haag CS	9	26	29	3	5	15
9	Vrederust	Scheveningen	14	31	40	4	5	15
11	Scheveningen	Den Haag HS	8	19	22	2	10	15
12	Duindorp	Den Haag HS	7	19	25	3	7	15
14	Scheveningen	Berestein	13	33	37	2	8	15
15	Moerwijk	Nootdorp	17	37	52	3	7	15
17	Statenkwartier	Wateringen	16	35	42	3	7	15
18	Clingendael	Rijswijk	15	31	49	7	10	15
23	Duindorp	Kijkduin	29	69	95	6	8	15

Appendix C: Questionnaire of international survey on service reliability

1. General characteristics of public transport systems

What is the company name?

…

What is the name, affiliation and email address of the contact person(s)?

…

What is the area of operation (city/region)?

…

What is the population of the area?

…

What is the number of boardings per year?

…

What is the number of lines?

…

2. Reliability characteristics

2.1 Do you measure the reliability of your public transport?

☐ No

☐ Yes, please state how:

…

2.2 What indicators do you use to measure reliability?

☐ Punctuality (average deviation of the timetable)

☐ Absolute punctuality (absolute average deviation of the timetable)

☐ Percentage of vehicles within a bandwidth

What is the bandwidth? …

☐ Regularity (average deviation of the headway timetable)

☐ Standard deviation of driving times

☐ Other: …

2.3 What is the value of these indicators per line?

…

3. Timetable design

3.1 How are driving times determined?

☐ Based on theoretical characteristics of fleet and infrastructure

☐ Based on measured actual data of previous period

☐ Other:…………

3.2 If driving times are determined in a theoretical way, what percentage or fixed amount of supplement is used per line per direction?

… % or … min.

3.3 If driving times are determined by actual data of the previous period,

A: What value is chosen out of the distribution?

☐ Mean

☐ Median

☐ … percentile

☐ Other: …

B: Differs the chosen value of 3.3A by day type, period of the day, or line:

☐ No

☐ Yes: please explain:

…

3.4 Is extra slack added to the driving times and if yes, how much and how is it distributed across the line?

☐ No

☐ Yes, as follows:

…

3.5 Do you apply holding points (i.e., stops where it is not allowed to depart ahead of schedule)?

☐ No

☐ Yes, please give the number of points per line and location:

3.6 Is there a difference between the schedule for drivers and the one for the public?

☐ No

☐ Yes, as follows:

…

4. Line network design

4.1 Do you have lines operating on the same track longer than 3 stops?

☐ No

☐ Yes, please state the number of lines and length of shared part

4.2 If you operate lines on the same track, do you coordinate them in the schedule?

☐ No

☐ Yes, as follows:

…

4.3 What is the longest line in the network?

Please state the line and length:

…

… km

4.4 Do you have a maximum length of a line during the design process?

☐ No

☐ Yes: … km

5. Infrastructure network design (only rail services)

Terminals

5.1 What types of vehicles do you have?

☐ One directional

☐ Bidirectional

☐ Combination of one and bidirectional. Please state percentage bidirectional:

…%

5.2 Could you show what the terminals look like? Please indicate the rush-hour frequency for all lines using it as well. Could you state how vehicles use the tracks as well?

5.3 What type of platform do you prefer?

☐ On the side, because:

…

☐ Between the track (island), because:

…

5.3 Where do you prefer the switches to be located?

☐ Before the platform, because:

…

☐ After the platform, because

…

5.4 Do you change the driver at the terminal at every arrival?

☐ No

☐ Yes

☐ Only a few times per day: approx … times per day

5.5 In case of more lines using the terminal, do you coordinate their arrival/departures?

☐ No

☐ Yes: …

<u>Stops</u>

5.4 If more than one line use a stop, how many stopping places do you design (How many vehicles can use the stop similiarly)?

☐ One

☐ Two

☐ More: …

☐ Depends on number of lines/frequencies/other:…

5.5 What are the threshold values of number of lines and total frequency to add a stopping place?

… lines

Total of … vehicles per hour

Appendix D: Bunching of public transport vehicles

In (Newell, 1964) is stated that the delay exponentially increases with the number of stops on a line. The velocity of this increase depends on the ratio of arrival speed of passengers at the stop and boarding speed (k-value). If the k-value is high, the boarding time is relatively high. If k exceeds the value of 1, an instable situation occurs, namely more passengers arrive at the stop than are able to board during the same time frame. Figure E.1 shows the development of initial delays with different values of k. Huddart (1974) uses a k-value of 0.05 (on average) while in The Hague a k-value between 0.005 and 0.03 is more realistic. These values are shown for a few stops in The Hague in Table E.1 (Van Oort 2003). These values are calculated using actual data or estimates based on experience.

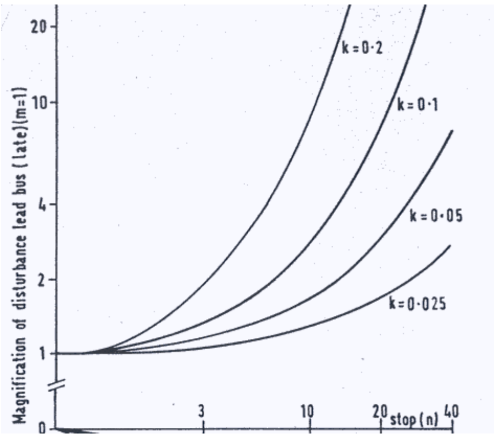

Figure E.1: Increase of initial delay using k-value

Table E.1: Actual K-values in The Hague

Line	Stop	Period	Passengers' arrival [pass/s]	Boarding velocity [pass/s]	k-value	Stop type
Default stop			0.01	1.7	0.006	Quiet
1	Delft. station	7-9 a.m.	0.066	3.4	0.02	Crowded
Default stop			-	-	0.03	Very Crowded

Combining Table E.1 and Figure E.1 helps to assess the delay propagation in a practical case, for instance in The Hague. On average, an initial delay is doubled after 40 stops. In the cases, presented in Chapters 5 and 6, this is not explicitly incorporated, but all results should be reviewed in terms of the impact of delay propagation.

Summary

Service reliability and urban public transport design

The last few decades have shown a substantial increase in personal mobility. Urban traffic and transport volumes have been increasing for years. However, the share of public transport in this mobility growth did not change much and still remains rather limited. To ensure the accessibility and liveability of our cities for future generations, however, a substantial quality leap in public transport is necessary. This will facilitate a desired modal shift from car traffic towards public transport, which is safer, cleaner and produces less congestion. In this thesis, we demonstrate that several promising opportunities exist to improve service reliability (i.e. the certainty of service aspects compared to the schedule as perceived by the user), being one of the most important quality aspects of public transport. Literature shows that in urban public transport substantial attention is given to ways to improve service reliability at the operational level. It is not clear how and to what extent strategic and tactical design decisions in public transport systems might affect service reliability. Only traffic light priority and exclusive lanes are considered during the planning of urban public transport in order to improve the level of service reliability. We expect that more instruments at these planning levels enable high-quality services at the operational level, especially with regard to service reliability.

In this thesis, we present several planning instruments that facilitate enhanced service reliability. In addition, we show forecasting tools we developed and we introduce a new indicator that expresses the impacts of service reliability more effectively than traditional indicators, namely the additional travel time per passenger. This way, the assessment of public transport benefits will be substantially improved, thereby enabling cost-effective quality improvements. We show the impacts of unreliable services on passengers, being average travel time extension, increased travel time variability and a lower probability of finding a seat in the vehicle. We demonstrate how actual vehicle trip time variability (i.e. service variability) affects service reliability and passenger travel time. In order to gain insights into the mechanisms between these two aspects, we performed research based on empirical data of the public transport system in The Hague. Furthermore, we conducted an international survey of service reliability. Several traditional quantifications of service

reliability are presented, such as punctuality and regularity. We demonstrate the shortcomings of these traditional indicators, namely a lack of attention for passenger impacts. Traditional indicators focus too much on the supply side of public transport, which does not allow a proper analysis of passenger effects. To deal with the shortcomings of traditional indicators, we developed a new indicator, being the average additional travel time per passenger. This indicator translates the supply-side indicators, for instance punctuality, into the additional travel time that a passenger on average needs to travel from the origin to the destination stop due to service variability. The average additional travel time may be calculated per stop or per line and enables explicit consideration of service reliability in cost-benefit calculations, since the level of service reliability may be translated into regular travel time. In our research we demonstrate that our indicator enables optimization of network and timetable planning and that the use of traditional indicators may lead to conflicting conclusions in terms of service reliability. We also demonstrate the benefits of using reliability buffer time (RBT, as described by Furth and Muller 2006) as an indication of the effects of uncertain arrivals for passengers (i.e. the variability of the average additional travel time per passenger).

To improve service reliability through enhanced network and timetable design, we selected five planning instruments by analysing the causes of service variability. The main external causes are the weather, other traffic, irregular loads and passengers' behaviour. Other public transport, driver behaviour, schedule quality and network and vehicle design are the main internal causes of unreliability. Since the arrival pattern of passengers is very important when calculating service reliability effects, we performed a passenger survey in The Hague. It showed that passengers tend to arrive at random at their departure stop if scheduled headways are 10 minutes or less. In the case of longer headways, passengers on average plan their arrival about 2 minutes prior to the scheduled vehicle departure time. Applying instruments during the planning stages will reduce the impacts of these causes.

At the strategic level, these instruments are:

- Terminal design;
  The configuration and number of tracks and switches at the terminal determines the expected vehicle delay and thus service reliability.

- Line length;
  The length of a line is often related to the level of service variability and thus service reliability.

- Line coordination.
  Multiple lines on a shared track may offer a higher level of service reliability than one line (assuming equal frequencies).

The following instruments may be applied at the tactical level:

- Trip time determination;
  In long-headway services, scheduled vehicle departure times at the stop, derived from scheduled trip times, determine the arrival pattern of passengers at their departure stop. Adjusting the scheduled trip time may affect the level of service reliability and passenger waiting time.

- Vehicle holding.
  Holding early vehicles reduces driving ahead of schedule and increases the level of service reliability. The design of the schedule affects the effectiveness of this instrument.

The terminal design instrument relates to (new) rail lines with tail tracks as terminal or short-turning facilities. For high-frequency, distributed lines, we recommend compact tail tracks with double crossovers directly after the stop. Concerning (new) lines with a clear break point in passenger pattern, we recommend to split the line or to apply holding points. For long-headway services we propose to use the 35-percentile value for scheduled trip time. And if parts of lines are very crowded, we suggest investigating the effects of coordination.

A tentative cost-effectiveness assessment showed that the tactical instruments (trip determination and vehicle holding) are cost-effective in almost every case. Their benefits are substantial and the costs are nil. These instruments should be considered in the design of every public transport system. However, the vehicle holding instrument is only beneficial if the passenger pattern has a clear break point and trip time determination only is relevant in long-headway services. It is presented that strategic instruments have considerable benefits as well. Optimized terminal design enables enhanced service reliability. Coordination and shorter lines may result in reduced passenger travel times as well. However, these instruments may look costly due to necessary additional infrastructure and or (occasionally) additional vehicles.

We demonstrated that the costs are limited in relation to the potential welfare benefits. We roughly estimated the costs of unreliability at € 12 million per year in The Hague and we estimated the potential savings at € 8 million per year by applying the five planning instruments we analysed in our research. The estimated costs of these instruments are assessed to be only a part of the benefits with a maximum of € 3 million per year, showing the added value of the instruments. The results of our international survey show that similar results are achievable in other cities as well.

In this thesis we presented planning instruments that facilitate enhanced service reliability. To achieve a higher level of service reliability in practice, we recommend considering service reliability explicitly in the design of infrastructure networks, service networks and timetables using our developed control framework and tools. Service reliability effects should be incorporated in a sophisticated way into cost-benefit analyses of public transport projects, using the average additional travel time per passenger we introduced. This way, welfare gains and additional revenues may be calculated. Optimized strategic and tactical design improves service reliability and also simplifies the operational process with regard to service reliability. Enhanced service planning will allow passengers to benefit from improved service reliability tomorrow!

Samenvatting

Betrouwbaarheid in relatie tot het ontwerp van stedelijk openbaar vervoer

Zowel het regionale als stedelijke personenvervoer is de afgelopen decennia sterk gegroeid. De rol van het openbaar vervoer (OV) in deze toename is beperkt. Deze rol is echter van groot belang om in de toekomst de steden bereikbaar en leefbaar te houden, daarom is een substantiële kwaliteitssprong van het OV noodzakelijk. Door een verhoogde kwaliteit wordt de concurrentiepositie met de auto verbeterd en kan er daadwerkelijk een modal shift plaatsvinden. Deze is wenselijk omdat het OV schoner en veiliger is en daarnaast minder ruimtebeslag kent en congestie kan verminderen. In dit proefschrift laten we zien dat er veelbelovende maatregelen bestaan om de kwaliteit van het OV kostenefficiënt te verhogen, waarbij de focus ligt op betrouwbaarheid. Betrouwbaarheid is de zekerheid van de dienstuitvoering zoals ervaren door de reiziger en is één van de belangrijkste kwaliteitskenmerken van het OV-product. Momenteel is er vooral aandacht voor betrouwbaarheid en het verbeteren daarvan op operationeel niveau. Onze hypothese is dat er tijdens de planning van OV weinig aandacht is voor dit kwaliteitsaspect. Alleen prioriteit bij verkeerslichten en vrije banen worden tijdens het ontwerp van netwerk en dienstregeling expliciet meegenomen om de betrouwbaarheid positief te beïnvloeden. In dit proefschrift laten wij zien dat er meer instrumenten zijn die tijdens het ontwerp kunnen worden ingezet om de betrouwbaarheid van de dienstuitvoering te verbeteren. Daarnaast presenteren wij rekeninstrumenten die wij hebben ontwikkeld om effecten van netwerk- en dienstregelingontwerp op de betrouwbaarheid te kunnen voorspellen. We introduceren een nieuwe indicator om betrouwbaarheid op een goede manier te presenteren, beter dan met de huidige indicatoren, die vooral op het aanbod focussen. Onze focus ligt op de effecten voor de reiziger. Door de nieuwe indicator en rekeninstrumenten zijn kosteneffectieve maatregelen te ontwikkelen die de betrouwbaarheid van stedelijk OV verbeteren.

In dit proefschrift laten we de effecten van een onbetrouwbare dienstuitvoering op reizigers zien. Het gaat dan om drie effecten, namelijk de verlenging van de gemiddelde reistijd, de spreiding van de gemiddelde reistijd en de afname van de zitplaatskans en comfort in het voertuig. Wij demonstreren hoe de variatie van de rijtijden van de voertuigen (i.e. variatie van de dienstuitvoering) doorwerkt in de betrouwbaarheid van de dienstuitvoering en de reistijd van de reiziger. Door empirische analyse van het OV in Den Haag en door ons internationale onderzoek naar betrouwbaarheid in relatie tot planning in andere delen van de wereld, hebben we inzicht gekregen in de mechanismen tussen het aanbod (variatie in voertuigaspecten) en de vraag (betrouwbaarheid voor de reiziger). We presenteren verschillende indicatoren die in de praktijk worden gebruikt voor betrouwbaarheid, zoals stiptheid en regelmaat en laten zien wat de tekortkomingen zijn van deze maten. Dit betreft vooral het feit dat deze indicatoren zijn gericht op de kwaliteit van het aanbod en niet op de kwaliteit voor de reizigers. Hierdoor is geen goede analyse mogelijk van maatregelen die de betrouwbaarheid beïnvloeden. Om hieraan tegemoet te komen, hebben we een nieuwe indicator ontwikkeld, de gemiddelde extra reistijd per reiziger als gevolg van onbetrouwbaarheid. Deze indicator vertaalt de genoemde aanbodindicatoren naar effecten voor de reiziger, zijnde de extra reistijd die een reiziger tussen herkomst en bestemming ervaart omdat de dienstuitvoering onbetrouwbaar is. Deze extra reistijd kan bepaald worden voor een gehele lijn of per halte en maakt het mogelijk om betrouwbaarheid mee te nemen in beoordelingen van maatregelen, zoals in maatschappelijke kosten baten analyses (MKBA's). In ons onderzoek laten we zien dat het gebruik van deze indicator het ontwerp van netwerk en dienstregeling kan optimaliseren en dat het gebruik van traditionele indicatoren kan leiden tot suboptimale oplossingen, met betrekking tot betrouwbaarheid. Naast de extra reistijd laten we ook zien dat de "Reliability Buffer Time"(ontwikkeld door Furth en Muller 2006) goed gebruikt kan worden om de spreiding in de extra reistijd (en bijbehorende onzekere aankomsten) te vertalen naar reizigerseffecten.

Om de betrouwbaarheid van de dienstuitvoering te verbeteren door een beter ontwerp van netwerk en dienstregeling hebben we in ons onderzoek vijf instrumenten onderzocht. Deze instrumenten zijn geselecteerd na een analyse van de oorzaken van onbetrouwbaarheid. Externe oorzaken zijn het weer, ander verkeer, onregelmatig reizigersaanbod en reizigersgedrag. In dit proefschrift laten we zien dat de belangrijkste interne oorzaken bestaan uit ander OV, bestuurders- en chauffeursgedrag, dienstregelingskwaliteit en het ontwerp van netwerk en voertuigen. Omdat het aankomstpatroon van reizigers op de vertrekhalte van groot belang is voor de berekening van betrouwbaarheidseffecten hebben we een reizigersonderzoek uitgevoerd in Den Haag. Dit onderzoek liet zien dat reizigers vanaf een interval van 10 minuten geneigd zijn aselect naar de halte te gaan en in het geval van langere intervallen de dienstregeling raadplegen en daarbij gemiddeld 2 minuten voor het vertrek van het voertuig op de halte zijn.

Op het strategisch niveau zijn de onderzochte instrumenten:

- Ontwerp van eindpunten

  De configuratie van eindpunten, inclusief aantal sporen en wissels, bepaalt deels de verwachte vertraging per voertuig en daarmee de betrouwbaarheid van de dienstuitvoering.

- Lijnlengte

  De lengte van de lijn is over het algemeen van invloed op de mate van spreiding en daarmee op de betrouwbaarheid

- Afstemming tussen lijnen

  Meerdere lijnen op een gezamenlijk traject kunnen een hogere betrouwbaarheid voor reizigers bieden dan één (met eendezelfde totale frequentie)

Voor wat betreft het tactische niveau kunnen de volgende instrumenten ingezet worden voor een betere betrouwbaarheid:

- Rijtijdbepaling
  Als intervallen lang zijn, bepalen de geplande vertrektijden van de voertuigen op de halte (afgeleid van de rijtijd) de aankomst van reizigers op deze (vertrek)halte. Als deze tijd wordt aangepast, verandert de mate van betrouwbaarheid en de wachttijd voor reizigers.

- Voertuigen vasthouden (op wachthaltes)
  Het vasthouden van vroege voertuigen op de halte kan de betrouwbaarheid verhogen. De dienstregeling is van invloed op de effecten hiervan op reizigers.

Het ontwerp van eindpunten betreft (nieuwe) raillijnen met tailtracks als eindpunt of voorzieningen om kort te keren. Voor hoogfrequente lijnen met veel spreiding in rijtijden, raden we compacte tailtracks aan met overloopwissels direct achter de halte. Wanneer (nieuwe) lijnen een duidelijk breekpunt in het reizigerspatroon hebben onderweg, raden we aan om wachthaltes te introduceren of om de lijn in twee delen te splitsen. In het geval van laagfrequente lijnen raden we aan om de rijtijden te ontwerpen op basis van de 35-percentielwaarde van de rijtijd uit een vorige periode. Als een lijn erg druk is op een deel van het traject, is afstemming met andere (korttraject) lijnen een mogelijkheid om de betrouwbaarheid te verbeteren.

Een ruwe kosten-batenanalyse laat zien dat de tactische instrumenten, rijtijdbepaling en het vasthouden van voertuigen, in vele gevallen kosteneffectief zijn. De baten zijn substantieel en extra kosten zijn er nauwelijks en daarom zouden deze instrumenten altijd moeten worden bekeken bij het ontwerp van OV-systemen. Rijtijdbepaling is alleen van belang bij lage frequenties. Het vasthouden van voertuigen op wachthaltes verbetert echter alleen de betrouwbaarheid als er een duidelijk breekpunt in de passagierspatronen over de lijn zijn. In dit proefschrift laten we zien dat de strategische instrumenten ook kosteneffectief kunnen zijn in het verbeteren van de dienstuitvoering. Het is mogelijk om eindpunten te optimaliseren met betrekking tot betrouwbaarheid. Kortere lijnen en afstemming kunnen eveneens de betrouwbaarheid van de dienstuitvoering vergroten. Deze maatregelen lijken vaak kostbaar doordat er extra infrastructuur of voertuigen nodig kunnen zijn, maar wij tonen aan dat deze extra kosten beperkt zijn ten opzichte van de opbrengsten. In een grove schatting laten we zien dat de maatschappelijke kosten van extra reistijd als gevolg van betrouwbaarheid ca. € 12 miljoen per jaar zijn in Den Haag. Met de genoemde maatregelen kunnen deze kosten met ca. € 8 miljoen afnemen, terwijl de kosten hiervoor niet meer dan ca. € 3 miljoen zijn. Ons internationale onderzoek naar betrouwbaarheid in de rest van de wereld laat zien dat soortgelijke winsten ook in andere steden mogelijk zijn.

In dit proefschrift hebben we instrumenten gepresenteerd die tijdens het ontwerp van OV kunnen worden toegepast om de betrouwbaarheid van de dienstuitvoering te vergroten. Wij adviseren betrouwbaarheid expliciet mee te nemen tijdens het ontwerpproces van openbaar vervoer (zowel netwerk als dienstregeling), waarbij ons analysekader en onze rekeninstrumenten kunnen helpen. In maatschappelijke kosten-baten analyses moet betrouwbaarheid op een verantwoorde manier meegenomen worden. Onze indicator, de gemiddelde extra reistijd per reiziger, helpt hierbij, waardoor de maatschappelijke baten en extra inkomsten berekend kunnen worden. Optimale ontwerpen voor netwerk en dienstregeling verbeteren de betrouwbaarheid van het OV en maken de uitvoering minder complex. Door een verbeterd ontwerpproces kunnen reizigers een verhoogde betrouwbaarheid ervaren, morgen al!

Curriculum Vitae

Niels van Oort

Niels van Oort was born on October 16th 1978 in Uden, the Netherlands. After completing secondary school, he enrolled in the Civil Engineering programme at Delft University of Technology in 1997, where he specialized in traffic and transport. He finished his studies in 2003, with a research study of the impacts of public transport planning on actual services. He performed this research in the Research and Development department of HTM, the public transport operator in The Hague, the Netherlands. After his graduation, he joined this department as a researcher. During this time, he was involved in several public transport projects, with a special focus on network and timetable design. Niels cooperated in the launch of a new light rail system, RandstadRail, and was involved in international projects, as a consultant of HTM Consultancy. During this period, Niels conducted much research on impacts of timetable and network design on passengers. In order to gain more insights into this topic, he decided to start a PhD research at the department of Transport and Planning at Delft University of Technology in December 2005 under the supervision of Professor Piet Bovy. He combined his practical work at HTM with scientific research at the university. In 2009, he visited Professor Nigel Wilson at MIT in Boston in order to collaborate on public transport-related research. Niels gave guest lectures at both Delft University of Technology and at the NHTV in Breda (Bachelor traffic and transport). Aside from his job and research, he was a board member of the Jonge Veranderaars of Railforum, a network of young professionals working in the rail and public transport business. In addition, he was a board member of the association of traffic and transport engineers, KIVI NIRIA. At HTM he founded a network of young employees to exchange knowledge and experience. During his research, Niels wrote several papers for both scientific and practical journals and conferences and presented his work worldwide. He also conducted an international survey among international operators, authorities and researchers to gain insights into service reliability issues related to network and timetable planning. In January 2010, he joined Goudappel Coffeng, a Dutch consultancy company. He is involved in several public transport projects, in the Netherlands and abroad. These projects are related to issues such as demand forecasting, quality improvements and network and timetable design. At Goudappel Coffeng, Niels applies the methods and results of his research to improve the level of service reliability of urban public transport in the Netherlands and abroad.

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