

# Assessing Travel Time Reliability in Urban Networks from a Road User Perspective

## A Case Study in the City of Rotterdam

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Master Thesis





# Assessing Travel Time Reliability in Urban Networks from a Road User Perspective

A Case Study in the City of Rotterdam

by

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# Preface

This Master Thesis forms the concluding piece of an eight-year period of being a student in Delft. I retain numerous good memories to this time. I learned many things about civil engineering and transportation, but also about myself. Looking back I think I can say that I underwent a major personal development. For all of this I am very grateful to the people I met and got to know in the bygone years.

Writing this thesis was not the most easy thing for me to do and I am relieved, now that it is finished. Nonetheless, during this process I learned a lot about myself which is not taught in the courses and this helped me to get to know myself and make decisions for the future.

I did not always make it easy for my supervisors, but they did a great job and this research would not have been this successful without their efforts. I would like to thank them very much. I want to thank Goof van de Weg for putting a tremendous effort in supporting my research, his critical reviews of my work, and his valuable suggestions to improve it. I am his first graduation student, and he did a great job. I would also like to thank Victor Knoop, for always being cheerful, honest, and straight to the point. I want to thank Harko Stolte, for his refreshing views on the subject, and for helping me to also focus on the non-technical aspects of writing a thesis.

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*Robin Abma  
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# Summary

Travelers like short travel times. So, from the traveler's perspective, it seems fair to use the mean travel time or mean speed in order to measure the traffic flow performance of a route. However, short travel times might not be the only aspect which is of importance to travelers. It is hypothesized that predictable travel times are also of value to travelers. Hence, the size of variation in travel times, or in other words, Travel Time Reliability (TTR) plays a role in the way that travelers judge the performance of a route, and it is likely that it influences the behavior of travelers as well. When the mean travel time is used as an indicator for the performance of a route, no insight is gained into the size of the variation in travel times within the observed period.

The goal of this research is to develop and evaluate a performance method for routes in urban areas in which Travel Time Reliability is included. This method is called the *project method*. Reasons for this research are: (a) it is hypothesized that TTR influences road user behavior, and insight into this relation provides valuable information for road managers and traffic engineers in order to improve the performance of traffic networks, (b) the field of TTR is fairly unexplored territory, and (c) it is possible to perform extensive data analyses, due to the recent increase in travel time data collection possibilities.

A literature survey is conducted to serve as a first step in reaching this goal. The literature study shows that there has not been much investigation into TTR in urban areas. The reasons for this are that (a) generally, motorways are most equipped with instruments for data collection, and (b) urban environments are more difficult to investigate, because these have more complex traffic interactions than motorways. Another important conclusion from the literature research is that there are three levels of time frames on which TTR can be approached: inter-day, inter-period, and inter-vehicle. For this research, inter-day variations are observed, because deviations from a daily pattern will influence TTR from a road user perspective. Inter-period variations will be known by road users and inter-vehicle variations only have a small influence on travel times. Literature also shows that TTR is defined as: "The ability of the transport system to provide the expected level of service quality, upon which users have organized their activities." This implies that a high TTR does not necessarily mean that travel times on a route are constant during a day, but that travel times that are experienced by road users are approximately equal to their expected travel times.

Although a formal definition of TTR is found, the definition of a TTR measure is ambiguous. Many TTR measures that are found in literature can be used, while there is no theoretical reason to justify selection of one TTR measure over another. All TTR measures that are found are evaluated on the basis of both general criteria for a good TTR measure and specific criteria which the project method should meet.

Comparison of the TTR measures leads to the selection of the measures of which the project method is constructed. The project method consists of three measures, assessing the following attributes: (1) average conditions, (2) size of the variation in travel times, and (3) the occurrence of extreme travel times. An important feature of the project method is that it divides the day into three periods: morning peak, inter-peak, and evening peak. This is done because according to the definition, TTR should be measured relative to the user expectation. It is assumed that the travel time expectations of road users are equal to the mean travel time and within these periods the mean travel time is approximately constant. This division in three parts also provides a more detailed insight into the performance of a route during the day.

In order to find the relation between the assessment of a route by the project method and the judgment of a route by road users, a stated preference survey is conducted among a small group of respondents. With the results, a linear model which predicts the road user judgment of route performance, based on the outcomes of the project method. This is called the *user model*. The user model shows that both a higher mean speed and a lower variability in travel times increases the performance grade given by road users. However, the influence of the variability is relatively small, when compared to the influence of the mean speed. Extreme travel times seem to have no significant effect on the performance grade of a route, given by road users.

The final step in the process is to find whether the project method gives an improved insight into the performance of urban routes, compared to the method which is currently used in the city of Rotterdam. The latter uses average speeds, calculated over a quarter of a year. The project method and the current method are compared by means of a case study. In this case study, real travel time data from two routes in Rotterdam is used. From the case study, two major conclusions are drawn. First, the current method can overestimate mean speeds in the peak hours, and the error becomes larger when the mean speed on a route varies strongly within a day. This is due to the fact that weekends are also involved in the current method, in which the speed is generally higher, and the start and end times of the peak periods are chosen differently. Second, the current method barely shows the influence of a low TTR. Hence, the project method gives a more accurate and detailed insight into the performance of a route.

Since the case study shows that the project method provides a more accurate and detailed insight into the performance of a route, it is recommended to use it in practice. It can be used in Rotterdam, but also in other cities for which travel time data is available.

In order to improve the knowledge in the field of Travel Time Reliability, the following directions for further research are suggested. First, in this research it was assumed that TTR has an impact on the behavior of road users. However, it is uncertain how and to what extent TTR influences the behavior of road users. Insight into this relation provides valuable information for network providers and traffic engineers, and it is therefore recommended to investigate this. Likewise, it is recommended to investigate which factors influence TTR and how the relation between these factors and TTR is defined. Finally, there are several options to improve the user model. Conducting a revealed preference survey on a large group of respondents will help to get a more reliable model. Also, it could be useful to make a distinction between user groups, since the value of reliability may differ between these groups. Moreover, there might be other factors which influence how road users grade the performance of a route, such as: time of day, specific route characteristics, alignment of the road, traffic intensity, and the surroundings of a route. It is recommended to investigate how these factors influence the judgment of the performance of a route by road users.



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# 1

## Introduction

In this day and age, the world is changing rapidly: technological breakthroughs happen in quick succession and have a large impact on peoples lives. People live in prosperity and this increases their demands. This also applies to the field of traffic & transportation. Travelers demand short, but also reliable travel times. Complex logistic processes also require companies to have reliable travel times. This research focuses on Travel Time Reliability (TTR) and investigates how TTR can be used to assess the performance of urban routes.

The mean travel time or mean speed that is realized on a route is regularly used in practice as a performance indicator. However, this method has a flaw. Travel times on a route can strongly fluctuate within a measurement period. Observing the mean speed does not give insight into the size of this variation. Moreover, a large variation in travel times can make it very hard for travelers to predict travel times.

It is hypothesized that the size of this variation in travel times influences the behavior of road users (König and Axhausen, 2002). This might have an effect on: destination choice, route choice, departure time choice, and mode choice. The relation between variation in travel times and road user behavior is important to road network managers and traffic engineers, because this provides them with possibilities to influence the behavior of road users, in order to improve the performance of a road network.

Travel Time Reliability is defined as: *"the extent to which travelers are able to correctly predict travel times"*. Most travelers will – knowingly or unknowingly – predict the travel time of a trip they will make, so that it can be fitted into their planning (Bogers, 2009). This prediction is influenced by factors, such as: familiarity with the route, time of day, traffic information, and weather. When the variation in travel times increases, the chance that the realized travel time deviates from the predicted travel time increases, and therefore TTR decreases. In such a case, travelers will either have an increased probability of arriving late at their destination or they will have to plan extra time for their trip in order to make sure that they will arrive on time. Arriving late is inconvenient and planning extra time virtually increases the travel time. Therefore, from a traveler's perspective, a high TTR is desirable.

Hence, it is possible to have a situation in which the average travel time improves over a certain period, while the TTR decreases. We have already stated that it is likely that both average travel times and TTR are important to travelers. Thus, overall this situation can have a negative effect on the appreciation of the route by travelers, while the performance method which only takes average speed into account shows an improved result. Therefore, in order to have a performance method which is in line with the judgment of the road user, it seems appropriate to include TTR in a performance method for a route.

The use of TTR as a performance indicator is fairly unexplored territory. In order to bridge this gap, the goal of this Master Thesis is to develop and evaluate a method to assess the performance of routes in urban areas, which takes Travel Time Reliability into account.

### 1.1. Background

In order to be able to comprehend the objectives of this investigation, it is important to understand the concept of Travel Time Reliability. This concept is explained in this section. Subsequently, the

importance of TTR in general and for the *Gemeente Rotterdam* in particular is explained.

### 1.1.1. What is Travel Time Reliability?

Dictionary (2013) defines *reliable* as: "*consistently good in quality or performance; able to be trusted*". Apparently, there are actually two slightly different definitions. Considering the first definition, a reliable travel time for a certain route would be a constant travel time, whatever the circumstances are. However, the second definition implies something different, since a traveler can *trust* on an on-time arrival when travel times are *predictable*. This does not necessarily imply a constant travel time for a route, because different circumstances can influence expectations of the traveler. For example, in case of a heavy snow storm, car drivers will generally expect a longer travel time than in a situation with good weather conditions.

This predictability is an important feature. FHWA (2005) states that by its very nature, roadway performance is consistent and repetitive, and yet highly variable and unpredictable. It is consistent and repetitive in the sense that peak usage periods occur regularly and can be predicted with a high degree of reliability, both by traffic engineers and road users. For instance, the relative size and timing of morning and evening peaks is well known in most communities. At the same time, roadway performance is highly variable and unpredictable. On any given day, unforeseeable circumstances such as a small increase in traffic intensity, individual road user behavior, crashes and other calamities, bad weather, and road works, can dramatically change the performance of the roadway, affecting both travel speeds and throughput volumes.

Hence, travel times on a route will show a fixed pattern, but unforeseeable circumstances can lead to serious deviations from this pattern. The more often these deviations occur and the more severe they are, the less predictable and thus the less reliable travel times are.

OECD (2010) provides a general definition for Travel Time Reliability which fits in with these considerations:

*The ability of the transport system to provide the expected level of service quality, upon which users have organized their activities.*

The key of this definition is that the expectations of the user are in accordance with the experienced travel time. For example: most road users will expect a longer travel time in a large city when they plan to make a trip during the morning peak than when they want to drive at night. Hence, *reliability* is equivalent to *predictability* of travel time for a certain trip. In other words: the better a realized travel time corresponds to the predicted travel time, the higher the TTR.

### 1.1.2. The Importance of Travel Time Reliability

Martchouk *et al.* (2009) states that in the past, travel time has always been the most important measure associated with the effectiveness of a transportation system. However, recently a single measure of travel time has become insufficient. This has several reasons.

First of all, Bremmer *et al.* (2004) states that Travel Time Reliability and predictability is of utmost importance to the public and is often of even greater concern than the travel time itself. Variability in travel times leads to uncertainty that commuters and haulers find frustrating and costly.

Also, OECD (2010) explains that changes in commerce and personal travel patterns have increased the importance of reliable transport systems. Reliable transport networks and services are required because of more complex and inter-related supply chains and increasingly complex scheduled activities. These are the result of economic developments and lifestyle changes. For example, factories use *just in time deliveries* in order to reduce stock costs, and people face changing patterns of employment as well as increased disposable income, recreational choices and leisure time.

Furthermore, there has been a rapid development of communication and other technologies over the past decades. This has led to a culture in which people expect to continuously receive up-to-date and reliable information that is desired at any moment. This also applies to traveling information; think of existing route planners which use real-time congestion data in order to give travel time predictions as well as route advice. Hence, TTR starts to play an increasingly important role.

Finally, FHWA (2005) states that people may add a buffer to their travel time, in order to increase the probability that they arrive at their destination on time. Consequently, these travelers will arrive early on some occasions. This is not necessarily undesirable, but the extra time is still carved out of their day, while this time could have been used for other pursuits.

## 1.2. Interest of the *Gemeente Rotterdam* in Travel Time Reliability

The *Gemeente Rotterdam* is responsible for providing a well-functioning road network to inhabitants of Rotterdam and other people who wish to use Rotterdam's urban road network. In order to meet this goal, the *Gemeente Rotterdam* constructs new roads, maintains existing roads and applies traffic management measures.

In order to monitor the performance of the main roads within the city, the *Gemeente Rotterdam* uses a flow objective. This objective states that cars on the city's main routes should travel with a mean speed of at least 25 km/h (*Gemeente Rotterdam*, 2003). This mean speed is determined on the basis of continuous travel time measurements. Hence, the calculated speed includes delays caused by signalized intersections and disturbances. The calculation procedure that the *Gemeente Rotterdam* currently uses to evaluate the flow objective is explained in detail in appendix A.

However, the performance of these main routes is averaged over each quarter of the year. Hence, it does not provide information on the variation of travel time within this period. Also, it does not correspond with the Travel Time Reliability definition (see 1.1.1), as it does not give any information on whether the achieved levels of service over time meet the expectations of the travelers.

Therefore, the *Gemeente Rotterdam* wants to gain insight into the TTR for road vehicles on the 7 main routes. These main routes were previously defined by the *Gemeente Rotterdam* – see section 5.2 for more detailed information. Furthermore, there is the desire to formulate a new flow objective, which, besides mean speed, takes TTR into account. This will provide a better insight into the performance of the routes from a traveler's perspective.

## 1.3. Research Objectives

Considering the preceding information and reasoning, the main objective of this Master Thesis is:

**Develop and evaluate a performance method for routes in urban areas,  
in which Travel Time Reliability is included.**

The following sub-objectives are set to reach the main objective:

### Sub-objective 1

Establish an overview of useful insights into the field of Travel Time Reliability.

### Sub-objective 2

Determine which measures of Travel Time Reliability are available and evaluate these.

### Sub-objective 3

Develop a new method to assess the performance of a route, in which Travel Time Reliability is included (the *project method*).

### Sub-objective 4

Develop a model to describe the relation between the project model and the judgment of a route by road users (the *user model*).

### Sub-objective 5

Evaluate the project method by analyzing travel time data of the main routes in Rotterdam, and comparing the results to the results of the current method (case study).

## 1.4. Scope

Although the sub-objectives were formulated in the previous section, there is still a variety of possibilities for the elaboration of this research. This section explains the focus and limitations of the research.

### Focus on the city of Rotterdam

This research uses travel time data from the city of Rotterdam. So, the analysis is limited in a geographical sense. Also, the focus is on urban routes. Highways have different characteristics, so that the methods from this research cannot directly be used there. However, the developed performance method might also be used in other urban areas.

### Focus on the road user perspective

Network managers and road users might have different interests in, and views on route performance. For instance, a network manager will focus on the performance of the complete network and the traffic flow mechanisms and phenomena that occur. Furthermore, the network manager might have an interest in the economic performance of the network or route. Conversely, a road user will focus on its individual travel times on a single route. This research will use the road user perspective, because it is impossible to investigate multiple aspects in this Master Thesis and the *Gemeente Rotterdam* (the network manager) also has, among other things, an interest in how road users value TTR. However, this implies that it does not necessarily mean that the whole network performs well from a traffic flow or economic perspective, when a route receives a high performance score according to the results in this research.

### Focus on inter-day variation

There are different levels on which TTR can be studied. The first level is a variation in travel times between individual vehicles. However, it is assumed that these variations are minor and do not influence the judgment of the route performance by travelers. Also, there is a variation in travel times within a day. Nonetheless, it is assumed that these variations are more or less predictable and hence do not influence the type of TTR that was discussed in the previous sections. This research focuses on the third level of variation, namely inter-day variation. This is the variation in travel times between different days, which is less predictable and hence influences the judgment of the road users.

## 1.5. Research Approach and Document Outline

The focus of this research will be on urban areas. This research will be performed in cooperation with the *Gemeente Rotterdam*. It consists of a theoretical and a practical part. The theoretical part includes defining TTR and creating the project method, in which TTR is included and assessed from the perspective of road user. Subsequently, a case study is conducted. In this practical part, the findings from the first part will be used to assess the functioning of the project method. This is done by means of analyses, using real travel time data. Furthermore, the value of travel time reliability to road users is investigated. This is done by means of a survey in which respondents rate different combinations of realized travel times on a route.

The sub-objectives that were set in section 1.3 define the structure of this report. Figure 1.1 shows this structure.

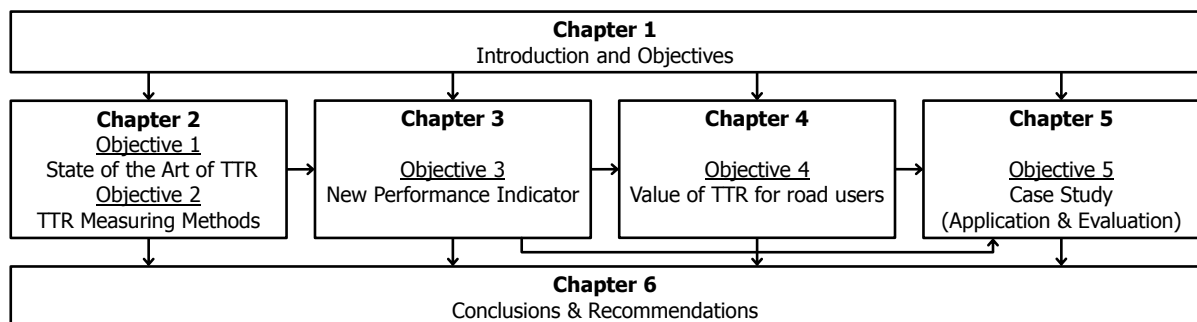


Figure 1.1: Overview of the report structure. The arrows indicate the relations between chapters.

In order to describe the state of the art (sub-objective 1) and give an overview of the available methods to measure TTR (sub-objective 2), a literature survey is performed. In order to reach sub-objective 1, discussion with colleagues from the *Gemeente Rotterdam* is also used, for the choice of a measure depends on what information the *Gemeente Rotterdam* wants. The results of this literature study are described in chapter 2. Based on the results of the literature survey, the project method (sub-objective 3) is designed. This is explained in chapter 3. In chapter 4, the judgment of the road user is involved when this is related to the project method with the user model (sub-objective 4). This is done by means of a linear regression based on a survey. Finally, the project method is evaluated by means of a case study (sub-objective 5), which is described and performed in chapter 5.

# 2

## State of the Art and Measures of Travel Time Reliability

This chapter provides an overview of the literature on TTR. Essentially, the state of the art of TTR is described. Special attention is paid to methods which measure TTR. Altogether, the literature survey serves a starting point for defining the project method, to determine route performance, which is detailed in chapter 3.

### 2.1. Introduction

The literature survey is conducted in order to reach sub-objectives 1 and 2, which were set in section 1.3: *"Establish an overview of useful insights into the field of Travel Time Reliability."* and *"Determine which measures of Travel Time Reliability are available and evaluate these."* In order to meet these sub-objectives, the following steps are made:

1. Describe the state of the art in Travel Time Reliability (section 2.2). In this step, a description of the emergence of TTR as a performance indicator is provided. Furthermore, it shows which lessons are learned from previous investigations. This is done by reviewing analysis methods and conclusions from several investigations.
2. Find the methods that are used to measure TTR and determine their properties (section 2.3). This part provides a range of TTR measures that were developed and used in previous investigations. Subsequently, the relevant characteristics of these measures are determined. Furthermore, an explanation of criteria which the project method should satisfy is provided.

### 2.2. State of the Art of Travel Time Reliability

This section starts with answering the question why and how TTR has become important. Next, lessons that have been learned from previous investigations into TTR are detailed. Finally, a reference case is discussed in order to observe what can be learned from previous investigations.

#### 2.2.1. The Emergence of Travel Time Reliability as a Performance Measure

Hellinga (2011) states that in the past, analysis of transportation networks focused primarily on the estimation and evaluation of average conditions for a given time period. These average conditions might be expressed in terms of average traffic stream speed; average travel time between a given origin and destination pair; or some average generalized cost to travel from an origin to a destination. This generalized cost typically includes terms reflecting time as well as monetary costs. These terms are summed by multiplying the time based measures by a value of time coefficient. A common characteristic

of all of these approaches is that they reflect average or expected conditions and do not reflect the impact of the variability of these conditions. One reason for this is that models become much more complicated when this variability would be included. Also, a vast amount of data from a long period of time is needed. Unfortunately, collecting data is often costly and time-consuming.

Hellinga (2011) also observes that more recently, there has been an increasing interest in the reliability of transportation networks. It is hypothesized that reliability has value to transportation network users and may also impact user behavior. Influence on traveler behavior may include: destination choice, route choice, time of departure choice, and mode choice. It is useful for road managers and planners to have knowledge about the relations between TTR and road user behavior, because this can be used to predict or even deliberately influence this behavior by applying traffic management measures. Consequently, there has been an effort to better understand the issues surrounding reliability, and to answer a number of important questions such as:

1. How is transportation network reliability defined?
2. How can/should network reliability be measured in the field?
3. What factors influence reliability and how?
4. What instruments are available to network managers, policy makers, and network users that impact reliability and what are the characteristics of these causal relationships?
5. What is the value of reliability to various transportation network users (e.g. travelers, freight carriers, etc.) and how is this value affected by trip purpose?
6. How do transportation network users respond to reliability in terms of their travel behavior? (E.g. departure time choice, mode choice, route choice etc.)
7. How can reliability (and its effects) be represented within micro and macro level models? (Microscopic models focus on individual vehicles, while macroscopic models pertain to the properties of the traffic flow as a whole.)
8. How important is it to consider the impact of reliability in transportation project benefit/cost evaluations?
9. Does the consideration of the impact of reliability within the project evaluation process alter the order of preference of projects within the list of candidate projects?

Hellinga (2011) states that the above list of questions, which is likely not exhaustive, indicates that there currently exists a very large knowledge gap with respect to reliability. Various research efforts around the world are beginning to fill in these gaps, but the body of knowledge is still relatively sparse and there is not yet even general agreement on terminology. Note that the first, second, and (partially) fifth question are part of this investigation.

### **2.2.2. What is Learned from Previous Investigations**

Even though there are still many questions open in the field of Travel Time Reliability, some investigations were already performed. These can provide valuable information for this research and can serve as a starting point for this research project.

#### **Definition of Travel Time Reliability**

As mentioned in section 1.1.1, the OECD (2010) provides a general definition for Travel Time Reliability:

*The ability of the transport system to provide the expected level of service quality, upon which users have organized their activities.*

The key of this definition is that a route is reliable if the expectations of the user are in accordance with the experienced travel time. But this does not directly lead to a TTR measure. Nonetheless, this definition shows that user expectations should be taken into account when selecting a proper TTR measure.



### Research in Urban Areas

There are differences between the characteristics of roads in urban areas and motorways, which may lead to different approaches and conclusions when investigating TTR. These characteristics include: mean speed, speed differences between vehicles, intersections, and lane configurations.

There is a large research gap for Travel Time Reliability in urban areas. Most of the research has focused on motorways. As (Hellinga, 2011) points out, the reason for this is that freeways are most commonly equipped with instruments for data collection. However, the *Gemeente Rotterdam* has continuously been collecting travel time data from the urban roads from Rotterdam over the past few years (Vialis, 2007), which are very useful for this investigation. Hence, data is not a limiting factor in this investigation, thus there is potential to gain new insights.

Another reason for the initial focus on motorways is that an urban environment has more complex traffic interactions than a highway. Therefore, urban environments will be more difficult to investigate. However, the importance of and interest in TTR grows also in urban areas.

### Time Frames for TTR

Travel Time Reliability can be categorized by its time frame. Bates *et al.* (2001) discusses three levels of variability: inter-day, inter-period and inter-vehicle. Martchouk *et al.* (2009) explains these as follows:

- Inter-day: Variations in the travel time pattern between days. Some days of the week might have substantially different traffic volumes than others. For example, a Sunday will generally have less traffic than a Monday. Same weekdays should have about the same travel time pattern, but there can still be variations. Also, events such as road works or inclement weather cause inter-day variations.
- Inter-period: Variations in travel times during a day. Many road sections have a morning and evening peak, during which travel times are larger. These variations are caused by variations in traffic volume.
- Inter-vehicle: Relatively small differences in travel times between vehicles in a traffic stream. These are caused by interactions between vehicles and variations in driver behavior, including lane changes and speed differences.

Although Martchouk *et al.* (2009) shows that individual travel times on a motorway section can vary strongly in similar conditions, due to driver behavior, this study focuses on inter-day variations. It is assumed that inter-vehicle variations have no significant influence on Travel Time Reliability. In urban areas, the speed difference between vehicles will generally be smaller than on highways. The reasons for this are: the average speed on highways is higher, there is more overtaking, trucks cannot drive at the maximum allowed speed, and routes are longer.

Inter-period variations are also not considered, because it is presumed that road users know that travel times within a day vary according to a more or less fixed pattern.

It is the deviations from this daily pattern which are interesting in the light of TTR, since these cannot be predicted by road users. Therefore, the focus of this investigation is on inter-day variation.

### 2.2.3. Reference Case of Travel Time Reliability Research

This section gives an example of an investigation performed on Travel Time Reliability. This will help to generate ideas for the execution of the Rotterdam case study. Also, conclusions from this case are used as a starting point for the remainder of this research.

#### Analysis of Travel Time Reliability on Indiana Interstates (Martchouk *et al.*, 2009)

Martchouk *et al.* (2009) performed an investigation on the motorway Interstate-69 in the state of Indiana, USA. The first goal of this research was to determine whether data collection via *Bluetooth* can provide correct and useful data. The second objective was to observe daily and inter-daily variations as well as those due to poor weather conditions and estimate econometric models to predict travel time and variability.

The study of Martchouk *et al.* (2009) includes a comparison between travel times and standard deviations of travel time on a motorway section which were collected on two subsequent Mondays. The average travel time and the standard deviation of travel time were determined for every hour during these days. Subsequently, a t-test was executed for every hour to determine if there is a

significant difference in mean travel times. The results suggested that for that particular situation it is incorrect to assume that the travel times are identical for same days of the week. Major differences occur, especially at peak hours. This can be explained by the fact that traffic flow is unpredictable in congested conditions.

Similarly, standard deviations of the travel times between every hour of the two days were compared using the F-test. Similar to the mean speeds, standard deviations were significantly different in different periods. And again, the differences are larger in the peak hours.

The conclusion is that it may be incorrect to group travel times by day of the week as is often done in studies.

Martchouk *et al.* (2009) also investigated non-recurrent variability due to adverse weather. The impact of adverse weather was evaluated by collecting travel time data during a snowstorm and comparing them to a dataset collected during normal weather conditions. When plotting the data, it seemed that travel times increased during the snowstorm and were back to a normal level in about 6 hours after the snowstorm ceased. The comparison was done in a similar way as comparing the two Mondays. A mean speed was calculated for every hour and the hours of the two days were compared using a t-test. The experiment indicated that for 38 out of 40 hours considered, the average travel times are significantly different at a 90% significance level.

In addition to an increase in the average travel time, the variance in travel times during the same time period also rises. F-tests indicated that for all the observed hours, the variance in travel times is significantly different with a confidence interval of 90 %.

In conclusion, adverse weather conditions such as a snow storm, results in higher travel times and an increased standard deviation of travel time. This effect may last hours after the event, depending on the severity and resulting road conditions.

## 2.3. Overview and Evaluation of Measures of Travel Time Reliability

The first part of this chapter described the state of the art of TTR. The remainder of this chapter focuses on TTR measures.

The definition of a measure for Travel Time Reliability is not unambiguous; researchers tend to use different measures. Until now, no reasons are found to favor one measure over another in general, since one measure is not intrinsically better than the other. However, different measures provide different information. Hence, a measure or set of measures that is chosen should satisfy the requirements, which will be explained in detail later on in this chapter.

In this section, first, known TTR measures are listed and explained (subsection 2.3.1). Subsequently, in subsection 2.3.2 the relevant characteristics of these measures are described. The next subsection (2.3.3) lists and explains the criteria for a useful TTR measure. Finally, a comparison between the TTR measures is made in subsection 2.3.4. Subsequently, the choice for a measure that will be used in the analysis is made in chapter 3.

### 2.3.1. Available Measures of Travel Time Reliability

Hellinga (2011) has given an overview of TTR measures which are used in practice. These are presented here, together with explanations and examples. All the measures are calculated per route and per direction.

#### Buffer Index (BI)

The Buffer Index is the difference between the 95th percentile travel time and the average travel time, normalized by the average travel time. (Lomax *et al.*, 2003)

$$BI = \frac{t^{95\%} - \bar{t}}{\bar{t}} \quad (2.1)$$

The outcome of this formula is extra time needed to be on time in 95% of the cases, expressed as a percentage of the mean travel time. The larger this percentage, the larger the relative difference between the mean travel time and the 95-percentile travel time, and hence the larger the variability in travel times.

*Example: On a certain route, travel times of a few months are measured and stored. From the data, it is calculated that the mean travel time is 8 minutes and the 95-percentile is at 15 minutes. This means that an extra 87.5% time of the mean travel time is needed in order to be on time in 95% of the cases.*

### Buffer Index 2 (BI\*)

A second version of the Buffer Index is the difference between the 95th percentile travel time and the median travel time, normalized by the median travel time. (SHRP, 2010)

$$BI^* = \frac{t^{95\%} - t^{50\%}}{t^{50\%}} \quad (2.2)$$

The BI\* is similar to the BI, but the median travel time is used instead of the mean travel time. Thus, the extra time needed to be on time in 95% of the trips is expressed as a percentage of the median travel time. The outcomes are similar when the distribution of travel times is symmetrical. The differences between BI and BI\* become larger when the distribution of travel times is more skewed. Travel time distributions are generally skewed to the right, as delays can occur without a limit, but vehicles cannot have shorter travel times than the free flow travel time. This means that the median travel time will be equal to or lower than the mean travel time, but never higher. This makes the difference between  $t^{95\%}$  and  $t^{50\%}$  generally larger than the difference between  $t^{95\%}$  and  $\bar{t}$ . Hence, the BI\* will be equal to or larger than BI, but never smaller.

*Example: On a certain route, travel times of a few months are measured and stored. From the data, it is calculated that the median travel time is 6 minutes and the 95-percentile is at 15 minutes. This means that an extra 150% time of the median travel time is needed in order to be on time in 95% of the cases.*

### Planning Time Index (PTI)

The Planning Time Index is the ratio of the 95th percentile travel time to the free flow travel time. (Lomax *et al.*, 2003)

$$PTI = \frac{t^{95\%}}{t^f} \quad (2.3)$$

This value represents the time required to ensure that the traveler arrives on-time in at least 95% of the trips, expressed as a percentage of the free flow travel time. The larger this percentage, the larger the relative difference between the free flow travel time and the 95-percentile travel time.

*Example: It is known that on a certain route the free flow travel time is 4 minutes and the 95-percentile is at 15 minutes. This means that a travel time which is 375% of the free flow travel time is needed in order to be on time in 95% of the cases.*

### Misery Index (MI)

The Misery Index is calculated by taking the average of the highest five percent of travel times and dividing this by the free-flow travel time. (Lomax *et al.*, 2003)

$$MI = \frac{t'}{t^f} \quad (2.4)$$

The outcome of this measure tells something about how bad the worst trips are compared to the free flow travel time. The minimum and best value is 1. The larger this value is, the worse the 5% longest trips are, compared to the free flow travel time.

*Example: On a certain route, the free flow travel time is 4 minutes and the average of the 5% worst trips is 20 minutes. This gives a misery index of 5.*

### On Time Probability (OTP)

This is the probability that a traveler will experience a travel time that is less than  $x$  minutes different from the median travel time. (Kouwenhoven *et al.*, 2005)

$$OTP = \begin{cases} P(|t_i - t^{50\%}| < 10 \text{ minutes}) & \text{if } \bar{t} \leq 50 \text{ minutes} \\ P(|t_i - t^{50\%}| < 0.2t^{50\%}) & \text{otherwise} \end{cases} \quad (2.5)$$

There are two different cases when one uses this formula. If the average travel time is 50 minutes or less, then the outcome is the probability that a the difference between a realized travel time and the median travel time is smaller than 10 minutes. In the situation with a mean travel time larger than 50 minutes, the outcome is the probability that the difference between a realized travel time and the median travel time is larger than 0.2 times the median travel time. This implies that for trips longer than 50 minutes, the absolute margin increases as the mean travel time increases. The outcome tells something about how many trips are close to the median travel time, with a certain margin. The value lies between 0 and 1. A value close to 0 means that there are a lot of travel times which strongly deviate from the median travel time and TTR is small. A value close to 1 means that the realized travel times are concentrated around the median travel time and TTR is large.

*Example: The mean travel time on a road section is 18 minutes. The median travel time is 16 minutes. On the basis of many observed trips, the probability that a certain trip takes between 6 and 26 minutes can be calculated.*

### Not Long Probability (NLP)

NLP gives the probability that a traveler will experience a travel time that is not “too long” where this is defined as not more than  $x$  minutes longer than the median travel time (Kouwenhoven *et al.*, 2005)

$$NLP = \begin{cases} P(t_i - t^{50\%} < 10 \text{ minutes}) & \text{if } \bar{t} \leq 50 \text{ minutes} \\ P(t_i - t^{50\%} < 0.2t^{50\%}) & \text{otherwise} \end{cases} \quad (2.6)$$

This measure is similar to the *On Time Probability*, with the only difference that the NLP only takes travel times into account that are “too long”, while OTP also uses travel times that are “too short”. The use of NLP presumes that travelers only find travel time unreliable when it is much longer than the median travel time, while the use of OTP assumes that road users also find a travel time that is much shorter than they expected unreliable. The outcome tells something about how many trips are not longer than the median travel time, with a certain margin. The value lies between 0 and 1. A value close to 0 means that there are a lot of travel times which are much longer than the median travel time and TTR is small. A value close to 1 means that the realized travel times are concentrated around the median travel time and TTR is large.

*Example: The mean travel time on a road section is 18 minutes. The median travel time is 16 minutes. On the basis of many observed trips, the probability that a certain trip takes no longer than 26 minutes can be calculated.*

### Standard Deviation (STD)

This is a measure of the variance of the data about the mean value.

$$\sigma = \sqrt{\frac{1}{M-1} \sum_{i=1}^M (t_i - \bar{t})^2} \quad (2.7)$$

The STD is a measure which is often used in statistics. It shows how much variation from the average exists. A low standard deviation indicates that the observed travel times tend to be close to the mean; a high standard deviation indicates that the observed travel times are spread out over a large range of values.

*Example: Imagine that 5 travel times are observed on a road section. These are (in seconds) 123, 186, 79, 205 and 230. The average travel time is then 165 s. The standard deviation is 62 s. Of course, in practice a larger dataset should be used in order to get more reliable results.*

### Coefficient of Variation (COV)

The COV is the standard deviation of travel times normalized by the mean of travel times. (Lomax *et al.*, 2003)

$$COV = \frac{\sigma}{\bar{t}} \quad (2.8)$$

This measure divides the STD by the mean of observed travel times. This gives an indication of the standard deviation relative to the mean. This is relevant, because a deviation of 10 minutes on a 3

hour trip will be perceived less inconvenient than a deviation of 10 minutes on a 10 minute trip. A value close to 0 indicates a relatively low spread of travel times, while a large value indicates a spread of travel times that is relatively high.

*Example: Using the data that are used in the STD example, the COV is 0.38.*

### Skew Statistic (SS)

The Skew Statistic is the ratio of the difference between the 90 th percentile travel time and the median travel time to the difference between the median travel time and the 10 th percentile travel time. (Lint *et al.*, 2008)

$$\lambda^{skew} = \frac{t^{90\%} - t^{50\%}}{t^{50\%} - t^{10\%}} \quad (2.9)$$

This TTR measure tells something about the skewness of the travel time distribution. When  $\lambda^{skew}$  lies between 0 and 1, the distribution is left-skewed. When  $\lambda^{skew}$  is larger than 1, the distribution is right-skewed. When the outcome is 1, the distribution is symmetrical. Since  $\lambda^{skew}$  is a ratio it can be interpreted and applied regardless of the absolute magnitude of travel times. In terms of reliability this is very relevant: a deviation of 5 minutes on a trip of two hours would not be interpreted as an indication of unreliability, while a five-minute delay on a trip, which on average takes five minutes, certainly would. It is therefore argued that large values of  $\lambda^{skew}$  should be interpreted as unreliable, since it implies that at least in 10% of the cases travel times occurred that are significantly larger than median.

*Example: On a certain route, the median travel time is 10 minutes, while  $t^{90\%}$  is 18 minutes and  $t^{10\%}$  is 8 minutes. Thus  $\lambda^{skew}$  equals 4, which means that the travel time distribution is strongly right-skewed.*

### Width Statistic (WS)

The Width Statistic is the difference between the 90 th percentile travel time and the 10th percentile travel time, normalized by the median travel time. (Lint *et al.*, 2008)

$$\lambda^{width} = \frac{t^{90\%} - t^{10\%}}{t^{50\%}} \quad (2.10)$$

As explained, if  $\lambda^{width}$  equals 1 the travel time distribution is symmetric. In such a case the width of the distribution can be used in order to say something about reliability. The wider the distribution is (relative to the median), the larger the range of travel times that may occur and hence the lower TTR. The closer the outcome is to 0, the smaller the distribution of travel times and hence the higher the TTR.

*Example: Assume a route with a median travel time of 10 minutes a  $t^{10\%}$  of 8 minutes and a  $t^{90\%}$  of 12 minutes. Hence,  $\lambda^{skew}$  equals 1 in this case and  $\lambda^{width}$  equals 0.4. This means that the distribution of travel times is quite small and that the TTR is thus quite high.*

### Unreliability Index (UI)

This is a measure of the likelihood of experiencing a very long travel time (Lint *et al.*, 2008)

$$UI = \begin{cases} \frac{\lambda^{width} \ln(\lambda^{skew})}{L} & \text{if } \lambda^{skew} > 1 \\ \frac{\lambda^{width}}{L} & \text{otherwise} \end{cases} \quad (2.11)$$

For different freeway stretches the values for  $\lambda^{skew}$  and  $\lambda^{width}$  may be very different; for example,  $\lambda^{width}$  values around 1 are not likely on very long road stretches. In order to get rid of this "location-specificity", the outcome is divided by the route length  $L$ , implying we interpret travel time per unit length.

*Example: Assume the same information as given in the SS example and a route length of 5.5 km.  $\lambda^{skew} = 4 > 1$ , so the first option is chosen. Furthermore,  $\lambda^{width} = 1$ . This gives an UI of 0.25.*

## 2.3.2. Characteristics of Travel Time Reliability Measures

In this section, the properties of the different TTR measures and ways to classify these are explained. Subsequently, these are used to compare the TTR measures with one another. (see section 2.3.4)

### Perspective

Hellinga (2011) notes that typically there are two perspectives when Travel Time Reliability is considered:

- The perspective of the **service provider**
- The perspective of the **service user**

The measures of the service provider (in this case the *Gemeente Rotterdam*) are focused on the network and its performance with respect to serving the transportation demands at some minimum acceptable quality of service. Possible measures include:

1. The fraction of trips that are served at some defined minimum quality of service.
2. Mean time to failure, where failure is defined in terms of a quality of service less than some threshold.
3. Fraction of time at which the network operates above some defined level of service.
4. The degree to which the network is able to satisfy the travel demand even when temporary capacity reductions may exist as a result of incidents, maintenance, unplanned events, etc.

Conversely, the service user (road user) focuses on trip characteristics and not on network characteristics. The only characteristics that have been consistently viewed as significant are those that relate to travel time. Hence, reliability from a traveler's perspective is most often expressed in terms of the variability of trip travel times.

As was already mentioned in section 1.4, this research will focus on the service user perspective. Hence, when selecting a measure, whether or not a measure uses the perspective of the road user plays a role.

### Categories

A different way to label the TTR measures is by the type of method that is used. Tu (2008) defines 5 categories of Travel Time Reliability Measures:

1. **Statistical Range Methods**, which describe reliability in terms of some measure of the variance associated with the distribution. Martchouk *et al.* (2009) states that statistical measures are effective in communicating the extent of unreliability to professionals. Nonetheless, these may not be meaningful to users because it is difficult for individuals to apply the concept of standard deviation to their individual travel time. *Statistical Range Methods* are also unable to capture variation due to different events separately, thus providing a very general measure of reliability for the roadway.
2. **Buffer Time Methods** capture the extra time required by a traveler to ensure that they arrive prior to some preferred arrival time with some level of confidence. Martchouk *et al.* (2009) states that most users can relate to buffer time methods because when planning a trip one would like to arrive on time in a vast majority of situations. The 95th percentile travel time ensures the user is only late 1 out of every 20 trips. The buffer measures can be used to calculate a single value of reliability for the road segment or different values that depend on time of day and day of the week.
3. **"Tardy Trip" Methods** reflect the travel times of some portion of the worst trips relative to the average or expected trip travel time. Hence, these methods assume that extremely long trips have the most impact on road users judgment, whereas the smaller variations do not have a large impact. Note that in both *Statistical Range Methods* and *Buffer Time Methods* the worst trips play a minor role or no role at all.
4. **Probabilistic Methods** report the probability that the travel time will be less than some predefined threshold. Effectively, these methods are the inverse of the *Buffer Time Methods*. Just as with *Statistical Range Methods*, these methods are useful, but might be hard to understand for the typical road user.
5. **Skew-width Methods** capture the width and asymmetry of the travel time distribution. These are the real scientific methods, which try to provide a detailed image of the reliability. However, some amount of background knowledge is necessary in order to understand these methods.

### 2.3.3. Criteria for the Indicators in the Project Method

Besides the characteristics which were explained in the previous section, also a set of criteria is used to compare the TTR measures. These criteria are formulated and explained in this section. First, a number of general criteria for a suitable TTR measure are discussed. Second, criteria which apply to the project method as a whole are drawn up and explained.

#### General Criteria for the TTR Measure

Hellinga (2011) states that there is no theoretical reason to justify selection of one TTR-measure over another and uses the following criteria to select a suitable measure for Travel Time Reliability for a certain situation. The measure:

- ... can be readily **understood**. (by practitioners, researchers, the public and policy makers)
- ... can be **computed** using available data sources.
- ... is **compatible** with other reliability studies.
- ... is **meaningful** with respect to the policy measures it will be used to evaluate.

The criterion of understandability is important, since the measure will be used to evaluate the reliability of urban roads by the municipality. The municipality must be able to explain the results to the road users. Since not all road users are traffic engineers, the outcome of the measure should be easy to understand.

Secondly, obviously, the available data should be sufficient to apply the measure. In this case, each of the main routes is divided in multiple sections, of which travel times per minute are available. Vialis (2007) provides more detailed information about the collection and processing of travel time data.

Furthermore, note that compatibility is a criterion that is not applicable for this study, since this is the first TTR study in Rotterdam.

Next, the criterion of meaningfulness is obviously important. However, in this case the policy measures which will be evaluated depend on the outcomes of this study. Hence, this criterion is not considered in the comparison.

Moreover, there are some criteria which were mentioned in section 2.2.2. First, this means that the TTR measure should match the general definition of Travel Time Reliability. That is, it should show the variability relative to the travel time that is expected by the road user. Since there is no real-time information about the expectancy of users, the assumption is made that the expectancy of the road users equals the average travel time in a period of the day. However, note that in reality, this expectancy depends on many more factors, as was shown by (Bogers, 2009).

Second, the TTR measure should be able to grasp the desired variability period. In this case, that means inter-day variability.

#### Specific Criteria for the Project Method

Besides the aforementioned general criteria for a suitable TTR measure, it is of course important to realize what information the project method should provide. From discussions with the *Gemeente Rotterdam* it became clear that the project method should be able to:

1. ... tell how good the **average conditions** on a road are. As was stated, Travel Time Reliability seems to be an important feature for road users, but the average speed is still important. A road with a very reliable travel time but with an average speed of 10 km/h would not be very attractive to use.
2. ... provide information on the **degree of variation** of travel times. A wide distribution around the average travel time implies a low degree of reliability.
3. ... assess the **extreme travel times**. Road users may find delays or variation in travel times unpleasant, but their appreciation for a certain route may also be dependent on the frequency and severity of extreme travel times.

**2.3.4. Comparison of Travel Time Reliability Measures**

Now that an idea is established about what TTR measures are used, what characterizes these, and what criteria there are for a useful TTR measure, it is possible to compare the TTR measures. This is shown in table 2.1. The TTR measures - which were explained in section 2.3.1 - are listed in the first row. Each following row assesses the properties of the TTR measures, which are explained first. After the visual comparison by means of the table, the results are discussed.



1. **Perspective** indicates whether the measure uses the perspective of the service user (U) or the service provider (P).
2. **Method** refers to the type of method: Buffer Time (BT), Statistical Range (SR), Tardy Trip (TT), Probabilistic (P) or Skew-Width (SW).
3. **Predictability** indicates whether the measure determines TTR relative to average conditions. In other words, does it use average/median travel times (+), or free flow travel times (–) as a reference. A 0 is assigned when a measure uses free flow travel times but can be converted to use average/median travel times.
4. **Inter-day** shows whether the TTR measure is able to determine inter-day variation (+) or not (–).
5. **Understandable** indicates whether the outcomes of the TTR measure are understandable for the average road user. That is, the outcomes can be understood without any further explanation (+), it can be understood but it needs some small adaptation or explanation (0), or it is very hard to make the outcome understandable (–).
6. **Computable** shows whether the TTR measure can be computed with the available data. The possibilities are: can be computed (+), can be computed but there is need for some estimation with a chance of significant error (0), or it cannot be computed (–).
7. **Average** indicates whether (+) or not (–) the measure assesses the average travel time/speed on a route.
8. **Variation** shows whether (+) or not (–) the measure assesses the extent of variation in travel times.
9. **Worst Trips** indicates whether (+) or not (–) the measure assesses the longest travel times measured on a route.

Table 2.1: Comparison of the TTR measures by properties.

	Buffer Index	Buffer Index 2	Planning Time Index	Misery Index	On Time Probability	Not Long Probability	Standard Deviation	Coefficient of Variance	Skew Statistic	Width Statistic	Un-reliability Index
1. Perspective	U	U	U	U	U	U	U	U	U	U	U
2. Method	BT	BT	BT	TT	P	P	SR	SR	SW	SW	SW
3. Predictability	+	+	0	0	+	+	+	+	+	+	+
4. Inter-day	+	+	+	+	+	+	+	+	+	+	+
5. Understandable	0	0	0	–	0	0	–	–	–	–	–
6. Computable	+	+	0	0	+	+	+	+	+	+	+
7. Average	–	–	–	–	–	–	–	–	–	–	–
8. Variation	+	+	+	–	+	+	+	+	+	+	–
9. Worst Trips	–	–	–	+	–	–	–	–	–	–	+

Since some of the results in table 2.1 are disputable, some explanation is provided here.

1. **Perspective.** Evident.
2. **Method.** Evident.
3. **Predictability.** All TTR measures use either mean or median travel time, except for the Planning Time Index and the Misery Index, which use free flow travel time as a reference. However, it is possible to adapt these measures so that mean or median travel time is used.
4. **Inter-day.** All of the TTR measures are suitable for investigating interday-variation. However, all of them require that the day is split up into periods with approximately constant travel times. These could for instance be: morning peak, evening peak, period between morning and evening peak, and night period.
5. **Understandable.** There seems to be no TTR measure which is easy to understand without any modifications. All Buffer Time Methods (BI, BI\*, and PTI) are concepts of adding buffer time in order to arrive on time with a certainty of 95%, which is something that road users can relate to. However, these measures express the buffer time as a percentage of the mean, median, or free flow travel time. This is useful when the TTR of different sections is compared, but it is hard for road users to understand and to use in planning their trips. It would be better to translate these percentages to absolute travel times, which road users can use in their planning. That is why all Buffer Time Methods are rated 0. The misery index is rated –, because it provides a number which says nothing to a layman. However, note that the Misery Index is the only measure that assesses the severity of the worst trips, which could be something that road users find significant. The OTP and NLP measures are concepts that road users can understand. However, in order to make it more easy to understand and use, it should not be presented as the probability that a realized travel time lies within a 10 minute range from the median travel time, but as a probability that a trip can be made within a certain amount of time. Therefore, the OTP and NLP measures are rated 0. Finally, all Statistical Range and Skew-Width Methods are rated –, because knowledge of statistics is required to understand these, which a large share of the road users likely does not have.
6. **Computable.** Since travel time for a long period and with a high density is available, most of the measures can be computed without any problem. It is harder to compute the PTI and MI, since these use free flow travel time. Free flow travel time is a somewhat strange concept in urban areas, since one cannot speak of a free flow, since traffic is confronted with signalized intersections. Fortunately, it was already stated that using free flow travel times as a reference is not desirable because it does not satisfy the predictability requirement and this can easily be replaced with mean or median travel times. This will resolve the computability issue as well.

### Findings from the Comparison of TTR Measures

The following can be concluded about TTR measures that are found in literature:

- All TTR measures use the perspective of the road user. Since the goal of this research is to develop a method which assesses route performance from a road user perspective, this means that all TTR measures can be used according to this criterion.
- All five categories of TTR measures are represented.
- Two TTR measures (PTI and MI) do not use mean or median travel time as a reference and hence, are not useful for analysis. This can however easily be adapted so that these are useful.
- All TTR measures can be used to investigate inter-day variation.
- The BI, BI\*, PTI, OTP, and NLP are not easy to understand for road users, but can be understandable when they are presented in a slightly modified way. The MI, STD, COV, SS, WS, and UI are too difficult to understand for road users.
- All TTR measures can be computed with the available data.

- All of the TTR measures, except the MI and UI assess the variation of travel times. The MI and UI assess the worst trips.
- There is no TTR measure that satisfies all criteria, hence multiple measures are needed for analysis.
- None of the TTR measures returns information about the average conditions. Thus, this should be assessed by means of a separate measure.

### 2.3.5. Discussion: TTR measures

Regarding the above, it seems appropriate to use three separate measures to assess the three aspects that are examined: average conditions, degree of variation, and worst trips. This is favorable, since in the case of a route that shows a poor performance, the more specific cause of this performance can be found. However, this also has disadvantages, because there will be three separate assessments, which makes it more complex to understand for service users. Seeing this, it might be useful to combine the outcome of the three measures. This is investigated in chapter 4. However, detailed information on the performance of a route is lost in that case. Hence, this is a question of weighing up understandability against loss of information.

## 2.4. Conclusions & Recommendations

The literature survey in this chapter was conducted in order to reach sub-objectives 1 and 2, which were set in section 1.3: *"Establish an overview of useful insights into the field of Travel Time Reliability."* and *"Determine which measures of Travel Time Reliability are available and evaluate these."* This section displays the conclusions and recommendations connected with these sub-objectives.

### 2.4.1. Conclusions

The conclusions are grouped by the aforementioned sub-objectives. First, learnings about TTR from the past which are useful for this research are described. Second, an overview of TTR measures found in literature is provided, together with criteria for the evaluation and results of the evaluation.

#### Overview of Useful Insights into the Field of Travel Time Reliability

- There is an increasing interest in TTR, because this is assumed to have value to users and may impact user behavior. Consequently, there has been an effort to better understand the causes and consequences of TTR. However, the body of knowledge is still relatively sparse.
- Travel Time Reliability is defined as: "The ability of the transport system to provide the expected level of service quality, upon which users have organized their activities." Hence, Travel Time Reliability should be measured relative to the expectations of road users.
- There has not been much investigation into TTR in urban areas; most research focuses on motorways. Due to large differences in the characteristics of these road types, a different approach might be needed and conclusions may also vary. However, the TTR is likely to influence road users in urban areas as well and hence desire for research on TTR in urban areas is present.
- There are three levels of time frames to approach TTR: inter-day, inter-period, and inter-vehicle. For this research, inter-day variations are observed, because deviations from a daily pattern will influence TTR, whereas inter-period variations will be known by road users.

#### Overview and Evaluation of Available TTR Measures

- The definition of a TTR measure is not unambiguous. There are many different TTR measures that can be used. A list of possible TTR measures is provided in section 2.3.1.
- TTR measures can be classified on the basis of different characteristics:
  - Perspective: service provider or service user. The service provider focuses on the network performance while the service user focuses on trip characteristics.

- Category: statistical range methods, buffer time methods, tardy trip methods, probabilistic methods, and skew-width methods. These categories are all based on different mathematical principles.
- There is no theoretical reason to justify selection of one TTR-measure over another. However, there are criteria, which partially depend on the type of investigation that is done, that can be used to select a proper TTR measure. These are:
  - General criteria. The TTR measure:
    - ◊ ... can be readily **understood**. (by practitioners, researchers, the public and policy makers)
    - ◊ ... can be **computed** using available data sources.
    - ◊ ... is **compatible** with other reliability studies.
    - ◊ ... is **meaningful** with respect to the policy measures it will be used to evaluate.
  - Specific criteria for the project method that is developed in this research. The measure used in the project method should be able to:
    - ◊ ... tell how good the **average conditions** on a road are. As was stated, Travel Time Reliability seems to be an important feature for road users, but the average speed is still important. A road with a very reliable travel time but with an average speed of 10 km/h would not be very attractive to use.
    - ◊ ... provide information on the **degree of variation** of travel times. A wide distribution around the average travel time implies a low degree of reliability.
    - ◊ ... assess the **worst trips**. Road users may find delays or variation in travel times unpleasant, but their appreciation for a certain route may also be dependent on the frequency and severity of extreme travel times.
- A list of TTR measures found in literature, together with explanations and examples, is provided in section 2.3.1.
- All TTR measures use the perspective of the road user. Since the goal of this research is to develop a method which assesses route performance from a road user perspective, this means that all TTR measures can be used according to this criterion.
- All five categories of TTR measures are represented in the TTR measures that were found in literature. Hence, the whole range of mathematical techniques is used.
- PTI and MI do not use mean or median travel time as a reference and hence are not useful for analysis. However, they can easily be adapted so that they are useful.
- All TTR measures can be used to investigate inter-day variation. Hence, no TTR measure drops out due to this criterion.
- The BI, BI\*, PTI, OTP, and NLP are not easy to understand for road users, but can be understandable when they are presented in a slightly modified way. The MI, STD, COV, SS, WS, and UI are too difficult to understand for road users and can therefore not be used for analysis.
- All TTR measures can be computed with the available data.
- All of the TTR measures, except the MI and UI assess the variation of travel times. The MI and UI assess the worst trips.

#### 2.4.2. Recommendations

The recommendations are grouped by theme. First, recommendations are made about which requirements the project method should meet. Subsequently, recommendations on which TTR measure to use are given. Finally, a recommendation for further research is done.

- **Project Method**

- The project method should be able to assess three attributes: average travel time conditions, degree of variation in travel times, and worst trips. As these attributes are likely to have an influence on the judgment of road users.
- There is no TTR measure that satisfies all criteria for the project method, hence multiple measures need to be combined in the project method.
- A balance between understandability and loss of information should be made when the new project method is designed.

- **TTR measures**

- For the design of the project method, TTR measures should be used that are understandable to road users and computable with the available data.
- Use TTR measures that are based on mean or median travel time rather than free flow travel time, as this relates to the fact that reliability depends on the expectancy of the road user.
- None of the TTR measures returns information about the average travel time conditions. Thus, this should be assessed by means of a separate measure.

- **Further research**

- Deeper investigation into Travel Time Reliability is desirable, for TTR is likely of importance to travelers and may influence their behavior. Another reason is that not much research on Travel Time Reliability has been performed as the field is relatively new. This is especially true for cities; the investigation that has been performed, was mostly done on motorways. A list of possible research questions is provided in section 2.2.1.
- As this research focuses on a first step in creating a performance indicator including TTR for urban routes from traveler's perspective, directions for further research in urban areas would be:
  - ◊ The value of TTR to various transportation network users.
  - ◊ The impact of TTR on traveler behavior.
  - ◊ The factors that influence TTR in an urban network.



# 3

## Developing the Project Method

This chapter uses the findings from the literature review (chapter 2) in order to develop the project method, which measures the performance of a route, in which TTR is included. The project method will later on be tested and used to analyze two main Routes in the city of Rotterdam (see chapter 5).

### 3.1. Introduction

This chapter deals with the third sub-objective of this research: *"Develop a new method to assess the performance of a route, in which Travel Time Reliability is included (the project method)."* The result of this chapter is a method which can be used to analyze the travel time data. The project method will be tested in chapter 5.

In chapter 2 the concept of Travel Time Reliability was explained. Also, different TTR measures were described and compared on the basis of key characteristics. Finally, requirements for the project method and the TTR measures were stated. Using these findings as a starting point, this chapter tries to achieve its objective.

Section 3.2 discusses the three elements of the project method, which were discussed in section 2.3.3: average conditions, variation, and extremes. Based on the comparison in the previous chapter, appropriate measures are chosen for each of these elements. Subsequently, section 3.3 explains how the results of the project method should be interpreted.

### 3.2. Elements of the Project Method

In this section, the three elements of the project method (respectively average travel times, variation in travel times and extreme travel times) are discussed and for each of these elements an appropriate measure is chosen, based on the results of chapter 2. Together, these elements will form the project method.

Two assumptions are used as a starting point for developing a project method. First, recall that a good TTR means that travelers are able to correctly predict travel times. Second, the assumption was made that the travel time which is predicted by road users equals the average travel time on a route.

Note that although the latter assumption is used, it is sensible to validate or correct this by means of further research. It is likely that travel time expectations are influenced by factors such as: weather, time of the year, holidays, road works, events, traffic information, and familiarity with the route.

In order to assess TTR based on the previously mentioned assumptions, the average travel time should be approximately constant within the observed period. Therefore, the day is split up into three periods in which the average travel time is approximately constant: morning peak, evening peak and the period between the peaks (inter-peak period). The times when these periods start and end are determined on the basis of expert opinion, in discussion with colleagues of the *Gemeente Rotterdam*. However, if the method is implemented, it is recommended that an unambiguous definition of these periods is defined. The night time is not considered, as travel times are generally lower, and there is less variation during the night.

Furthermore, one of the conclusions of the previous chapter is that there is no TTR measure that assesses all three aspects that we aim to measure, namely: average travel times, degree of variation

in travel times, and extreme travel times. Hence, these elements should be assessed by separate TTR measures. The following sections discuss each aspect individually. Figure 3.1 provides a schematic overview of the setup of the project method.

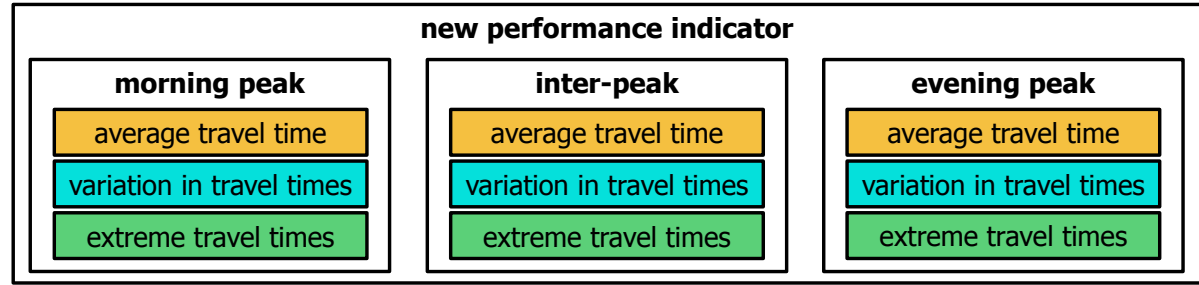


Figure 3.1: Schematic overview of the setup of the project method.

Note that this approach leads to 9 separate outcomes when a route is analyzed. This is advantageous in the sense that a more detailed image of the performance of a route is obtained. However, at the same time this makes it more difficult to quickly understand the results and to compare routes. There is no straightforward method to compare the different attributes with each other. Chapter 4 continues on this subject by finding a method to combine the individual aspects of the project method into a single judgment grade from the perspective of a road user. However, the consequence of this is that detailed information about the performance of a route is lost. A trade-off has to be made between understandability and loss of information.

### 3.2.1. Average Travel Time

One outcome of the comparison of TTR measures is that none of the TTR measures assesses average conditions. This makes sense, since average conditions are *de facto* not a part of TTR. However, average conditions play a role in the performance of a route and should thus be used in the project method.

An obvious measure to assess average conditions on a route is to use the mean travel time. In mathematical form, this is:

$$\bar{t} = \frac{1}{M} \sum_{m=1}^M \left[ \frac{1}{N_m} \sum_{i=1}^{N_m} t_{m,i} \right] \quad (3.1)$$

In this equation:

- $\bar{t}$  [min] is the mean travel time
- $M$  [-] is the number of minutes in the considered period of the day
- $m$  [-] is the index of the minute for which the average travel time is calculated
- $N$  [-] is the number of measurements in the considered minute
- $i$  [-] is the index of a single measurement within a minute
- $t$  [min] is the measured travel time

Note that travel times corresponding to a minute of the day means that these travel times are realized for vehicles that entered the route in that minute. For example, when the data shows that on a certain day and route the travel time corresponding to 09:00-09:01 is 10 minutes. This means a travel time of 10 minutes was realized by vehicles entering the route between 09:00 and 09:01. Hence, these vehicles are at the end of the route somewhere between 09:10 and 09:11.

Equation 3.1 is applied separately for the morning peak, evening peak and period between the peaks. Also, the two directions of a route are separated.

In order to compare the travel times of different routes, which have different lengths ( $L$  [km]), the mean travel times should be translated into a mean speed ( $\bar{v}$  [km/h]):



$$\bar{v} = \frac{L}{\bar{t}/60} \quad (3.2)$$

For the analysis of average travel times, the following steps are followed:

**Step 1** Calculate the mean travel time for each minute of the day.

**Step 2** Define the start and end times of the three periods of interest.

**Step 3** Calculate the mean travel time over each period of the day.

**Step 4** Translate mean travel times  $\bar{t}$  into mean speeds  $\bar{v}$ .

This procedure is clarified by means of an example (see next page).

### Example 3.2.1. Calculation of average travel times

Suppose a researcher collects travel time data on a certain route in the direction of the center of Rotterdam. Figure 3.2 shows collected travel times on workdays for a period of three months in one direction. The aggregation level is 1 minute, which means that travel times within a minute are averaged. Hence, there is one travel time available for every minute.

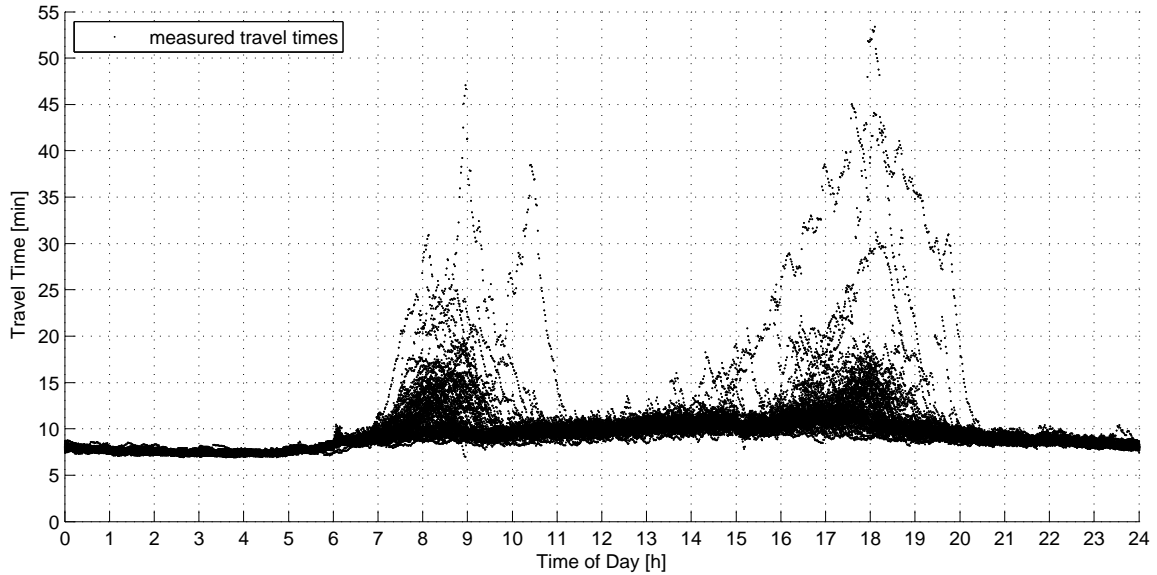


Figure 3.2: Measured travel times on workdays in a three month period.

**Step 1** is to calculate the mean travel time on each minute of the day. This is done on the basis of the observed travel times in that minute. This is the part of equation 3.1 between squared brackets. The graphical result is shown in figure 3.3.

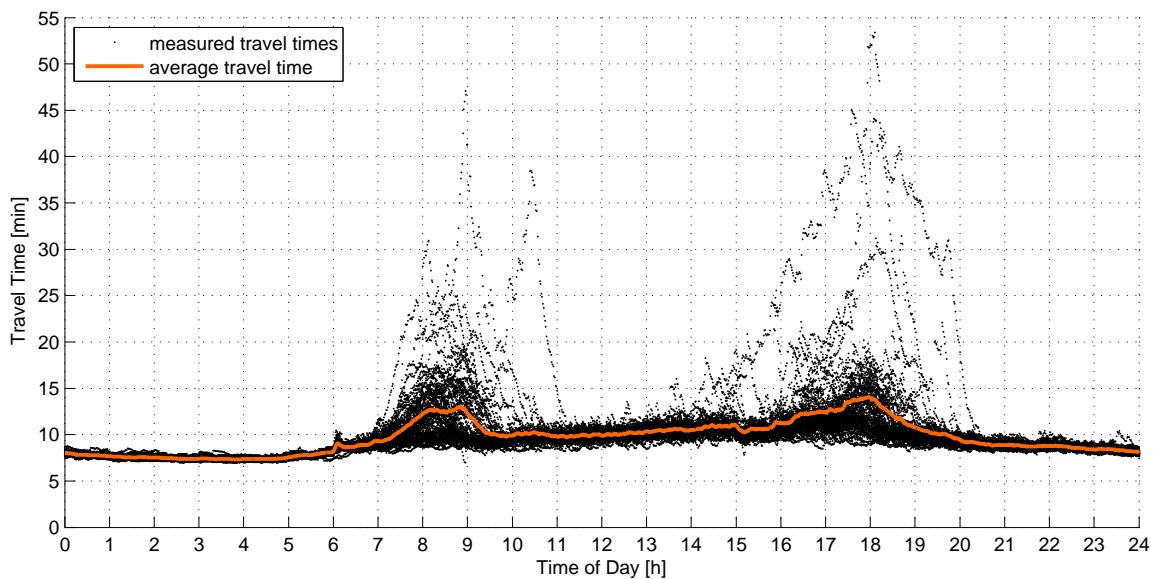


Figure 3.3: Measured travel times on workdays in a three month period, with the average per minute of the day.

**Step 2** consists of defining the start and end times of the three periods of interest. In this case, these periods are defined by means of expert opinion and discussion with colleagues of the *Gemeente Rotterdam*. The morning peak is from 07:30 to 09:15 and the evening peak is from 16:30 to 18:30. Now the in between period is automatically defined from 09:15 to 16:30. In figure 3.4 these period are marked by the vertical dotted lines.

**Step 3** is to calculate the mean travel time over each period of the day. This is done by averaging the average travel times within a period that were found in step 1. The result is shown in figure 3.4.

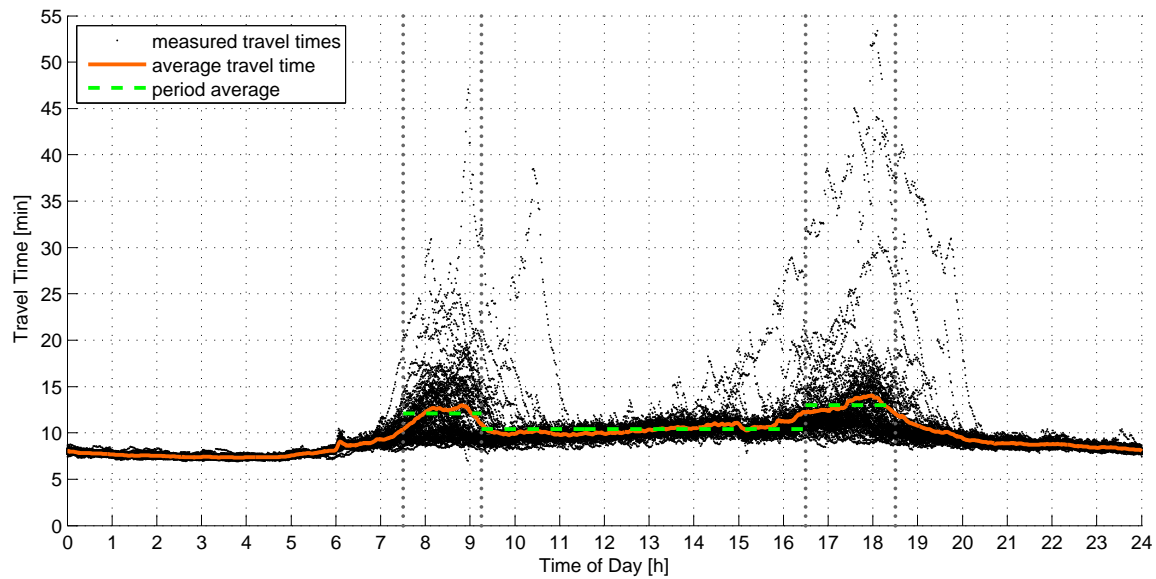


Figure 3.4: Measured travel times on workdays in a three month period, with the average per minute of the day and the average within the three periods of interest.

**Step 4** is to translate the mean travel times  $\bar{t}$  into  $\bar{v}$ . Since it is known that the length of the observed route is 5.719 km, this can be achieved by using equation 3.2.

The results are given in table 3.1.

Table 3.1: Average travel times and speeds per period of the day.

	Morning Peak	Inter-Peak	Evening Peak
<b>Average Travel Time (<math>\bar{t}</math>) [min]</b>	12.1	10.4	13.0
<b>Average Speed (<math>\bar{v}</math>) [km/h]</b>	28.4	33.0	26.4

### 3.2.2. Variation in Travel Times

A second attribute which needs to be present in the project method, is the variation in travel times. Table 2.1 shows that the Buffer Index, Buffer Index 2, On Time Probability, and Not Late Probability are TTR measures that assess variation in travel times and are able to meet all criteria. None of these measures scores a + on the *understandable* criterion, but it is possible to slightly adapt these measure to make it useful for road users by translating the percentage to an absolute buffer value. The OTP and NLP use a 10 minutes buffer, which is a subjective measure that is configured for motorways. Therefore, the BI or BI\* is more appropriate to use. The BI is preferable over the BI\*, since the mean travel time is used to measure the average condition and the assumption was made that the user expectation equals the average travel time. Hence, in order to assess the variation in travel times, the Buffer Index is used.

Recall that the Buffer Index ( $BI$  [-]) is calculated as follows:

$$BI = \frac{t^{95\%} - \bar{t}}{\bar{t}} \quad (3.3)$$

In this equation,  $t^{95\%}$  [min] is the 95th percentile travel time.

Equation 3.3 expresses the buffer time as a percentage of the average travel time. This can be used as a general indicator for the performance of the route and also to compare different routes. However, such a percentage is not useful for road users. So, in order to inform the road users, an absolute buffer time value ( $\widehat{BI}$  [min]) is desired, which is calculated as follows:

$$\widehat{BI} = t^{95\%} - \bar{t} \quad (3.4)$$

For the analysis of average travel times, the following steps are followed:

**Step 1** Determine the 95th percentile travel time ( $t^{95\%}$  [min]).

**Step 2** Calculate the buffer indices ( $BI$  [-] and  $\widehat{BI}$  [min]).

Similar to the procedure for average travel times, the usage of the Buffer Index is explained stepwise by means of an example. The data that is used is the same as in example 3.2.1.

### Example 3.2.2. Calculation of the Buffer Index

**Step 1** is to determine the 95th percentile travel time ( $t^{95\%}$  [min]). This is done by sorting all measured travel times in a considered period from shortest to longest and determining the travel time value at 95% of the list. The  $t^{95\%}$  for all three periods are shown in table 3.2 and drawn into figure 3.5.

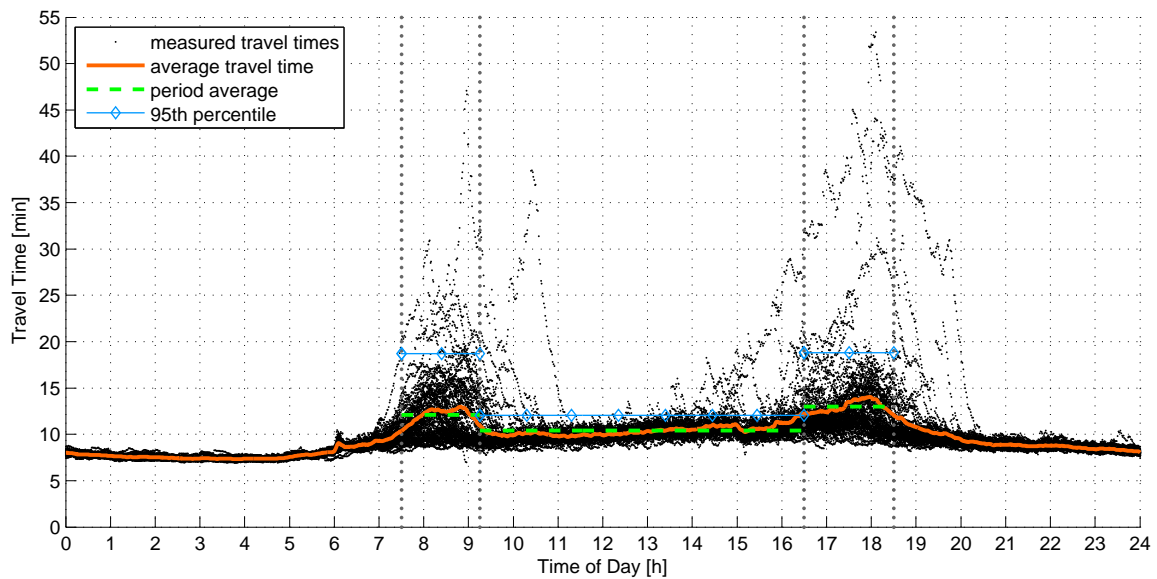


Figure 3.5: Measured travel times on workdays in a three month period, with the average per minute of the day, the average within the three periods of interest, and the 95th percentile in the three periods.

**Step 2** is to calculate the buffer indices ( $BI$  and  $\widehat{BI}$ ) by using equations 3.3 and 3.4. The results from step 1 and the average travel times from table 3.1 are needed for this. The results are displayed in table 3.2.

Table 3.2: Outcomes of calculation of the Buffer Index.

	Morning Peak	Inter-Peak	Evening Peak
95th perc. travel time ( $t^{95\%}$ ) [min]	18.7	12.1	18.8
Buffer Index ( $BI$ ) [%]	54.8	15.8	44.9
Absolute Buffer Index ( $\widehat{BI}$ ) [min]	6.6	1.6	5.8

### 3.2.3. Extreme Travel Times

The third element that the project method should assess are extreme travel times. Table 2.1 shows that the Misery Index and Unreliability Index are the two measures that consider the worst trips. However, these indexes both do not meet all the other criteria. Both have a negative score on the *Understandable* criterion. Because of the statistical knowledge that is needed to understand the UI, it is not usable. Therefore, a project method is developed.

It is assumed that road users will accept some deviation from the average travel time. However, if the deviation becomes too large, this will become unacceptable to travelers and it might influence

their behavior in terms of route choice, departure time choice, mode choice or destination choice. It is assumed that the precise magnitude of these worst trips is less important. Hence, the new measure is defined as the percentage of time in which the travel time was above some extreme threshold. The value of this threshold depends on the average travel time for a whole year, since it is reasonable that what is considered as an extreme travel time on a route does not change for each quarter of the year. The new measure is called the Bad Minutes Index (BMI [-]).

In mathematical form, this is:

$$BMI = \left[ \sum_{k=1}^K \begin{cases} 1 & \text{if } (t_k > w * \bar{t}_{year}) \\ 0 & \text{otherwise} \end{cases} \right] / K \quad (3.5)$$

In this equation:

- $K$  [-] is the total number of observed measurements
- $k$  [-] is the index of the observed measurement
- $w$  [-] is the multiplication factor to set the bad travel time threshold
- $\bar{t}_{year}$  [min] is the average travel time on a route for a period of the day in a complete year

For the analysis of extreme travel times, the procedure that is followed is:

**Step 1** Set the multiplication factor  $w$  [-].

**Step 2** Calculate the *bad travel time threshold* [min].

**Step 3** Count the number of measured minutes that exceeds the threshold.

**Step 4** Divide the number of minutes exceeding the threshold by the total number of measured minutes to obtain the *BMI* [%].

Following the same line, an example is provided in order to explain these steps (see next page).

### Example 3.2.3. Calculation of the Bad Minutes Index

**Step 1** is to set the multiplication factor  $w$ . In order to find the most meaningful value of  $w$ , further research is required. For now, it is assumed that road users experience a travel time of more than twice the average travel time as extreme. Thus,  $w = 2$  will be used. Hence, a minute is counted as bad when the travel time in that minute is larger than 2 times the average travel time in that period.

**Step 2** is to calculate the *bad travel time threshold* for each of the considered periods. This is done by multiplying  $w$  by the average travel times per period of the day for the whole year. Figure 3.6 shows the BMI threshold for the three observed periods.

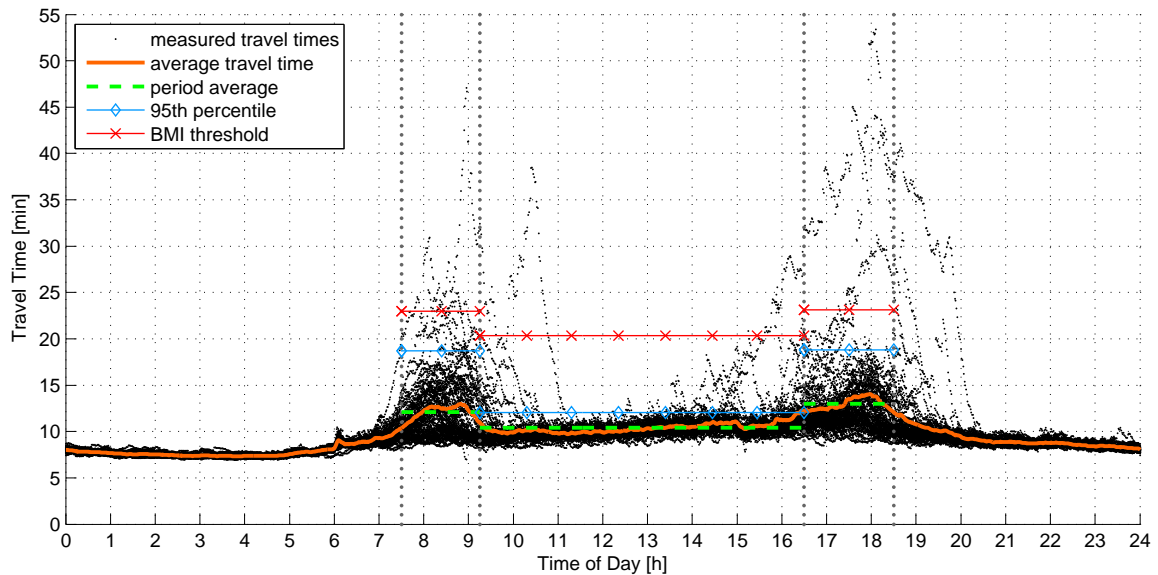


Figure 3.6: Measured travel times on workdays in a three month period, with the average per minute of the day, the average within the three periods of interest, the 95th percentile in the three periods, and the BMI threshold (based on the yearly average of travel times.)

**Step 3** is to count the number of measured minutes that exceeds the threshold. That is, the number of measured minutes that show a longer travel time than twice the average travel time. The results are shown in table 3.3.

**Step 4** consists of dividing the number of minutes exceeding the threshold by the total number of minutes that is measured. Table 3.3 shows the Bad Minutes Indexes for the three periods of the day.

Table 3.3: Outcomes of calculation of the Bad Minutes Index.

	Morning Peak	Inter-Peak	Evening Peak
bad travel time threshold [min]	23.0	20.4	23.1
no. of "bad minutes" [-]	125	151	249
no. of observed minutes [-]	6646	26335	7619
Bad Minutes Index (BMI) [%]	1.9	0.6	3.3

### 3.2.4. The Project Method: Result

Based on the previous sections, it is concluded that the project method consists of three elements (average travel time, Buffer Index, and Bad Minutes Index). These 3 elements are calculated in 3 periods of the day (morning peak, inter-peak, and evening peak). Hence, when a route is analyzed, there are 9 outcomes.

### 3.3. Interpretation of the Results of the Project Method

In order to clarify how the results could be interpreted, the results of the example in section 3.2 are explained in section 3.3.1. Subsequently, in section 3.3.2 the interpretation of the results of the project method are discussed.

#### 3.3.1. Example Interpretation

An example of the interpretation of the results from the examples in section 3.2 is provided in this section.

##### Example 3.3.1. Interpretation of the analysis results

The results of the example from section 3.2 are combined in table 3.4 and are explained here.

Table 3.4: Outcomes of the example.

	Morning Peak	Inter-Peak	Evening Peak
Average speed new indicator [km/h]	28.4	33.0	26.4
Buffer Index (BI) [%]	54.8	15.8	44.9
Bad Minutes Index (BMI) [%]	1.9	0.6	3.3

First, it can be seen that the average speed in the inter-peak period is much higher than the speed in the morning and evening peak. This is in accordance with expectations, as traffic volumes are much higher in the peaks, which causes delays.

Second, the average speed for both the current method and project method are compared. Calculating the average speed for the observed period following the calculation procedure of the current method that is used in Rotterdam (see appendix A) gives a speed of 32.5 km/h. This is a large overestimation for both the morning and evening peak mean speeds. This difference can be explained by the much higher speeds on Saturdays (36.0 km/h) and Sundays (35.1 km/h), which are taken into account in the calculation of the current method.

Furthermore, the Buffer Index is observed. The larger this Buffer Index is, the larger the variation in travel times and, hence, the smaller the Travel Time Reliability. Table 3.4 shows that the peaks have a much higher variation in travel times than the period between the peaks. This might be caused by variations in traffic volumes and the fact that a traffic network becomes less stable when traffic volumes are higher.

Finally, the Bad Minutes Index is considered. It can be seen that the inter-peak period performs relatively well and that the evening peak has the most minutes which exceed the threshold of twice the average travel time.

From this example it can already be concluded that the project method gives a much better insight into the speeds during the different periods of the day and week. However, this implies that the current goal of 25 km/h cannot be used unconditionally. For the new measures, i.e. the Buffer Index and the Bad Minutes Index, some years of experience will have to learn what a good performance is in an absolute sense.

The following section discusses the interpretation of the project method in a broader perspective.

#### 3.3.2. Discussion: Interpreting the Results of the Project Method

When travel time data of a route in one direction of some period is analyzed using the method that has been developed in this chapter, the outcome consists of 9 separate indicators. For each period of the day (morning-peak, evening-peak and the period between the peaks) there are 3 indicators: average travel time, variation in travel times and percentage of "bad minutes". The hypothesis is that a route performs well if all of these 9 indicators show a good result.

Now the question arises when an indicator scores good, sufficient or insufficient. The ideal situation would be an average speed of 50 km/h, with no variation and a BMI of 0. But due to the varying traffic intensity, complex traffic relations, and traffic management measures within an urban road network this seems unrealizable. Hence, the question is how the outcomes of the project method should be judged.

From experience with the current method it is known that there is no straightforward method to determine what a sufficient score is. The 25 km/h objective for the current method was set only after years of observations. Hence, the project method will have to be tested for some years to determine what sufficient scores are.

Also, note that there could be different requirements for different periods of the day, as well as for the different routes, due to specific characteristics, such as the number of (signalized) intersections, connection to motorways, and layout. For example, the average speed may be lower during peak hours than during off-peak hours in order to receive a positive rating.

However, although at this moment it is not possible to give an objective judgment of the results, it is possible to compare the results of different routes and to compare the results with current method which only uses average speed. Also, it is possible to test the working of the project method. All of this will be done in the case study in chapter 5.

Although splitting up the day in different periods provides more detailed information, all calculations presented in this chapter assume every measured minute has the same weight in the calculations. However, the traffic intensity may vary strongly during a day. As more road users experience a certain travel time when the intensity is higher, it might be more appropriate to use traffic intensities to weigh the minutes in the calculations. If this is done, the peak hours will play a more important role in the results. For example, the Bad Minutes Index would not count the number of bad minutes, but instead the percentage of vehicles that experiences a bad travel time. By doing this, the focus shifts from the road user perspective to network provider perspective. This research does not use the intensities, because there are no traffic intensity data available for the sections of the main routes in Rotterdam in the observed period, 2013. Nonetheless, in the future this will be the case. When this happens, it is advisable to investigate whether using these intensities gives a better insight.

Now that the project method is designed, it can be applied to the available travel time data. However, before doing so, it is useful to get an idea of how road user judgment is related to outcomes of the project method. Compared to the current method, this is a new aspect, which will be investigated in chapter 4.

### 3.4. Conclusions & Recommendations

The goal of this chapter was to meet sub-objective 3 (section 1.3): *"Develop a new method to assess the performance of a route, in which Travel Time Reliability is included (the project method)."* This section provides the conclusions and recommendations from this chapter.

#### 3.4.1. Conclusions

The following conclusions about designing a the project method are drawn:

- The project method should be applied to periods of time in which the travel time is approximately constant. Therefore the day is split up in three periods: morning peak, inter-peak, and evening peak. The project method is used separately on all three periods.
- The night is not considered in the analysis: low traffic volumes and shorter travel times make this period not interesting for analysis.
- The project method assesses the following attributes by means of the following measures:
  - Average travel times: mean speed. (section 3.2.1)
  - Variation in travel times: Buffer Index. (section 3.2.2)
  - Extreme travel times: Bad Minutes Index. (section 3.2.3)
- The project method gives a more detailed insight into the performance of a route.

#### 3.4.2. Recommendations

First, recommendations about how to use the project method and interpret its results are provided. These are used in the remainder of this research. Subsequently, recommendations for further research are provided:

- **Project method**



- Translate mean travel times into mean speeds in order to be able to compare different routes with one another.
- It is recommended to investigate the judgment of road users. This could then be related to the results of the indicators. By doing this, it is possible to gain insight into the effects of the attributes of the project method on the road user judgment.

- **Further research**

- The assumption that the expectation of road users equals the average speed in a period of the day should be validated or extended. It is likely that there are other factors which influence the travel time expectations of road users as well, such as: the weather, special events, holidays, road works, traffic information, and familiarity with the route.
- The “bad travel time threshold” was assumed to be twice the average travel time ( $w = 2$ ). This assumption should be validated or corrected. It might be so that for short routes there should be an absolute threshold, because in such a case a travel time which is twice the average travel time is easily realized but does not influence the judgment of the road users.
- The judgment of the outcomes of the different attributes of the project methods should be examined. (see section 3.3.2 for details)
- Investigate whether weighing the measured travel times by the traffic intensity contributes to the outcome of the project method. A higher intensity generally leads to a lower TTR. Therefore, the overall TTR may decrease. It has to be investigated whether this is desirable or not.



# 4

## The Influence of Travel Time Reliability on the Judgment by Road Users

The goal of this chapter is to find the relation between the project method, which was developed in chapter 3, and the judgment of a route by road users. This should make it possible to grade different combinations of the attributes in the project method, based on the opinion of road users. The result of this chapter will be used in the case study (chapter 5).

### 4.1. Introduction

It was already stated in chapter 1 that TTR is important to road users. Nonetheless, no statement was made about *how* important TTR is to road users. That is, it is unknown what the weight of TTR is in the judgment of a route by road users, compared to the average speed on a road. Hence, the purpose of this chapter is to achieve sub-objective 4 (see section 1.3): "Develop a model to describe the relation between the project model and the judgment of a route by road users (the *user model*)."

In order to reach this goal, a stated preference survey is conducted. In this survey, respondents will have to grade virtual situations. Another option to conduct a survey is the revealed preference survey, where the real behavior of respondents is investigated. However, conducting a revealed preference survey is too time-consuming for this research. The results of the survey are used to estimate the influence of the three attributes of the project method (mean speed, BI, and BMI) on the overall judgment of road users. In other words, how does each of the three attributes affect how a road user grades a route. This is done by means of a multivariate linear regression. When the size of these influences are known, a model is created. With this model, it is possible to reverse the process and estimate the road user judgment of a set of travel time data which contains the three attributes. This will be done in the case study, in chapter 5.

The outline of this chapter is as follows. In section 4.2 the setup of the survey is clarified. Subsequently, in section 4.3 the results of the survey are shown and explained. Finally, in section 4.4 the results of the survey are analyzed.

### 4.2. Survey Setup

This section first describes the exact goal of the survey (section 4.2.1). Subsequently, the design of the survey is explained in section 4.2.2.

#### 4.2.1. Goal of the Survey

The goal of conducting the survey is to estimate a model which is able to return a road user judgment grade based on the outcomes of the project method: mean speed, Buffer Index (BI), and Bad Minutes Index (BMI). This is visualized in figure 4.1.

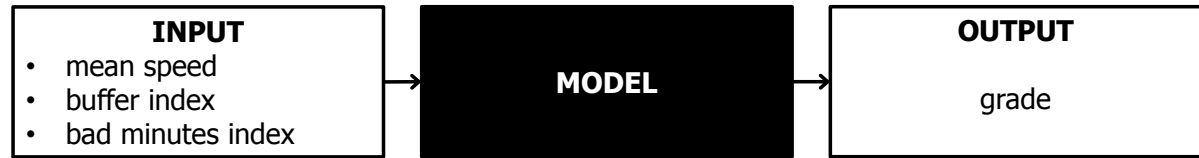


Figure 4.1: Model scheme.

In order to keep the model simple, a linear model is used. This linear model has the following form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k \quad (4.1)$$

In this equation:

- $Y$  is the response
- $\beta_0$  is a constant
- $\beta_1 \dots \beta_k$  are the parameters
- $X_1 \dots X_k$  are the predictors

It must be noted that the relation between the performance indicators of the project method and the road user judgment might be non-linear. If the linear model does not provide satisfactory results, a nonlinear model might be used. This can have many different forms. One or more terms in the model may have a constant exponent, or a predictor itself could be an exponent of another predictor, or it could consist of a Fourier series. In mathematical form, the linear model would be:

$$G = \beta_0 + \beta_v \bar{v} + \beta_{BI} BI + \beta_{BMI} BMI \quad (4.2)$$

In that sense, the goal of the survey is to estimate the betas in equation 4.2. The hypothesis is that  $\beta_v$  has a positive value, because the grade is likely to increase if the mean speed increases. Likewise,  $\beta_{BI}$  and  $\beta_{BMI}$  are assumed to have negative values, as the idea is that the grade decreases if the variability in travel times or the percentage of extreme travel times increases. Since there are both negative and positive betas with unknown magnitude, the sign of the constant  $\beta_0$  is unpredictable.

Now, in order to estimate the values of the betas, the process is reversed. Thus, a set of different combinations of the variables is selected and the respondents grade these. Subsequently, we try to find a set of betas with which it is possible to estimate the judgment grade of the road users, based on the input of the three variables.

This serves as a starting point for the design of the survey, which is discussed in the following section.

#### 4.2.2. Design of the Survey

As was stated in the previous section, in the survey a set of different combinations of outcomes of the project method needs to be judged by travelers. In order to be able to observe the effect of the three indicators on the judgment with the least possible number of respondents, it is important that the survey has an orthogonal design. This means that the three variables must have no correlation. Mathematically, this criterion is described by using the Pearson sample correlation coefficient (Pearson, 1901):

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y} = 0 \quad (4.3)$$

In this equation:

- $r$  is the Pearson sample correlation coefficient
- $x$  and  $y$  are the variables, consisting of  $n$  elements
- $\bar{x}$  and  $\bar{y}$  are the means of the variables

- $s_x$  and  $s_y$  are the standard deviations of respectively  $x$  and  $y$
- $n$  is the number of measurements of each variable

It can be derived from equation 4.3 that all combinations of two variables of the survey must meet the following criterion:

$$\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) = 0 \quad (4.4)$$

It is estimated that for each of the attributes 5 levels should be sufficient to estimate a model. Table 4.1 shows an orthogonal design for 3 variables with 5 levels.

Table 4.1: Orthogonal design for 3 variables with 5 levels.

no.	var.1 level	var.2 level	var.3 level
1	1	1	1
2	5	3	2
3	2	4	3
4	3	5	4
5	4	2	5
6	5	4	1
7	2	2	2
8	4	5	3
9	1	3	4
10	3	1	5
11	2	5	1
12	4	1	2
13	3	3	3
14	5	2	4
15	1	4	5
16	3	2	1
17	1	5	2
18	5	1	3
19	4	4	4
20	2	3	5
21	4	3	1
22	3	4	2
23	1	2	3
24	2	1	4
25	5	5	5

This set was created by the software program *Ngene 1.1.1* (Metrics, 2012). This software uses libraries of orthogonal arrays that have been found by mathematicians. It can be checked that all combinations of columns in table 4.1 (1-2, 1-3, and 2-3) satisfy equation 4.4.

In order to assure that the model is usable in the whole range of possible combinations of values of the variables, the full width of this range needs to be used in the survey. From preliminary data

analysis it is known that these ranges are, for each variable:

- Mean speed: 15 – 35 km/h
- Buffer Index: 10 – 150 %
- Bad Minutes Index: 0 – 10 %

The next step is to divide these ranges into 5 levels. This is shown in table 4.2.

Table 4.2: Levels for the 3 variables.

<b>level</b>	<b>mean speed [km/h]</b>	<b>BI [%]</b>	<b>BMI [%]</b>
<b>1</b>	15	10	0
<b>2</b>	20	45	2.5
<b>3</b>	25	80	5
<b>4</b>	30	115	7.5
<b>5</b>	35	150	10

Combining table 4.1 and table 4.2 leads to a set of different variable combinations which can be used in the survey. This is shown in table 4.3 (see next page).

Table 4.3: Orthogonal design for the survey.

no.	mean speed [km/h]	BI [%]	BMI [%]
1	15	10	0
2	35	80	2.5
3	20	115	5
4	25	150	7.5
5	30	45	10
6	35	115	0
7	20	45	2.5
8	30	150	5
9	15	80	7.5
10	25	10	10
11	20	150	0
12	30	10	2.5
13	25	80	5
14	35	45	7.5
15	15	115	10
16	25	45	0
17	15	150	2.5
18	35	10	5
19	30	115	7.5
20	20	80	10
21	30	80	0
22	25	115	2.5
23	15	45	5
24	20	10	7.5
25	35	150	10

Now, the shortest path to results would be to simply let respondents grade the combinations from table 4.3. However, the task of using these indicators which they have never used before requires an extensive explanation. Moreover, it is estimated that, due to lack of experience, the respondents are unable to grade these, even if they understand them, due to a lack of experience.

In order to overcome this issue, the values for the attributes in table 4.3 are "hidden" in sets of 40 travel times. For example, for the first combination in table 4.3 we try to find a set of 40 travel times, with a mean speed of 15 km/h, a Buffer Index of 10 % and a Bad Minutes Index of 0 %.

Respondents can better relate to travel times than to the three variables that are used. In addition, this will prevent the respondents from being biased by focusing on one of the three variables.

First, in order to make it possible to create sets of 40 travel times, the mean speeds from table 4.3 need to be translated into travel times. Hence, a route length is needed. A route length of 5 km is used. The results of translating mean speeds into travel times are displayed in table 4.4.

Table 4.4: Mean speeds and corresponding travel times.

level	mean speed [km/h]	travel time [s]	Travel time [min]
1	15	1200	20
2	20	900	15
3	25	720	12
4	30	600	10
5	35	514	8.6

Second, the entries in the third column of table 4.3 are substituted with the matching values from the third column of table 4.4. This gives a new set (table 4.5), which can be used to create the plots for the survey.

Table 4.5: Orthogonal design for the survey.

no.	travel time [min]	BI [%]	BMI [%]
1	20	10	0
2	8.6	80	2.5
3	15	115	5
4	12	150	7.5
5	10	45	10
6	8.6	115	0
7	15	45	2.5
8	10	150	5
9	20	80	7.5
10	12	10	10
11	15	150	0
12	10	10	2.5
13	12	80	5
14	8.6	45	7.5
15	20	115	10
16	12	45	0
17	20	150	2.5
18	8.6	10	5
19	10	115	7.5
20	15	80	10
21	10	80	0
22	12	115	2.5
23	20	45	5
24	15	10	7.5
25	8.6	150	10



For each of the 25 combinations of variable values in table 4.5 a set of 40 travel times is composed, which satisfies these values. An example (which corresponds to no. 4 in table 4.5) is provided in figure 4.2.

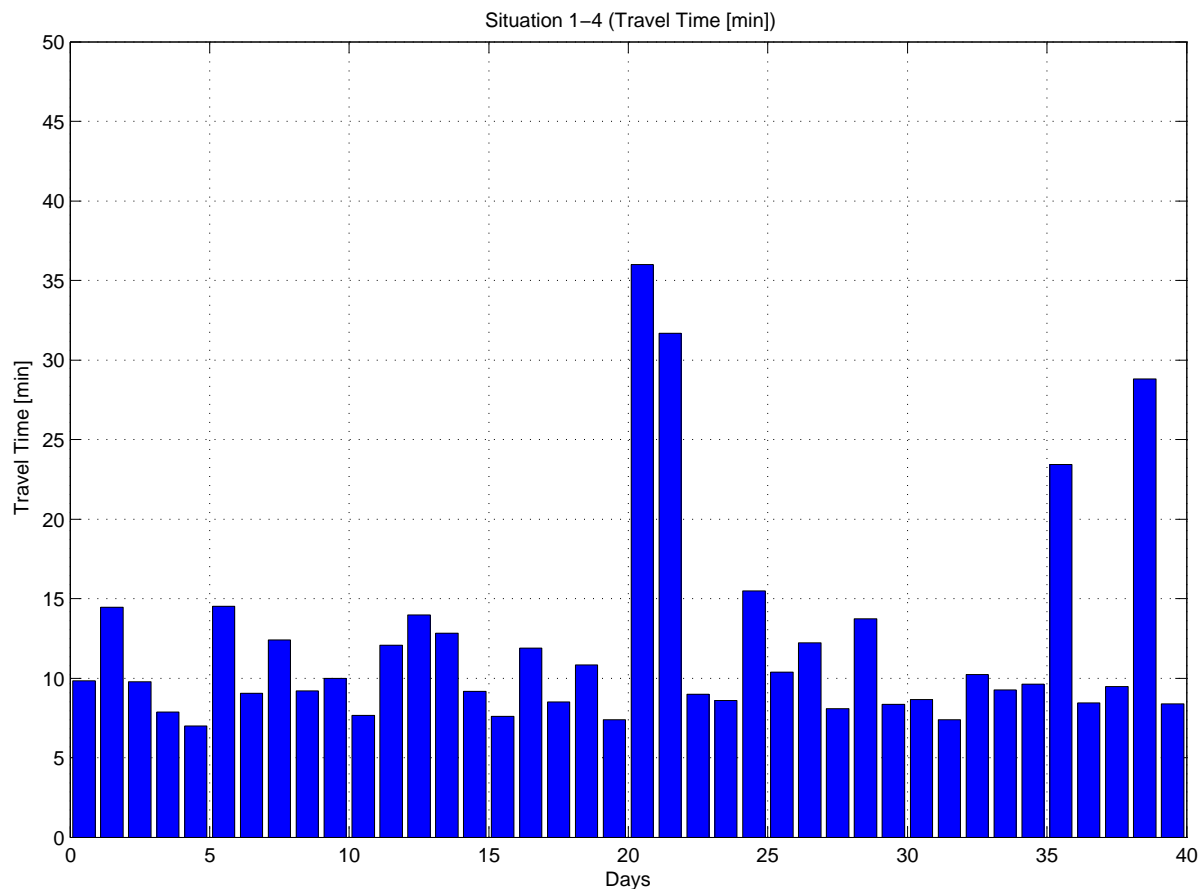


Figure 4.2: Example of a set of travel times which is used in the survey.

The respondents are asked to imagine that they drive to their work 40 times and experience the shown travel times. The assignment is to grade these combinations on the basis of how satisfied they would be with the observed travel times. This grade should be an integer between 1 and 10, where 1 means "very bad", 5 is "doubtful", 6 is "sufficient" and 10 means "excellent". No information is provided about whether they should specifically rate reliability. The survey can be found in appendix B.

Note that it is not possible to create a set of travel times for all of the combinations, because the BI and BMI are correlated. For instance, look at combination 10 in table 4.5 which has a very low BI of 10% and a very high BMI of 10%. It is impossible to create such a set, since extreme travel times also influence the variation. In such cases, the goal is to get as close as possible to the desired values. Although this causes the survey data to be not perfectly orthogonal, this has no large effects on the estimation of the model. Perfect orthogonality is an ideal situation, in which a very small number of respondents is needed. However, with a very non-orthogonal set it will also be possible to estimate a model. But, in such a case, a very large number of respondents is needed. Therefore, it is expected that small deviations from this orthogonality will not lead to estimation problems for the model.

### 4.3. Survey Results

The survey was filled out by 22 people, most of them employees of the *traffic and transport* department of the *Gemeente Rotterdam*. The results are shown in table 4.6. The last column shows the average grade per combination. Graphs of the results can be found on the CD that is attached to this report.

Table 4.6: Survey results.

	variables			grades per respondent																							
no.	$\bar{v}$ [km/h]	BI [%]	BMI [%]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	avg.	
1	15.0	9.9	0.0	5	8	8	6	8	6	9	5	4	3	5	4	3	5	8	6	4	2	4	8	5	8	5.64	
2	34.3	77.3	2.5	7	7	5	9	9	8	8	7	8	6	10	9	10	7	9	8	7	8	6	6	6	9	7.68	
3	20.0	114.6	5.0	6	7	6	9	7	7	8	5	5	5	9	4	7	6	6	7	5	5	5	6	5	7	6.23	
4	24.8	150.4	7.5	5	6	4	9	7	7	8	5	6	5	9	5	7	6	6	7	6	5	6	4	5	7	6.14	
5	29.8	73.7	5.0	7	7	5	10	7	7	8	6	7	5	9	6	8	6	7	7	9	7	7	5	6	7	6.95	
6	34.7	99.4	0.0	5	6	5	10	6	7	7	5	5	6	9	6	8	7	8	7	8	9	6	4	4	8	6.64	
7	19.9	45.6	2.5	4	7	7	7	6	6	5	4	5	4	8	3	5	5	7	6	6	4	5	5	5	6	5.45	
8	30.4	156.0	5.0	8	6	5	9	7	6	7	5	7	4	9	5	5	8	5	7	4	5	4	4	6	8	6.09	
9	15.1	101.3	7.5	5	5	3	6	5	4	5	3	4	3	7	2	3	3	5	5	4	2	5	5	3	3	4.09	
10	28.7	59.4	5.0	6	7	5	10	8	8	9	7	7	6	9	8	8	6	8	9	7	5	7	6	7	8	7.32	
11	20.9	160.5	5.0	4	6	5	8	5	4	6	5	5	5	8	1	5	4	5	6	5	4	6	4	5	6	5.09	
12	30.0	12.8	2.5	6	8	7	10	9	7	9	7	8	7	10	8	9	6	7	10	10	5	7	7	8	9	7.91	
13	25.0	80.5	5.0	5	7	5	10	6	6	8	6	7	6	9	4	6	5	7	7	7	4	5	5	5	6	6.18	
14	36.1	100.5	7.5	8	8	7	10	7	8	9	8	8	7	10	7	8	7	6	7	10	8	8	6	7	7	7.77	
15	15.5	120.7	10.0	3	3	2	7	3	4	4	3	3	4	7	2	2	1	4	4	2	3	4	3	3	3	3.36	
16	24.9	44.8	0.0	6	8	7	8	6	5	6	6	6	5	10	5	2	5	4	7	8	4	6	6	5	7	6.00	
17	14.8	100.0	2.5	4	3	6	5	4	3	5	3	4	4	7	2	2	1	5	5	4	2	3	4	3	4	3.77	
18	36.5	13.2	2.5	8	8	6	10	8	8	9	8	8	7	10	8	8	7	7	9	9	7	7	6	8	9	7.95	
19	30.0	115.5	7.5	7	7	5	10	6	7	8	6	6	6	9	5	7	6	8	8	8	6	6	6	6	6	6.77	
20	19.7	102.7	10.0	4	5	5	9	5	4	6	4	4	5	8	3	5	2	6	6	6	3	4	5	5	4	4.91	
21	30.1	79.8	0.0	4	7	6	10	5	6	7	6	6	6	9	6	4	6	7	7	8	6	7	6	7	7	6.50	
22	24.8	97.4	2.5	4	5	5	9	5	5	6	5	5	5	8	4	3	3	8	6	6	4	6	6	4	5	5.32	
23	15.0	58.4	5.0	4	5	6	3	6	3	8	3	5	3	6	2	2	1	5	7	5	1	4	6	5	2	4.18	
24	20.5	73.3	5.0	3	7	5	7	5	4	7	4	6	4	7	4	1	2	6	6	5	3	5	6	5	4	4.82	
25	35.1	144.1	10.0	7	7	5	10	6	8	8	7	8	6	10	8	9	8	7	7	9	9	6	6	7	8	7.55	

## 4.4. Analysis of the Survey Results

Now that the results of the survey are known, it is possible to estimate the model which will predict the judgment of road users on the basis of the three variables: mean speed, Buffer Index, and Bad Minutes Index. This will be done by means of a multivariate linear regression, in section 4.4.1. Subsequently, the model is visualized in section 4.4.2. Finally, section 4.4.3 discusses the value of reliability based on the results of the estimated model.

### 4.4.1. Performing the Multivariate Linear Regression

It is assumed that the results for each combination are normally distributed. Hence, the average grade for each of the combinations is used in the linear regression. A linear regression means that we try to find values for the betas in the model (see equation 4.2) so that it fits the observed values as good as possible. An *ordinary least squares* (OLS) method is used to do this. This method minimizes the sum of the squared residuals, where a residual is the difference between an observed value and the estimated function value.

As a start, a multivariate regression is performed to estimate all betas in equation 4.2. This yields the results as shown in table 4.7.

Table 4.7: Multivariate linear regression for the linear model in equation 4.2 .

$R^2 = 0.857$	Coefficients	P-value
$\beta_0$	+2.4533	$3.08 * 10^{-05}$
$\beta_{\bar{v}}$	+0.1650	$4.64 * 10^{-10}$
$\beta_{BI}$	-0.0085	0.01
$\beta_{BMI}$	+0.0299	0.50

$R^2$  is a value between 0 and 100 %, which indicates how good the regression fits the observed data: it is the percentage of the response variable variation that is explained by the linear model (Draper and Smith, 1981). For this fit, this is 86 %, which indicates that the regression fits the data quite well. This can also be seen in the figures in section 4.4.2. Furthermore, table 4.7 shows that  $\beta_{\bar{v}}$  has a positive value and  $\beta_{BI}$  has a negative value, which was expected. However,  $\beta_{BMI}$  unexpectedly has a positive value, which would indicate that the higher the BMI, the higher the judgment of the road users. Nevertheless, the last column of table 4.7 shows that the absolute P-value is greater than 0.05, which indicates that this variable is not significant with a 95 % certainty. Hence, the BMI variable is not statistically significant in this model.

Therefore, the next step is to discard the BMI factor from equation 4.2, so that the new linear model becomes:

$$G = \beta_0 + \beta_{\bar{v}}\bar{v} + \beta_{BI}BI \quad (4.5)$$

Based on this model, a new multivariate linear regression is performed, which yields the results that are shown in table 4.8.

Table 4.8: Multivariate linear regression for the linear model in equation 4.5 .

$R^2 = 0.853$	Coefficients	P-value
$\beta_0$	+2.5137	$1.30 * 10^{-05}$
$\beta_{\bar{v}}$	+0.1637	$2.16 * 10^{-10}$
$\beta_{BI}$	-0.0073	0.01

It can be seen that all the betas are statistically significant and that we have an  $R^2$  of 85%. If the coefficient values are substituted into equation 4.5, the following model is obtained:

$$G = 2.5137 + 0.1637\bar{v} - 0.0073BI \quad (4.6)$$

The model indicates that for an increase of the mean speed with 1 km/h, the grade given by road users increases by 0.164. And the grade decreases by the same amount if the mean speed decreases

by 1 km/h. Also, for an increase of the Buffer Index of 10 % the grade decreases by 0.073 and for a decrease of the Buffer Index of 10 % the grade increases by the same amount. From this, it can be concluded that the influence of the Buffer Index on the judgment by road users is relatively small. An extremely large BI of 150 % will only decrease the judgment grade by 1 point.

Finally, tables 4.9 and 4.10 show the results of a linear regression with only respectively mean speed and Buffer Index as a variable. Although the regression with only the mean speed has an outcome that is statistically significant, the  $R^2$  is lower than in the case when both the mean speed and Buffer Index are used. Hence, the model with only mean speed fits the results of the survey less well than the model with both mean speed and the Buffer Index. When only the Buffer Index is used, the Buffer Index parameter is statistically insignificant. Since the results of these two models with a single variable is worse than the model with both the mean speed and Buffer Index (equation 4.6), this is the best linear model and it will be used in the analysis.

Table 4.9: Linear regression for the model with only mean speed as a variable .

$R^2 = 0.800$	Coefficients	P-value
$\beta_0$	+1.8828	$3.41 * 10^{-04}$
$\beta_v$	+0.1634	$1.71 * 10^{-09}$

Table 4.10: Linear regression for the model with only the Buffer Index as a variable .

$R^2 = 0.051$	Coefficients	P-value
$\beta_0$	+6.6345	$2.01 * 10^{-10}$
$\beta_{BI}$	-0.0071	0.280

#### 4.4.2. Visualization of the Linear Model

Since the linear regression has shown that there are two significant variables in the model, it is possible to visualize this by means of a 3-d plot. This is shown in figure 4.3.

Figure 4.3 clearly shows that for both increasing mean speed and decreasing Buffer Index, the judgment grade increases. The range of grades for the observed mean speed and Buffer Index values lies between approximately 4 and 8.

Figure 4.4 shows the same plot as figure 4.3, but from an x-y view. This shows that data points were collected for the entire range of interest.

Figure 4.5 and 4.6 show the plot respectively from an x-z and y-z view, rotated to the angle of the plane. This provides the possibility to observe the effect of a single variable and to see the position of the observed points relative to the estimated model.

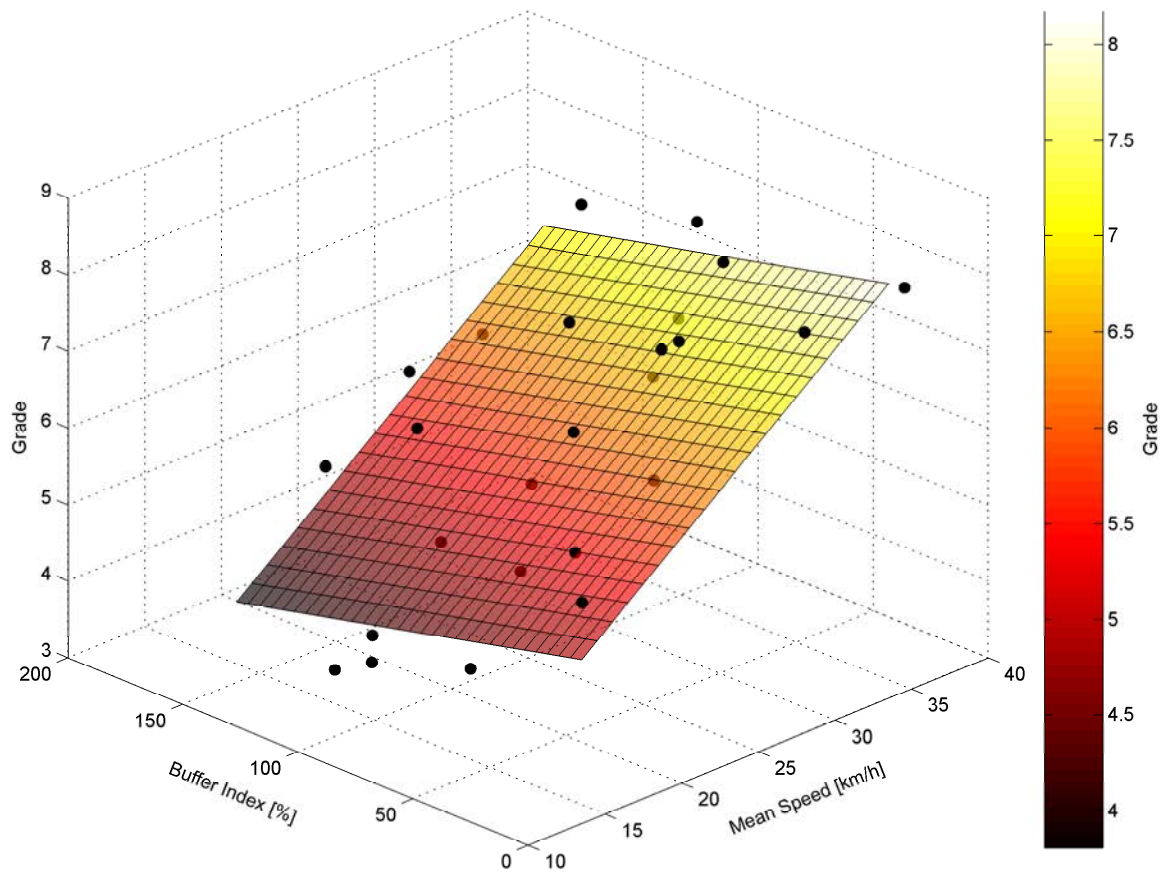


Figure 4.3: Visualization of the linear model (plane) and the results from the survey (dots).

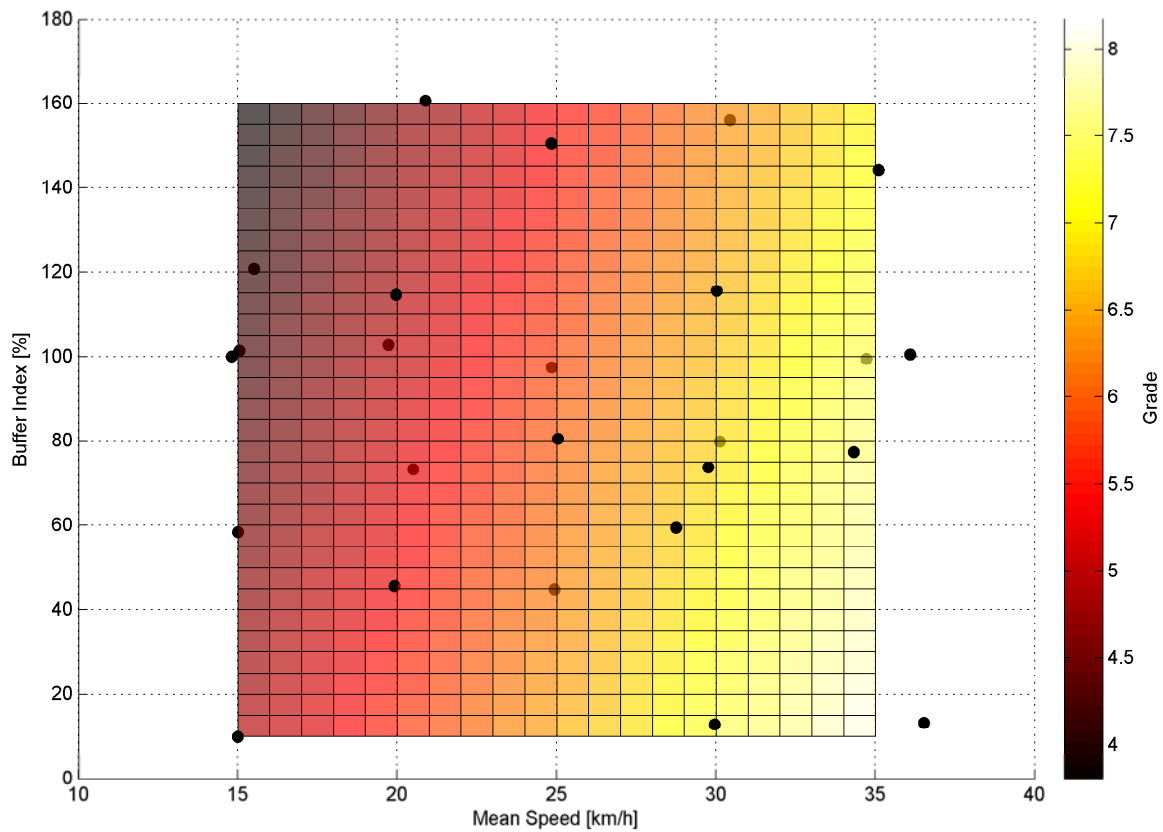


Figure 4.4: Visualization (X-Z view) of the linear model (plane) and the results from the survey (dots).

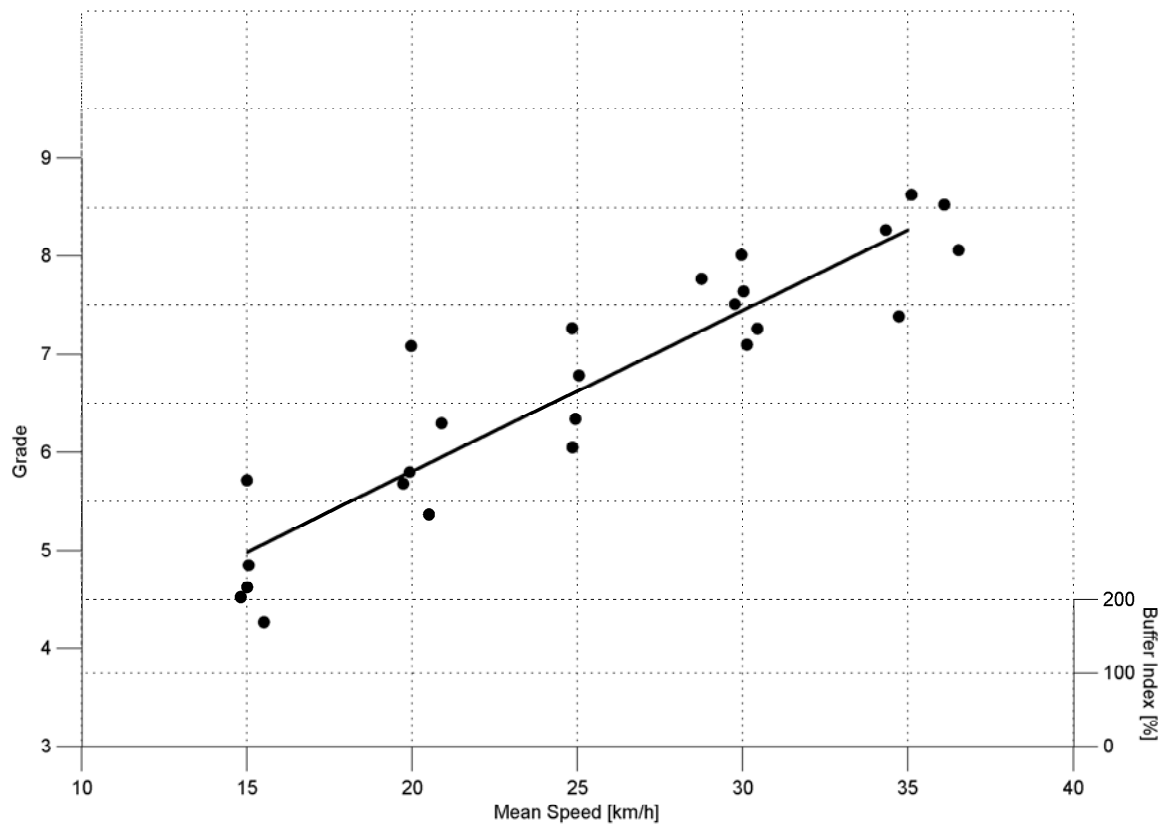


Figure 4.5: Visualization (Y-Z view) of the linear model (plane) and the results from the survey (dots).

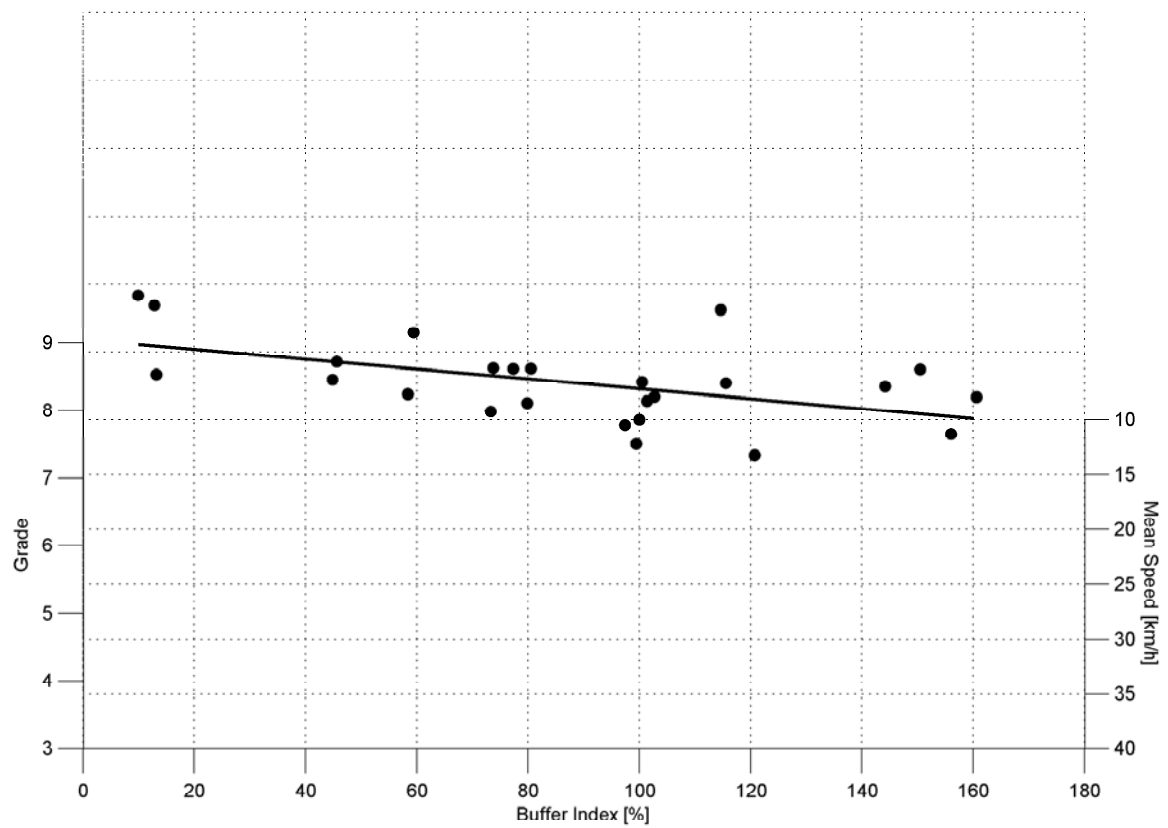


Figure 4.6: Visualization (X-Y view) of the linear model (plane) and the results from the survey (dots).

#### 4.4.3. Discussion: a Model for the Estimation of Road User Judgment

In this chapter, a model was developed to estimate the judgment of a route by road users, based on two characteristics: mean speed and variation in travel times. The results of the linear regression are good, thus the model will be used in the analysis of two routes in Rotterdam (chapter 5). However, some critical comments can be made about this model.

First of all, the survey that was conducted is a stated preference survey. This means that the respondents had to grade virtual situations. There is a probability that respondents would grade differently when they would have experienced the travel times. In particular, it is hypothesized that the extreme travel times play a much larger role in the judgment than was found in this research. Also, the model was only tested onto a relatively small group. Also, a revealed preference survey might show a larger influence the influence of the variation in travel times. Therefore, in order to validate or correct the model it is recommended to do further research by means of a revealed preference survey with a larger group of respondents.

Second, the respondents for this survey have similar characteristics. Most of the respondents are people from the *traffic and transport* department of the *Gemeente Rotterdam*. This means that they have specific experience with and knowledge about traffic. Also, they belong to specific social groups. It is known that both the value of time (VoT) and value of reliability (VoR) have different values for various groups of road user. For example, generally a road user with a high income traveling for business purposes might be willing to pay more for short travel times and a high rate of reliability than a family traveling for recreational purposes. Hence, it could be that the model that was developed in this chapter is valid for a limited group of road users. When further research is done, distinction should be made between user groups.

Moreover, there might also be other factors than mean speed and variability that influence the judgment of road users. These might, for instance, be the time of the day or specific route characteristics, such as: the number of (signalized intersections), vertical and horizontal alignment of the road, traffic intensity, and the surroundings of the route. The latter means for example that road users may find a lower speed or reliability acceptable when a route leads to a busy historical center of a city with much activity on the streets than when they drive through a monotonous suburb. Thus, it is possible that the model for estimating judgment of road users differs per route. Or, seeing it they other way around, with the current model a 6 might be a sufficient grade for route X, while route Y needs at least a 7 to get a positive rating by road users. When further research is done in this field, it is suggested that these route influences are investigated.

Also, the model that was developed in this chapter assumes a linear correlation between the variables (speed and variability) and the judgment of road users. Under the circumstances in this research this seems to work well. However, taking into account the suggestions in the previous paragraphs a linear model may not be sufficient when more variables are added to the model. Hence, more complex models might be necessary in the future.

Finally, although the user model shows that TTR influences the judgment of a route by road users, it is still uncertain how and to what extent this influences the behavior of road users. Deeper investigation into this relation is recommended in order to be able to influence the behavior of road users.

## 4.5. Conclusions & Recommendations

The purpose of this chapter was to achieve sub-objective 4 (see section 1.3): "Develop a model to describe the relation between the project model and the judgment of a route by road users (the *user model*)."

This section provides the conclusions and recommendations related to this sub-objective.

### 4.5.1. Conclusions

The conclusions in this section concern the developed model to estimate road user judgment of a route, based on the three variables that are in the project method which was developed in chapter 3.

- The BMI variable is statistically insignificant in the estimated model to predict road user judgment.
- The estimated model to predict road user judgment on a scale from 1 to 10 is:  $2.5137 + 0.1637\bar{v} - 0.0073BI$  (equation 4.6), with an  $R^2$  of 85 %. This means that for an increase of the mean speed with 1 km/h, the grade given by road users increases by 0.164. And the grade decreases by the same amount if the mean speed decreases by 1 km/h. Also, for an increase of the Buffer

Index of 10 % the grade decreases by 0.073 and for a decrease of the Buffer Index of 10 % the grade increases by the same amount. The influence of the Buffer Index on the judgment grade is relatively small.

#### **4.5.2. Recommendations**

The model that was developed in this chapter is a simple model which can be used as a starting point for developing a more extensive model. During the research, specific ideas came up to further develop this model, which are described below.

- Use a revealed preference survey on a large group of respondents in order to obtain reliable results to estimate a model.
- Make a distinction between various groups of road users, as their value of time and value of reliability can be different.
- Investigate whether there are other factors which influence road user judgment of a route and estimate the magnitude of this influence.
- Determine whether a linear model is sufficient when the previous recommendations are followed. If not, use a more complex model.
- Perform deeper research into the relation between TTR and the behavior of road users.



# 5

## Case Study: Application and Evaluation of the Project Method

In chapter 3 the project method was developed, in order to assess the performance of a route. Chapter 4 showed the development of the user model, which assesses the performance of routes from the perspective of a road user. In this chapter, the project method and the assessment model will be used to analyze travel time data of some routes in Rotterdam. Also, the project method will be compared with the current method in order to evaluate the performance of the project method.

### 5.1. Introduction

The goal of this chapter corresponds to sub-objective 5: *"Evaluate the project method by analyzing travel time data of the main routes in Rotterdam, and comparing the results to the results of the current method (case study)."* In order to perform the case study, the following steps are taken.

1. Describe the situation in Rotterdam (section 5.2). In order to be able to perform a proper analysis and to understand the outcomes, it is necessary to have insight into the characteristics of the routes and traffic system of Rotterdam.
2. Setup the case study (section 5.3). This section sets boundaries and explains the steps that are performed in the case study. Also, information about the available data is provided.
3. Perform the case study (section 5.4). An analysis of the travel time data is performed by means of the project method and the results are interpreted.
4. Evaluate the project method by reviewing the results and comparing it with the current method (section 5.5).

### 5.2. Description of the Rotterdam Case

Figure 5.1 shows the city of Rotterdam. The traffic system is characterized by a diamond-shaped ring road (*Dutch: ruit van Rotterdam*), consisting of motorways A20 (north), A16 (east), A15 (south), and A4 (west). The maximum allowed speed on these motorways is 100 km/h. The ring road is used by both local and through traffic.

On the urban roads within the ring road, the maximum allowed speed is 50 km/h. The S100 road encircles the city center. There are 7 main routes, which connect the ring road with the city center. These routes are marked by letters A-G in figure 5.1. The main routes all have 2x2 lanes. However, the characteristics of these routes can be very different, which will be shown in section 5.3.3. Besides the function of connecting the motorways with the city center, these routes also serve as access roads for the districts they run through.

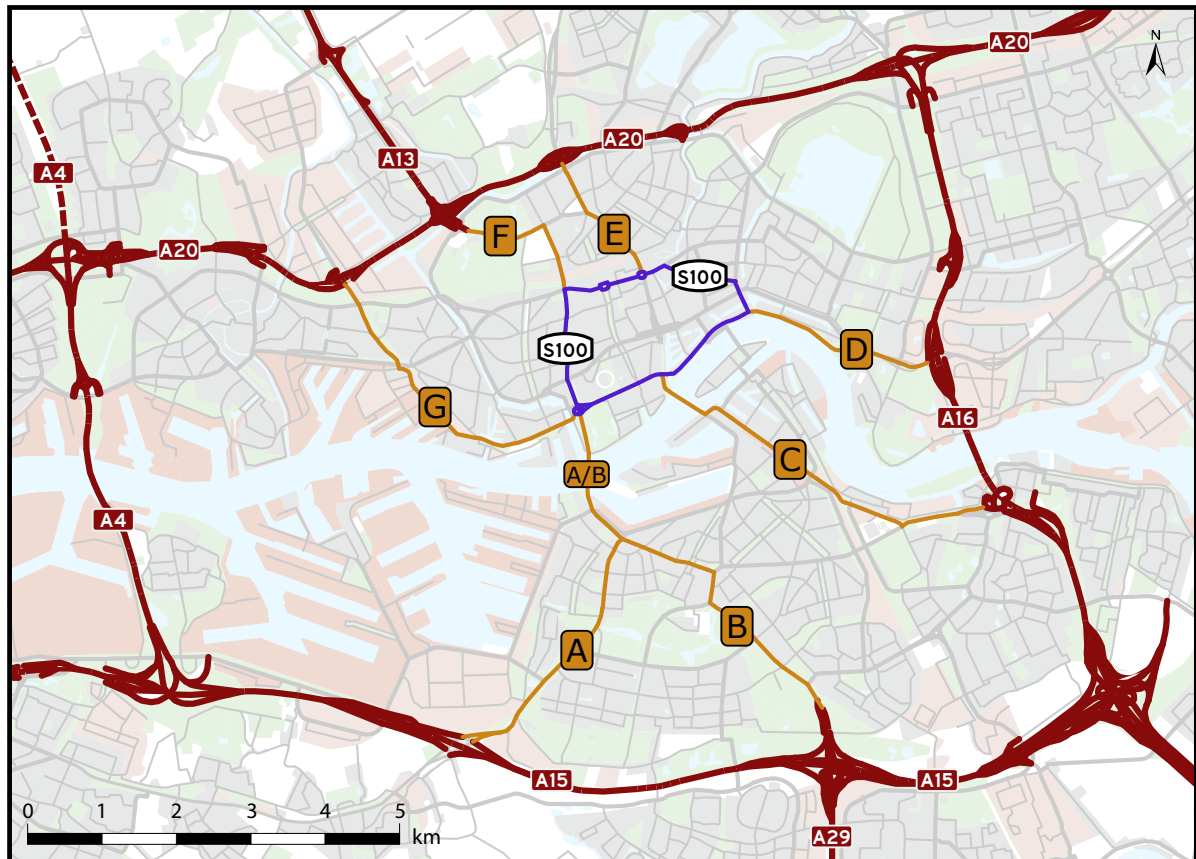


Figure 5.1: Rotterdam, with highways (A-roads), center ring road S100, and main routes A-G.

The Maas river, which runs through Rotterdam, has a major influence on the traffic system. There are several cross-river connections. From west to east these are: Beneluxtunnel (A4), Maastunnel (A/B), Erasmusbrug (C), Koninginnebrug & Willemsbrug (no main route), and Van Brienenoordbrug (A16). These cross-river connections play an important role in keeping the traffic system in and around Rotterdam performing well. If one of these connections fails, this will directly influence the intensities on other cross-river connections.

As described in section 1.2, the *Gemeente Rotterdam* has set a flow objective in order to ensure a good performance of the main routes in the city. This objective states that on the 7 main routes leading from the highway towards the city center and vice versa the mean speed should be at least 25 km/h. The detailed calculation procedure for this indicator can be found in appendix A.

### 5.3. Setup of the Case Study

Now that a description of the traffic system of Rotterdam is provided, the case study is set up in this section. This is done by performing the following steps: determine the scope of the case study (section 5.3.1), explain the available data (section 5.3.2), describe the routes that are investigated in the case study (section 5.3.3), describe the analysis steps (section 5.3.4).

#### 5.3.1. Scope of the Case Study

Investigating Travel Time Reliability of all the main routes in Rotterdam and comparing the results in all possible ways, would consume too much time for this research. Hence, the following choices are made to make the analysis manageable:

1. **2 out of 7 routes** are selected for analysis. These 2 routes are selected because they have different characteristics. These are:
  - **Route B: Vaanweg – Pleinweg.** This route is chosen because from experience it is known to have a high average speed, but it is sensitive to irregularities.

- **Route E: Schieweg – Schiekade.** It is expected that this route has a low but very constant mean speed.
2. **2 directions of the route** are investigated. The flows of inbound and outbound traffic might show different patterns and hence the performance indicator might show different results.
  3. **Only workdays** are taken into account. Workdays generally have more traffic and show a clear morning and evening peak. It is assumed that workdays show a similar pattern, so that the data of these days can be combined.
  4. **Only daytime** is considered. Chapter 3 already explains that the daytime is much more interesting, since there is less traffic during the night and the average speed is higher.
  5. **Routes are investigated as a whole.** Travel time data is available per section of a route, but in order to simplify the analysis, the route is initially investigated as a whole. When the results require this, it is possible to investigate one or more separate route sections.
  6. **Data from the year 2013** is used. In order to test the new performance indicator, data for an extensive period of time is needed. Moreover, traffic patterns and TTR could vary within seasons, so it is interesting to investigate at least a whole calendar year.

### 5.3.2. Available Data for the Case Study

The *Gemeente Rotterdam* initiated the project *Monitoring Rotterdam* in April 2004. The goal of this project is to systematically collect traffic data from important routes in Rotterdam. The design of the collection system, was completed in 2007. The choice was made to use a license plate recognition system, instead of data from signal installations, to collect travel time data. The quality of the license plate recognition system is better, because it measures travel times as opposed to signal systems, which calculate travel times based on the estimated delays at intersections and introduce an error.

The principle of the license plate recognition system is very simple (see figure 5.2). It uses cameras which are able to recognize a license plate. Figure 5.3 shows such a camera. When a vehicle passes a camera at the start of a section, its license plate is stored, together with a time stamp. When the vehicle passes a camera at the end of the section the license plate is scanned again. By subtracting the two times, the travel time of the vehicle is obtained. Since the length of a section between two cameras is known, it is also possible to calculate the mean speed of the vehicle on that section.

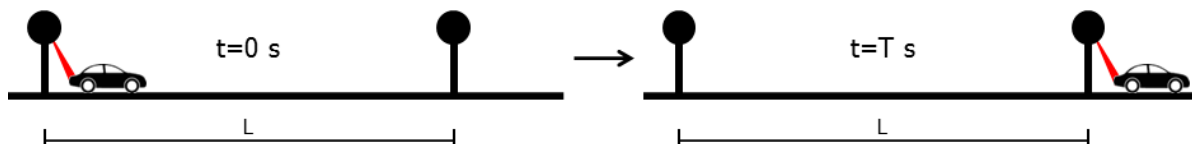


Figure 5.2: Principle of the license plate recognition system for measuring travel times. A vehicle is recognized at the start ( $t=0$  s) and end ( $t=T$  s) of the route. By subtracting the times of passage, the travel time is obtained.



Figure 5.3: A pole with two license plate recognition cameras.

Since 2009, the data collection system in Rotterdam is operational. All of the main routes are divided into sections on which travel times are continuously measured. For each of these sections, the system stores an observed travel time with an aggregation level of 1 minute. The data are used to display real time travel time information on DRIPs and to select a proper traffic management regimes. Moreover, the data are saved in order to calculate whether the flow objective is met.

Besides the license plate recognition cameras which measure travel times and thus mean speeds, there are detector loops which measure local speeds and intensities. For the intensities, three categories of vehicles are distinguished, namely cars, vans, and trucks.

Vialis (2007) provides more detailed information about *Monitoring Rotterdam*, the working of the license plate recognition system, and the algorithm that is used by this system.

### 5.3.3. Characteristics of the Routes that are Analyzed

As stated in section 5.3.1, route B (Vaanweg – Pleinweg) and route E (Schieweg – Schiekade) will be used for analysis. This section explains the characteristics of these routes.

#### Route B: Vaanweg – Pleinweg

Route B begins on the south side of Rotterdam, at the interchange with motorways A15 and A29 (Vaanplein). Via Vaanweg, Strevelsweg, Pleinweg, Doklaan, and Maastunnel, it reaches Droogleevers Fortuynplein, which lies on the center ring road S100. Note that vehicles with a height smaller than 3.6 meter can underpass Droogleevers Fortuynplein, which will reduce travel times as traffic signals are avoided. Furthermore, main route A shares the Maastunnel part with route B and route G also ends at Droogleevers Fortuynplein (see figure 5.1). Figure 5.4 shows the layout of route B, as well as its sections and the locations of signalized intersections.

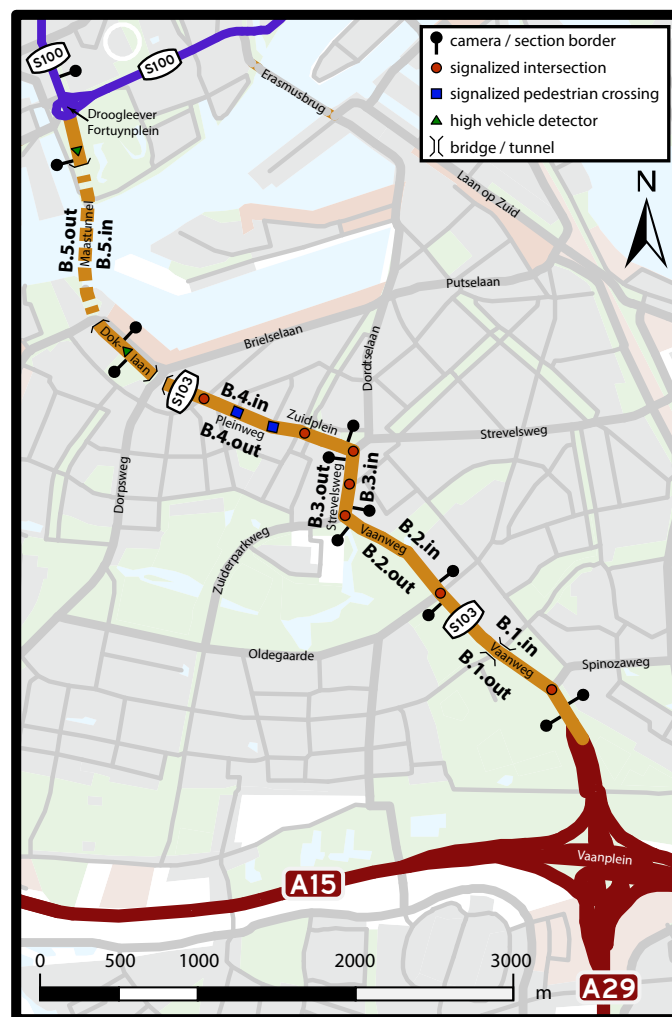


Figure 5.4: Layout of route B

The high vehicle detection system, which is mentioned in figure 5.4, is a system which prevents vehicles that are too high from entering the Maastunnel so that they cannot get stuck or damage the tunnel. When this system is activated, the high vehicle needs to turn around, which can cause delays for other traffic.

Table 5.1 provides detailed information about the lengths of the sections and number of intersections on route B. It consists of 5 sections and with a length of over 5 kilometers, this route is the longest of the main routes in Rotterdam. It can be seen that this route has a small number of signalized intersections in proportion to its length.

Table 5.1: Characteristics of route B: Vaanweg – Pleinweg.  
(SI = signalized intersection, SPC = signalized pedestrian crossing, HVD = high vehicle detector)

	IN				OUT			
Section	Length [km]	SI	SPC	HVD	Length [km]	SI	SPC	HVD
↓ Vaanplein								
B.1	1.154	2	0	0	1.102	1	0	0
↓ Vaanweg - Oldegaarde ↑								
B.2	0.787	1	0	0	1.600	1	0	0
↓ Vaanweg - Strevelsweg ↑								
B.3	0.382	2	0	0	0.399	2	0	0
↓ Zuidplein ↑								
B.4	1.557	2	2	1	1.600	3	2	0
↓ Maastunnel Zuid ↑								
B.5	1.839	0	0	1	1.389	0	0	1
Droogleever Fortuynplein ↑								
<b>TOTAL</b>	<b>5.719</b>	<b>7</b>	<b>2</b>	<b>2</b>	<b>5.261</b>	<b>7</b>	<b>2</b>	<b>1</b>

Figure 5.5 shows some photos taken on route B to give an impression of the surroundings of this route. The surroundings of this route are spacious, especially on Vaanweg. This probably allows drivers to drive faster than the maximum allowed speed of 50 km/h.



(a) From Droogleever Fortuynplein, looking in the direction of the northern entrance of the Maastunnel.



(b) Signalized pedestrian crossing on Pleinweg.





(c) View on Pleinweg from the center divider.



(d) Signalized intersection near Zuidplein.



(e) Vaanweg.



(f) Signalized intersection Vaanweg–Oldegaarde.

Figure 5.5: Impression of route B.

**Route E: Schieweg – Schiekade**

Route E runs in the northern part of the city. It starts at motorway A20, at the interchange Schieplein. From there it leads to the S100, via Schieweg and Schiekade to the roundabout at Hofplein. Figure 5.6 shows the layout of route E, as well as its sections and the locations of signalized intersections.

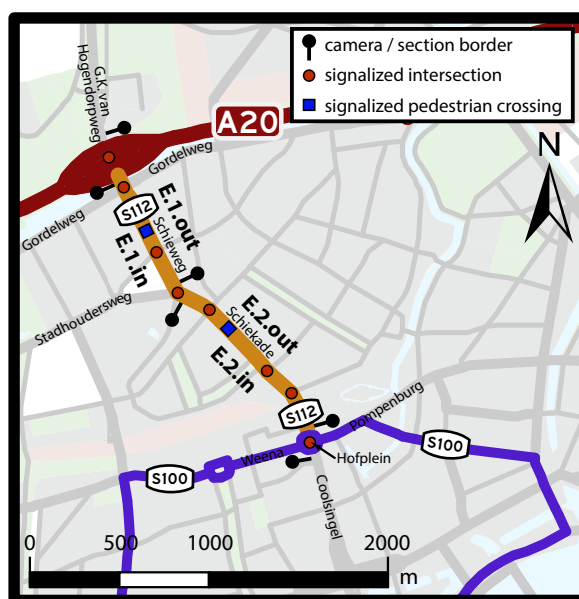


Figure 5.6: Layout of route E.

Table 5.2 provides detailed information about the lengths of the sections and number of intersections on route E. With a length of about 2 kilometers, this route is one of the shortest main routes in Rotterdam. It can be seen that this route has a large number of signalized intersections in proportion to its length.

Table 5.2: Characteristics of route E: Schieweg – Schiekade.

	IN				OUT			
Section	Length [km]	SI	SPC	HVD	Length [km]	SI	SPC	HVD
↓ Schieplein								
B.1	0.836	3	1	0	0.942	3	1	0
↓ Schieweg - Stadhoudersweg ↑								
B.2	1.176	4	1	0	1.121	4	1	0
Hofplein ↑								
<b>TOTAL</b>	<b>2.012</b>	<b>7</b>	<b>2</b>	<b>0</b>	<b>2.063</b>	<b>7</b>	<b>2</b>	<b>0</b>

Figure 5.7 shows some photos taken on route E to give an impression of the surroundings of this route. There are many signalized intersections and there is a tram line running on the center divider. The latter causes the cross sectional profile of this route to be relatively small.



(a) Schiekade, looking in the direction of Hofplein.



(b) Looking from Hofplein on Schiekade.



(c) Schiekade.



(d) Schiekade, seen from center divider with tram line.





(e) Schieweg.



(f) Schieplein and interchange with motorway A20.

Figure 5.7: Impression of route E.

### 5.3.4. Analysis Steps

The goal of the analysis is to provide insight into the performance of routes B and E according to the new performance indicator and judgment of the road users. This is done by first applying the project method and subsequently comparing results of: different periods, the two directions of a route, and different routes. This is detailed by the following list of analysis steps:

#### 1. Application of the project method

- (a) For each of the two main routes (B and E), in both directions, the project method is applied per quarter of the year 2013.
- (b) The value of the performance from a travelers perspective according to the model developed in chapter 4 is calculated.

#### 2. Interpretation of the results

- (a) The travel times are visualized by means of bandwidth graphs. These graphs are used in combination with the results of the project method order to obtain an image of the performance of the routes.
- (b) The results per period of the day are compared with each other.
- (c) The results per quarter of each route and direction are compared with each other.
- (d) The two directions of each route are compared with each other.
- (e) The results of the two observed routes are compared with each other.

## 5.4. Analysis of the Performance of Two Routes

Following the steps mentioned in section 5.3.4, in this section the case study is performed. This means that the project method is applied to travel time data of the two selected routes in both directions (section 5.4.1). Subsequently, the travel time data is visualized, explained, and interpreted by comparing the results in various ways (section 5.4.2).

### 5.4.1. Applying the New Method

The project method, which was developed in chapter 3 is applied to travel time data of the two selected routes in both directions separately. This is done for each quarter of the year 2013. According to the model that was developed in chapter 4, the judgment of road users based on the results of the project method is calculated. Finally, the current method (see appendix A) is also applied and these results are included in order to make a comparison between the current method and project method in the next part possible.



**Route B: Vaanweg – Pleinweg (Inbound)**

For route B inbound, the results of the aforementioned calculations are shown in table 5.3. Figures 5.8, 5.9, and 5.10 respectively display the outcomes for the 3 indicators of the project method. Figure 5.11 shows the performance grades.

Table 5.3: Performance Indicators for Route B Inbound.

		Morning Peak	Inter-Peak	Evening Peak	Current Indicator
<b>Q1</b>	<b>Average speed [km/h]</b>	28.2	34.1	30.8	<b>32.5</b>
	<b>Buffer Index (BI) [%]</b>	46.6	11.1	22.9	
	<b>Bad Minutes Index (BMI) [%]</b>	0.3	0.5	1.2	
	<b>Performance Grade</b>	<b>6.8</b>	<b>8.0</b>	<b>7.4</b>	
<b>Q2</b>	<b>Average speed [km/h]</b>	30.8	33.7	30.7	<b>33.1</b>
	<b>Buffer Index (BI) [%]</b>	47.0	13.3	32.4	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.0	0.0	
	<b>Performance Grade</b>	<b>7.2</b>	<b>8.0</b>	<b>7.3</b>	
<b>Q3</b>	<b>Average speed [km/h]</b>	32.5	34.0	31.8	<b>33.9</b>
	<b>Buffer Index (BI) [%]</b>	63.2	13.4	29.8	
	<b>Bad Minutes Index (BMI) [%]</b>	1.4	0.2	0.1	
	<b>Performance Grade</b>	<b>7.4</b>	<b>8.0</b>	<b>7.5</b>	
<b>Q4</b>	<b>Average speed [km/h]</b>	28.4	33.0	26.4	<b>31.2</b>
	<b>Buffer Index (BI) [%]</b>	54.8	15.8	44.9	
	<b>Bad Minutes Index (BMI) [%]</b>	1.9	0.6	3.3	
	<b>Performance Grade</b>	<b>6.8</b>	<b>7.8</b>	<b>6.5</b>	

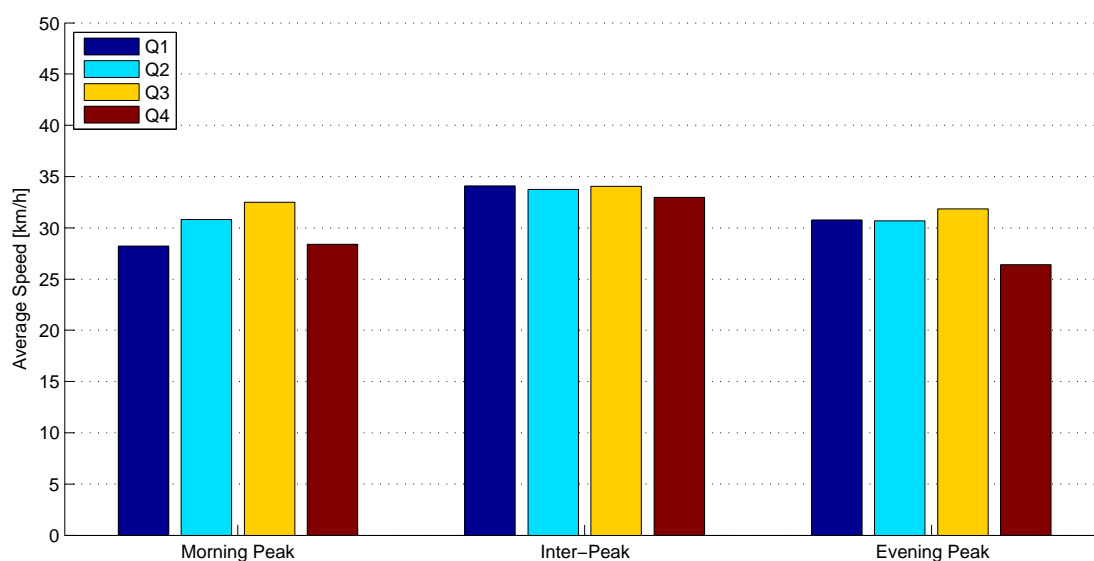


Figure 5.8: Mean speed on route B inbound in three periods of the day and per quarter of the year 2013.

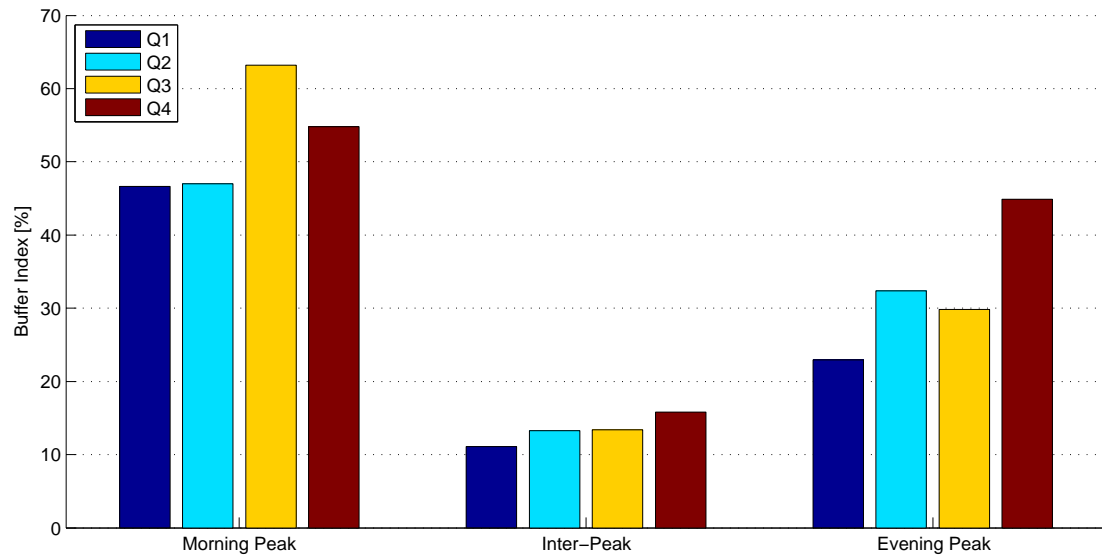


Figure 5.9: Buffer Index on route B inbound in three periods of the day and per quarter of the year 2013.

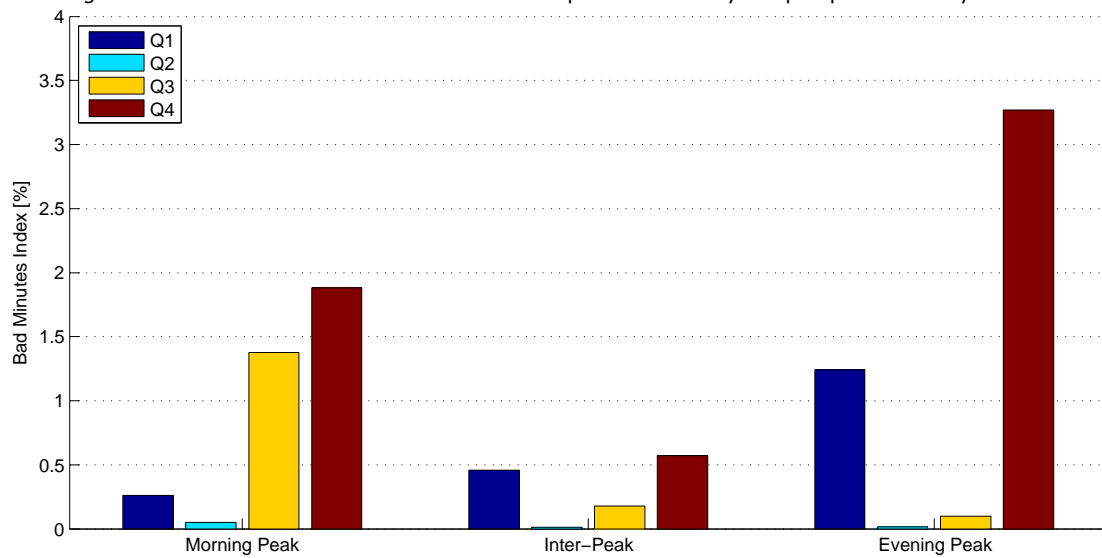


Figure 5.10: Bad Minutes Index on route B inbound in three periods of the day and per quarter of the year 2013.

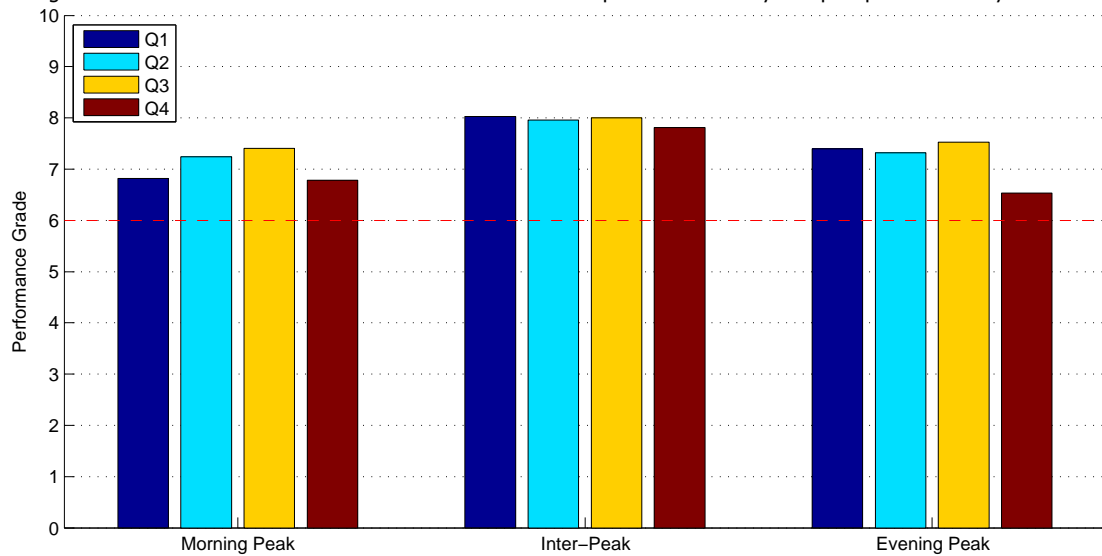


Figure 5.11: Performance Grade on route B inbound in three periods of the day and per quarter of the year 2013.

**Route B: Vaanweg – Pleinweg (Outbound)**

Table 5.4 shows the results of the calculations for route B outbound. For reasons of conciseness, the corresponding bar graph figures can be found in appendix C.

Table 5.4: Performance Indicators for Route B Outbound.

		<b>Morning Peak</b>	<b>Inter- Peak</b>	<b>Evening Peak</b>	<b>Current Indicator</b>
<b>Q1</b>	<b>Average speed [km/h]</b>	33.3	33.7	30.0	<b>33.1</b>
	<b>Buffer Index (BI) [%]</b>	11.5	13.1	60.0	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.2	1.4	
	<b>Performance Grade</b>	<b>7.9</b>	<b>7.9</b>	<b>7.0</b>	
<b>Q2</b>	<b>Average speed [km/h]</b>	33.6	33.3	31.5	<b>33.4</b>
	<b>Buffer Index (BI) [%]</b>	12.0	15.5	35.0	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.1	0.0	
	<b>Performance Grade</b>	<b>7.9</b>	<b>7.9</b>	<b>7.4</b>	
<b>Q3</b>	<b>Average speed [km/h]</b>	34.0	33.7	31.3	<b>33.7</b>
	<b>Buffer Index (BI) [%]</b>	11.1	13.7	51.9	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.0	0.7	
	<b>Performance Grade</b>	<b>8.0</b>	<b>7.9</b>	<b>7.3</b>	
<b>Q4</b>	<b>Average speed [km/h]</b>	33.5	32.1	21.7	<b>30.6</b>
	<b>Buffer Index (BI) [%]</b>	11.9	26.4	97.6	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.8	11.9	
	<b>Performance Grade</b>	<b>7.9</b>	<b>7.6</b>	<b>5.4</b>	

**Route E: Schieweg – Schiekade (Inbound)**

Table 5.5 shows the results of the calculations for route E inbound. The corresponding bar graph figures can be found in appendix C.

Table 5.5: Performance Indicators for Route E Inbound.

		Morning Peak	Inter-Peak	Evening Peak	Current Indicator
<b>Q1</b>	<b>Average speed [km/h]</b>	24.2	23.0	21.3	<b>22.8</b>
	<b>Buffer Index (BI) [%]</b>	15.11	16.6	11.6	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.0	0.0	
	<b>Performance Grade</b>	<b>6.4</b>	<b>6.2</b>	<b>5.9</b>	
<b>Q2</b>	<b>Average speed [km/h]</b>	23.3	21.8	21.4	<b>22.4</b>
	<b>Buffer Index (BI) [%]</b>	23.9	23.7	17.8	
	<b>Bad Minutes Index (BMI) [%]</b>	0.6	1.3	0.1	
	<b>Performance Grade</b>	<b>6.2</b>	<b>5.9</b>	<b>5.9</b>	
<b>Q3</b>	<b>Average speed [km/h]</b>	25.3	23.6	22.7	<b>24.3</b>
	<b>Buffer Index (BI) [%]</b>	17.9	19.5	13.6	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.0	0.1	
	<b>Performance Grade</b>	<b>6.5</b>	<b>6.2</b>	<b>6.1</b>	
<b>Q4</b>	<b>Average speed [km/h]</b>	23.9	22.2	20.2	<b>22.6</b>
	<b>Buffer Index (BI) [%]</b>	15.6	37.2	49.7	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.0	2.5	
	<b>Performance Grade</b>	<b>6.3</b>	<b>5.9</b>	<b>5.5</b>	

**Route E: Schieweg – Schiekade (Outbound)**

Table 5.6 shows the results of the calculations for route E outbound. The corresponding bar graph figures can be found in appendix C.

Table 5.6: Performance Indicators for Route E Outbound.

		<b>Morning Peak</b>	<b>Inter-Peak</b>	<b>Evening Peak</b>	<b>Current Indicator</b>
<b>Q1</b>	<b>Average speed [km/h]</b>	18.7	21.8	21.3	<b>21.5</b>
	<b>Buffer Index (BI) [%]</b>	60.5	14.7	42.4	
	<b>Bad Minutes Index (BMI) [%]</b>	1.8	0.2	0.2	
	<b>Performance Grade</b>	<b>5.2</b>	<b>6.0</b>	<b>5.7</b>	
<b>Q2</b>	<b>Average speed [km/h]</b>	20.6	22.0	21.5	<b>22.4</b>
	<b>Buffer Index (BI) [%]</b>	38.7	19.8	46.5	
	<b>Bad Minutes Index (BMI) [%]</b>	0.0	0.4	0.1	
	<b>Performance Grade</b>	<b>5.6</b>	<b>6.0</b>	<b>5.7</b>	
<b>Q3</b>	<b>Average speed [km/h]</b>	21.0	23.2	20.4	<b>22.9</b>
	<b>Buffer Index (BI) [%]</b>	52.7	18.1	76.8	
	<b>Bad Minutes Index (BMI) [%]</b>	0.6	0.3	2.7	
	<b>Performance Grade</b>	<b>5.6</b>	<b>6.2</b>	<b>5.3</b>	
<b>Q4</b>	<b>Average speed [km/h]</b>	17.0	22.1	15.7	<b>20.5</b>
	<b>Buffer Index (BI) [%]</b>	64.7	24.4	76.5	
	<b>Bad Minutes Index (BMI) [%]</b>	3.6	0.5	6.5	
	<b>Performance Grade</b>	<b>4.9</b>	<b>6.0</b>	<b>4.6</b>	

**5.4.2. Interpreting the Results of the Project Method**

Now that the calculations have been performed, the results can be interpreted. This section describes the interpretation of the results, according to the steps mentioned in the end of section 5.3.4.

**Visualization of Travel Time Data**

The results of applying the project method, which are shown in section 5.4.1 can be used for interpretation and evaluation of the project method. In order to get a better insight into the course of the travel time during the day and the size of variation in travel times, bandwidth graphs are used. Bandwidth graphs are created by overlaying travel time data of multiple days. This gives the possibility to observe both the mean travel time on a route during the day as well as the size of variation in travel times at a single glance. In order to keep the main body of this report concise, bandwidth graphs of each quarter of the year of the analyzed routes can be found in appendix C. Even more of these graphs (for different sections of the routes and periods of the year) can be found on the CD that is supplied with this report. This CD also contains the travel time data and the *Matlab* scripts that were used to create the figures. In the remainder of this section, it is explained how a bandwidth graph is created and how it can be used.

An example of a bandwidth graph is shown in figure 5.12. If only the mean travel time (dotted line) is observed, it can be seen that it varies along the day. A point on this line shows the travel time on the observed route when a vehicle enters the route at the corresponding time. The following pattern can be seen. The travel time on the observed route is a little less than 8 minutes during the night.

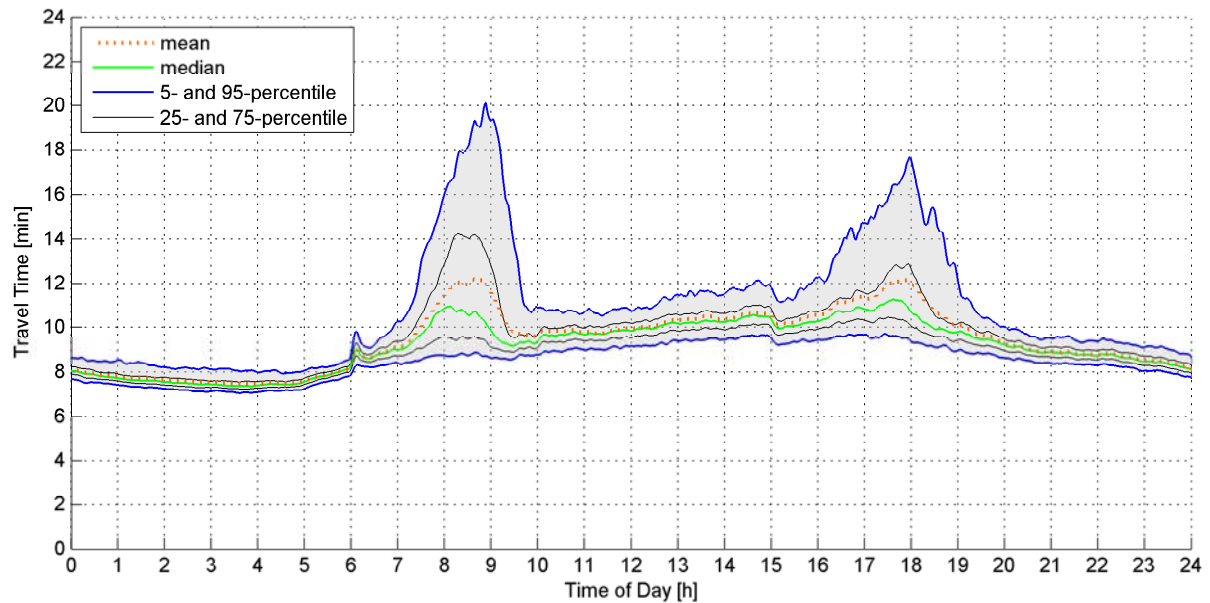


Figure 5.12: Example of a bandwidth graph of travel times on working days in a complete year.

Shortly after 07:00, the morning peak starts. The travel time increases to around 12 minutes at 08:00. This is caused by an increased traffic intensity both on the observed route, as well as on the routes crossing the observed route, by causing increased delays at signalized intersections. The travel time decreases to a little under 10 minutes between 09:00 and 09:30. During the afternoon, the travel time increases gradually, until it becomes 12 minutes between 17:30 and 18:00. From 18:00, the travel time decreases again, until it is 9 minutes at around 20:30. From 22:30, the travel time continues to decrease, to around 8 minutes at 24:00. The dents in this graph, which are visible at 06:00, 10:00, and 15:00 are caused by the application of different traffic management regimes at signalized intersections, which are focused on the changing traffic patterns during the day.

The size of the variation of travel times between different days can be determined by observing the distances between the solid lines. The solid lines represent (from top to bottom): the 95-, 75-, 50-, 25- and 5-percentile values of the observed travel times when a vehicle enters the route on a certain minute of the day. The  $x$ -percentile value is calculated by sorting the observed travel times in a certain minute of the day from shortest to longest and choosing the value that is at  $x$  % of the row. If the upper line (95-percentile) in figure 5.12 is observed, this means that in 5 % of the observed days, the travel time was higher than the corresponding value in the graph, while in 95 % the travel time was lower. Hence, if the percentile lines are further apart, the variation in travel times is larger. In figure 5.12, the variation in the peaks is larger than it is during the afternoon. During the night, the variation is relatively small. This can be explained by the fact that at night there are more or less free flow conditions, due to low traffic intensities. During the peaks, the intensity increases, causing more complex traffic relations, which increases the variation in travel times.

To conclude, a few remarks about bandwidth graphs:

- Bandwidth graphs can be created from travel times measured in different periods. For example: a month, a quarter of a year, or a year. However, when too few days are used, the influence of single days on the graph can be too large. On the other hand, when too many days are used, the effect of extremes is not visible anymore. For this analysis, we choose to use quarters of a year. This period seems to have the right amount of days to form a reliable image, and possible seasonal influences, such as weather and varying traffic intensities, can be observed.
- Note that the distance between the 95-percentile line and the median is generally equal to or larger than the distance between the 5-percentile line and the median. This means that the travel time distribution is right-skewed. In other words, a delay relative to the median travel time is generally larger than a shorter travel time relative to the median. This is explained by the fact that in theory a travel time can increase infinitely (for example when a road is completely blocked for some time), while it can never be shorter than approximately the free flow travel time.

- A bandwidth graph can be created from travel times measured in different periods. For example: a month, a quarter of a year, or a year. However, when too few days are used, the influence of single days on the graph can be too large. On the other hand, when too many days are used, the effect of extremes is not visible anymore. For this analysis, we choose to use quarters of a year. This period seems to have the right amount of days to form a reliable image, and possible seasonal influences, such as weather and varying traffic intensities, can be observed.

### **Comparison of Periods of the Day**

Tables 5.3 – 5.6 show that the mean speed in the evening peak is generally significantly lower than during the off-peak period. This is especially true for the evening peak in quarter 4. The difference between morning peak and off-peak period is generally smaller and sometimes the mean speed in the morning peak is even larger.

When the buffer indices are observed, different patterns per route and direction arise. For route B inbound, the Buffer Index is the highest in the morning peak (average of 42.3 %), followed by the evening peak (26.0 %) and the inter-peak period (10.7 %). The outbound direction yields a different result: evening peak (48.9 %), inter-peak (13.7 %) and morning peak (9.3 %). It can be seen that for this route, the period with the highest intensity (morning peak for inbound traffic and evening peak for outbound traffic) also have the largest variation in travel times. For route E inbound, the buffer indices are on average between 14.5 and 19.4 %, so it is small and there are small differences. However, for the outbound direction for route E, the morning peak (43.3 %) and evening peak (48.4 %) are significantly less reliable than the inter-peak period (15.4 %). This can be explained by spillback effects from the busy motorway A20, via the interchange at the end of the outbound route. This happens when there is a traffic jam on the motorway near the interchange, which prevents traffic from getting onto the motorway. This will eventually cause a traffic jam on the underlying road network, leading to longer travel times, possibly also for traffic that does not want to enter the motorway. The corresponding bandwidth graphs on the CD attached to this report show that a major part of the decrease of mean speed and reliability in the peak hours originates in section E.1 (see figure 5.7), which is the section that connects route B and motorway A20.

The Bad Minutes Index generally shows very low values, which means that extreme travel times rarely occur. An exception on this is the quarter 4.

### **Comparison of Quarters of a Year**

In tables 5.3 – 5.6 it can be seen that generally quarter 4 has the worst performance of all quarters, followed by quarter 1, although the differences are not enormous. Both the current method as well as the project method and the Buffer Index show this. Quarter 3 generally performs best. This can be explained by seasonal effects. Fall and winter fall in quarters 1 and 4. The weather in these quarters is generally worse than in quarters 2 and 3. This causes more people to travel by car, instead of going by bicycle. This will lead to increased traffic intensities and longer travel times. Moreover, bad weather and darkness may also cause the road capacity to drop, which can also lead to longer travel times. The better performance of quarter 3 is explained by the fact that the summer holidays take place in this quarter. During the holidays, traffic intensity is generally lower, because many people are on vacation or do not travel to their work or school during peak hours. This will lead to smaller travel times.

### **Comparison of Directions of a Route**

If tables 5.3 and 5.4 are compared, it can be seen that the mean speeds and performance grades lie in the same range for both inbound and outbound traffic on route B. The current method shows the same image. However, note that for both directions the evening peak in quarter 4 performs significantly worse compared to the other periods. It can also be seen that for the inbound direction, the morning peak generally has the lowest score, while for the outbound direction the evening peak has the lowest score. This can be explained by traffic patterns. More road users will enter the city in the morning, to go to work or school, and they will leave the city in the evening peak.

For route E (tables 5.5 and 5.6), it can be seen that the mean speeds and performance grades are generally slightly higher for inbound traffic. This can again be explained by spillback effects from motorway A20.

### Comparison of Routes B and E

The first thing that becomes clear when tables 5.3 and 5.4 are compared with tables 5.5 and 5.6 is that the mean speed on route B are always much higher than on route E: an average of 31.5 km/h on route B and 21.6 km/h on route E. This can be explained by the very different character of both routes: route E has a narrower profile than route B and there are 2.7 times as much signalized intersections per km on route E than on route B. The assumption that route B has much higher mean speeds than route E is therefore confirmed.

Averaging of the buffer indices of both routes yields the following results: route B inbound – 32.9 %, route B outbound – 30.0 %, route E inbound – 21.9 %, and route E outbound – 44.7 %. This means that the assumption that route E has a higher reliability than route B is not completely true. The inbound direction of route E seems to be more reliable than both directions of route B, but the outbound direction of route E has a higher Buffer Index, indicating that the variation in travel times is larger. This is explained by the interchange between route E and motorway A20, which can cause spillback. The variation in traffic intensities and other circumstances on the motorway do also affect the reliability on route E.

## 5.5. Evaluation of the Project Method

Now that the analysis of two routes is performed by means of the project method, it is compared with the current method.

Tables 5.3 – 5.6 show that the current method speed in many cases overestimates the averages speeds in the peak periods, while it slightly underestimates the speed in the inter-peak periods. There are two reasons for this. First, the start and end times of the peak periods are chosen differently in both methods. In the current method, the morning peak starts at 7:00 and ends at 9:00, while the evening peak period is from 16:00 until 18:00. The project method determined the start and ends of the peak periods visually (see chapter 3). The morning peak is from 07:30 to 09:15 and the evening peak from 16:30 to 18:30. These times capture the effect of the peaks better, which makes the differences between the periods within a day larger than for the current method. Second, the current method also takes weekend days into account. In weekends, there is generally much less traffic and there are no peak periods. This means that travel times will be shorter on weekend days. This will increase the calculated average speed.

It can also be seen that the outcome of the current method is much closer to the outcomes of the project method when the differences in mean speeds between the periods within a day are smaller. Hence, for a route with a higher variation in travel times within a day, the current method provides less accurate results and the project method gives a more detailed insight into the performance of a route.

Furthermore, the current method barely shows the influence of a lower reliability. For example, observe quarter 4 of route B Outbound (table 5.4). The evening peak has a mean speed of 21.7 km/h and a Buffer Index of 97.6 %, but the current method shows a speed of 30.6 km/h, which is much above the minimum of 25 km/h. This proves that the current method in some cases does not provide information about the performance of a route that is detailed enough.

## 5.6. Conclusions & Recommendations

The goal of this chapter was to achieve sub-objective 5: *"Evaluate the project method by analyzing travel time data of the main routes in Rotterdam, and comparing the results to the results of the current method (case study)."* This section provides the conclusions and recommendations related to this sub-objective.

### 5.6.1. Conclusions

The first conclusion drawn from the research in this chapter is about the visualization of travel time data. Bandwidth graphs provide the opportunity to present big amounts of travel time data in such a way that it is easy to observe the daily pattern of the travel time on a route, as well as the size of the variation in travel times.

Second, there are some conclusions to be drawn from the case study, in which the project method was applied to real travel time data of two routes in Rotterdam.

- Within a day, both mean speed and TTR on a route can strongly vary.



- Spillback effects from motorways can have a large impact on the mean speed and TTR of an urban route.
- The order of performance of routes per quarter of the year from best to worst is: 4, 1, 2, 3. These are caused by seasonal effects. However, the difference in the performance between quarters is generally small.
- A route generally shows a similar performance in both directions. However, there might be variations due to traffic patterns which are dominant in the morning in one direction and dominant in the other direction in the evening. Also, spillback effects from other roads can influence the performance of one direction of a route, while the opposite direction is not affected.
- The comparison of two different routes showed that low travel times are not necessarily linked to a high TTR and vice versa. A route can have high travel times, while at the same time a high TTR and vice versa.

Finally, a comparison between the current method and the project method yields the following results.

- The current method overestimates the mean speeds in peak periods in many cases, while it slightly underestimates the speed in inter-peak periods. This is caused by (1) a different choice for the start and end times of the peak periods, and (2) the fact that weekend days are also included in the current method, on which the mean speed is generally higher.
- The outcome of the current method is much closer to the outcomes of the project method when the differences in mean speeds between the periods within a day are smaller. Hence, for a route with a higher variation in travel times within a day, the current method provides less accurate results and the project method gives a more detailed insight into the performance of a route.
- The current method barely shows the influence of a decreased TTR. In some cases, this means that although the indicated mean speed is high, the TTR can be very low. In such a case, the current method does not provide a representative image of the performance of a route.

### 5.6.2. Recommendations

Based on the conclusions that were drawn in the previous section, the following recommendations for practice can be made.

- Use bandwidth graphs in order to quickly get an idea about the travel time pattern and travel time variation size on a route. Bandwidth graphs of different periods of the year can be created in order to compare their performance. Bandwidth graphs of sections within a route can be used to get a more precise insight into the contribution of different sections to the travel time and TTR.
- Use the project method instead of the current method. The current method can provide a incorrect image of the performance of a route. The mean speed within some parts of the day can be greatly overestimated by the current method. Moreover, the current method does not always show the influence of an increased variability in travel times.
- The project method is not specifically adapted to the Rotterdam situation. It can be used in the city of Rotterdam, but the method can of course also be used on urban routes in other cities, when travel time data are available. In order to obtain reliable results, travel time measurements of at least a few weeks should be used. Also, the aggregation level should not be too high, in order to prevent loss of detail. The project method gives a more detailed insight into the performance of a route compared to the current method, which only uses mean speeds.



# 6

## Conclusions & Recommendations

In this research, a new method to assess the performance of urban routes was developed: the project method. Traditional methods use average conditions – generally speed or travel time – to measure the performance of a route. However, it is hypothesized that the size of the variation of travel times has an impact on user behavior. Therefore, variability in travel times, which can be regarded as Travel Time Reliability (TTR), is included in the project method.

In order to be able to add a factor for TTR to project method, first a definition of TTR was established. Second, the appropriate measures for TTR were selected and the project method was created. Subsequently, by means of a survey, a model (the user model) was created by in order determine the relation between the project method and the judgment of routes by road users. Finally, both the project method and the user model were applied to real travel time data from Rotterdam. Based on the results, the project method was evaluated.

In this chapter, the conclusions of the research will be presented first (section 6.1). Subsequently, recommendations for practice (section 6.2) and recommendations for further research (section 6.3) are presented.

### 6.1. Results, Contributions, and Conclusions

The main objective of this Master Thesis was:

**Develop and evaluate a performance method for routes in urban areas, in which Travel Time Reliability is included.**

The core of the conclusions of this research can be phrased as follows:

**In this research, we showed that expressing the performance of a route by not only the mean speed, but by the TTR as well, increases the insight into the performance of a route. The reason for this is that insight into the size of the variation in travel times is not captured when only the mean speed is calculated. Also, observing the morning peak, evening peak, and inter-peak period separately, provides a more detailed image of the performance of a route. Furthermore, we showed that TTR influences the judgment of route performance by road users: a higher variation yields a decreased appreciation. However, compared to the influence of the mean speed, the influence of TTR is relatively small.**

**In order to obtain a better insight into the field of TTR and to be able to use it in practice, it is recommended to investigate which factors influence TTR and how TTR affects the behavior of travelers.**

The detailed conclusions of this research are explained in the remainder of this section. These are arranged according to the five sub-objectives that were formulated at the start of the research:

**Sub-objective 1**

Establish an overview of useful insights into the field of Travel Time Reliability.

**Sub-objective 2**

Determine which measures of Travel Time Reliability are available and evaluate these.

**Sub-objective 3**

Develop a new method to assess the performance of a route, in which Travel Time Reliability is included (the *project method*).

**Sub-objective 4**

Develop a model to describe the relation between the project model and the judgment of a route by road users (the *user model*).

**Sub-objective 5**

Evaluate the project method by analyzing travel time data of the main routes in Rotterdam, and comparing the results to the results of the current method (case study).

### 6.1.1. Overview of Insights into the Field of Travel Time Reliability

The literature review yielded different learnings, which were used as a starting point for this research. This section explains these.

#### The Emergence of Travel time Reliability as a Performance Measure

In the past, analysis of transportation networks focused primarily on the estimation and evaluation of average conditions for a given time period. However, recently, there has been an increasing interest in TTR, because this is assumed that TTR and predictability is of utmost importance to the public and is often of even greater concern than the travel time itself. Variability in travel times leads to uncertainty that commuters and haulers find frustrating and costly. Moreover, TTR may influence road user behavior. It is useful for road managers and planners to have knowledge about the relations between TTR and road user behavior, because this can be used to predict or even deliberately influence this behavior by applying traffic management measures. Consequently, there has been an effort to better understand the causes and consequences of TTR. However, the body of knowledge is still relatively sparse.

#### The Definition of Travel Time Reliability

*Travel Time Reliability* is defined as: "The ability of the transport system to provide the expected level of service quality, upon which users have organized their activities." Hence, a route with a high TTR means that the travel time that road users experience during a trip is equal to the travel time that was expected. The larger the deviation and the more often it occurs, the lower the TTR of a route. Thus, a large TTR does not necessarily imply that the travel time on a route is constant during the day.

#### Research in Urban Areas

There has not been much investigation into TTR in urban areas; most research focuses on motorways. There are two major reasons for this. The first reason is that freeways are most generally equipped with instruments for data collection. A second reason is that urban environments are more difficult to investigate, because these have more complex traffic interactions than motorways. Due to large differences in the characteristics of these road types, a different approach might be needed and conclusions may also vary.

#### Time Frames for TTR

There are three levels of time frames to approach TTR: inter-day, inter-period, and inter-vehicle. For this research, inter-day variations are observed, because deviations from a daily pattern will influence TTR. Inter-period variations will be known by road users and inter-vehicle variations only have a small influence on travel times.

### 6.1.2. Overview and Evaluation of Available Measures of Travel Time Reliability

The definition of a TTR measure is ambiguous. There are many TTR measures that can be used. Furthermore, there are different options to classify and evaluate the different TTR measures. These are explained in this section.

#### Classification of TTR Measures

TTR measures can be classified on the basis of different characteristics:

- Perspective: service provider or service user. The service provider focuses on the network performance while the service user focuses on trip characteristics.
- Category: statistical range methods, buffer time methods, tardy trip methods, probabilistic methods, and skew-width methods. These categories are all based on different mathematical principles.

#### Criteria for the Selection of a Proper TTR Measure

There is no theoretical reason to justify selection of one TTR-measure over another. However, there are criteria, which partially depend on the type of investigation that is done, that can be used to select a proper TTR measure. These are:

- General criteria. The TTR measure:
  - ... can be easily **understood** (by practitioners, researchers, the public and policy makers).
  - ... can be **computed** using available data sources.
  - ... is **compatible** with other reliability studies.
  - ... is **meaningful** with respect to the policy measures it will be used to evaluate.
- Specific criteria for the project method that is developed in this research. The measure used in the project method should be able to:
  - ... tell how good the **average conditions** on a road are. As was stated, *Travel Time Reliability* appears to be an important feature for road users, but the average speed is still important. A road with a very reliable travel time but with an average speed of 10 km/h would not be very attractive to use.
  - ... provide information on the **degree of variation** of travel times. A wide distribution around the average travel time implies a low degree of reliability.
  - ... assess the **extreme travel times**. Road users may find delays or variation in travel times unpleasant, but their appreciation for a certain route may also be dependent on the frequency and severity of extreme travel times.

#### Evaluation of TTR Measures

A comparison of the available TTR measures, based on the aforementioned classifications and criteria yields the following results:

- All TTR measures use the perspective of the road user. Since the goal of this research is to develop a method which assesses route performance from a road user perspective, this means that all TTR measures can be used according to this criterion.
- All five categories of TTR measures are represented in the measures found in literature: statistical range methods, buffer time methods, "tardy trip" methods, probabilistic methods, and skew-width methods. Hence, the whole range of mathematical techniques is used.
- PTI and MI do not use mean or median travel time as a reference. Therefore, they are not useful for analysis. However, this can easily be adapted so that these measures are useful.
- All TTR measures can be used to investigate inter-day variation. Hence, no TTR measure drops out due to this criterion.

- The BI, BI\*, PTI, OTP, and NLP are not easy to understand for road users, but can be made understandable when they are presented in a slightly modified way. The MI, STD, COV, SS, WS, and UI are too difficult to understand for road users and can therefore not be used for analysis.
- All TTR measures can be computed with the available data.
- All of the TTR measures, except the MI and UI assess the variation of travel times. The MI and UI assess the worst trips.

### 6.1.3. Development of the Project Method

Based on the evaluation of the TTR that were found in literature, the project method was constructed. The following conclusions are drawn for the project method.

#### Split up the Day

According to the aforementioned definition, TTR depends on the expectations of the road user. Furthermore, it was assumed that the expectations of road users are equal to the mean travel time in a certain period. Therefore, in order to have a good reference point for determining TTR, the travel time should be approximately constant in the observed period. In order to assure this, the day should be split up in three periods: morning peak, inter-peak, and evening peak. Within these periods, travel times are approximately constant. The project method is used separately on all three periods.

#### Only Daytime is Observed

The night is not considered in the analysis: low traffic volumes and shorter travel times make this period not interesting for analysis.

#### Composition of the Project Method

The project method assesses the following attributes by means of these measures:

- Average travel times: mean speed.

$$\bar{t} = \frac{1}{M} \sum_{m=1}^M \left[ \frac{1}{N_m} \sum_{i=1}^{N_m} t_{m,i} \right] \quad (6.1)$$

- Variation in travel times: Buffer Index.

$$BI = \frac{t^{95\%} - \bar{t}}{\bar{t}} \quad (6.2)$$

- Extreme travel times: Bad Minutes Index.

$$BMI = \left[ \sum_{k=1}^K \begin{cases} 1 & \text{if } (t_k > w * \bar{t}_{year}) \\ 0 & \text{otherwise} \end{cases} \right] / K \quad (6.3)$$

For a detailed explanation of the working of these measures, see section 2.3. For an overview of how the project method is applied to the travel time data, see section 3.2.

### 6.1.4. Relation between the Project Model and Road User Judgment

In an earlier stage of the research, it was assumed that there are three attributes which play a role in the judgment of the performance of a route: mean speed, degree of variation in speed, and extreme travel times. A simple model to describe the relations between these attributes and the judgment by road users was produced by means of a stated preference survey, which was conducted among a small group of 25 colleagues at the *Gemeente Rotterdam*. This showed that the influence of mean speed and degree of variation in speed on the road user judgment is statistically significant. However, the occurrence of extreme travel time has no statistically significant influence.

The estimated model to predict road user judgment on a scale from 1 to 10 is:

$$2.5137 + 0.1637\bar{v} - 0.0073BI \quad (6.4)$$

The estimation yields an  $R^2$  of 85 %. This value indicates how well the model is able to predict the measured data, where 0 % means that there is no correlation between the model and the data and 100 % means the model fits the data perfectly. The model shows that for an increase of the mean speed with 1 km/h, the grade given by road users increases by 0.1637. And the grade decreases by the same amount if the mean speed decreases by 1 km/h. Also, for an increase of the Buffer Index of 10 % the grade decreases by 0.073 and for a decrease of the Buffer Index of 10 % the grade increases by the same amount. This model will be used to estimate the performance of routes from a traveler's perspective. The user model shows that the influence of the Buffer Index on the judgment grade is relatively small.

### 6.1.5. Evaluation of the Project Method

Bandwidth graphs were developed in order to visualize travel time data for the evaluation. These bandwidth plots provide the opportunity to present big amounts of travel time data in such a way that it is easy to observe the daily pattern of the travel time on a route, as well as the size of the variation in travel times.

Second, there are some conclusions to be drawn from the case study, in which the project method was applied to real travel time data of two routes in Rotterdam.

- Within a day, both mean speed and TTR on a route can strongly vary.
- Spillback effects from motorways can have a large impact on the mean speed and TTR of an urban route.
- The order of performance of routes per quarter of the year from best to worst is: 4, 1, 2, 3. These are caused by seasonal effects. However, the difference in the performance between quarters is generally small.
- A route generally shows a similar performance in both directions. However, there might be variations due to traffic patterns which are dominant in the morning in one direction and dominant in the other direction in the evening. Also, spillback effects from other roads can influence the performance of one direction of a route, while the opposite direction is not affected.
- The comparison of two different routes showed that low travel times are not necessarily linked to a high TTR and vice versa. A route can have high travel times, while at the same time a high TTR and vice versa.

Finally, a comparison between the current method and the project method yields the following results.

- The current method overestimates the mean speeds in peak periods in many cases, while it slightly underestimates the speed in inter-peak periods. This is caused by (1) a different choice for the start and end times of the peak periods, and (2) the fact that weekend days are also included in the current method, on which the mean speed is generally higher.
- The outcome of the current method is much closer to the outcomes of the project method when the differences in mean speeds between the periods within a day are smaller. Hence, for a route with a higher variation in travel times within a day, the current method provides less accurate results and the project method gives a more detailed insight into the performance of a route.
- The current method barely shows the influence of a decreased TTR. In some cases, this means that although the indicated mean speed is high, the TTR can be very low. In such a case, the current method does not provide a representative image of the performance of a route.

## 6.2. Recommendations for Practice

In this research, a new method (the project method) to analyze the performance of urban routes was developed. This section details how this method can be valuable to network managers and road users.

### **Bandwidth Graphs**

Use bandwidth graphs in order to quickly get an idea about the travel time pattern and travel time variation size on a route. Bandwidth graphs of different periods of the year can be created in order to compare their performance. Bandwidth graphs of sections within a route can be used to get a more precise insight into the contribution of different sections to the travel time and TTR.

### **Usage of the Project Method in Practice**

It is recommended to use the project method instead of the current method. The current method can provide a incorrect image of the performance of a route. The mean speed within some parts of the day can be greatly overestimated by the current method. Moreover, the current method does not always show the influence of an increased variability in travel times.

The project method can be used in the city of Rotterdam, but the method can of course also be used on urban routes in other cities, when travel time data are available. In order to obtain reliable results, travel time measurements of at least a few weeks should be used. Also, the aggregation level should not be too high, in order to prevent loss of detail. The project method gives a more detailed insight into the performance of a route compared to the current method, which only uses mean speeds.

## **6.3. Future Research Directions**

Deeper investigation into *Travel Time Reliability* is desirable, for this research shows that TTR is likely of importance to travelers and may influence their behavior. Behavioral impact may include: route choice, departure time choice, mode choice or destination choice. Another reason is that not much research on *Travel Time Reliability* has been performed as the field is relatively new. This is especially true for urban areas; the investigation that has been performed, was mostly done on motorways. Finally, in the last few years, the amount of travel time data that is generated and saved has increased enormously. This increases the possibilities to perform thorough analyses.

During this research, some specific questions arose, which can be the next steps in the quest for a full understanding of the concept of Travel Time Reliability and how this relates to the experience of road users. These are treated in the remainder of this section.

### **Influencing Factors and Consequences of TTR**

In this research, it was discovered that TTR has an impact on the behavior of road users. However, it is uncertain how and to what extent TTR influences the behavior of road users. Insight into this relation provides valuable information for road managers and traffic engineers and it is therefore recommended to investigate this.

Likewise, it is recommended to investigate which factors influence TTR and how this takes place. Examples of these factors are: weather, lighting conditions, traffic intensity, road works, and incidents. When it is known how these factors influence TTR, road managers can take directed actions to improve TTR.

### **Improvement of the Project Method**

The assumption that the expectation of road users equals the average speed in a period of the day should be validated or extended. It is likely that there are other factors which influence the travel time expectations of road users as well, such as: the weather, special events, holidays, road works, traffic information, and familiarity with the route. It should be investigated whether this influence is significant.

Furthermore, the "bad travel time threshold" was assumed to be twice the average travel time ( $w = 2$ ). This assumption should be validated or corrected. It might be so that for short routes there should be an absolute threshold, because in such a case a travel time which is twice the average travel time is easily realized but does not influence the judgment of the road users.

Finally, in the calculations of the project method, every considered minute of the day is equally important. However, in reality, traffic intensities vary and a larger intensity means that more road users experience the conditions that are present at that time. Hence, it could be an improvement to weigh the measurements by the intensities. By doing this, the focus shifts from the road user perspective to network provider perspective. It is recommended to investigate the value of this to the project method.



**Improvement of the User Model**

It is recommended to improve the simple model that was developed in chapter 4 can by means of the following steps.

- First, in this research a stated preference survey was conducted on a small group of respondents. It is recommended to conduct a revealed preference survey on a large group of respondents. By doing this, more reliable results are obtained, which can be used to estimate a model.
- Second, when the model was developed, it was assumed that all road users value TTR in the same way. However, it is likely that this is not the case in reality. It could depend on factors such as age, income, and trip purpose. Hence, it is recommended to make a distinction between various groups of road users, as their value of time and value of reliability can be different. Implementation of this factor will likely improve the accuracy of the model.
- Moreover, the model only uses mean speeds and the degree of variability in mean speeds. However, it is likely that there are other factors which influence the judgment of the performance of a route by road users. These might, for instance, be the time of the day or specific route characteristics, such as: the number of (signalized intersections), vertical and horizontal alignment of the road, traffic intensity, and the surroundings of the route. When the effect of these factors on the road user judgment is known, this will improve the accuracy of the predictive model.
- Finally, a simple linear model was used in this investigation. However, when more factors are added to the model, a linear model could become insufficient. Therefore it is recommended to determine whether a linear model is sufficient when the previous recommendations are followed. If not, it is advisable to use a more complex model.



# List of Acronyms

BI	=	Buffer Index
BI*	=	Buffer Index 2
CD	=	Compact Disc
COV	=	Coefficient of Variation
DRIP	=	Dynamic Route Information Panel
HVD	=	High Vehicle Detection
MI	=	Misery Index
NLP	=	Not Late Probability
OLS	=	Ordinary Least Squares
OTP	=	On Time Probability
PTI	=	Planning Time Index
SI	=	Signalized Intersection
SPC	=	Signalized Pedestrian Crossing
SS	=	Skew Statistic
STD	=	Standard Deviation
TTR	=	Travel Time Reliability
UI	=	Unreliability Index
VoR	=	Value of Reliability
VoT	=	Value of Time
WS	=	Width Statistic



# List of Symbols

$BI$	=	[-] buffer index (=extra travel time needed to arrive on time in 95% of the cases, expressed as a percentage of the average travel time)
$\widehat{BI}$	=	[min] absolute buffer time
$BI^*$	=	[min] buffer index 2 (=extra travel time needed to arrive on time in 95% of the cases, expressed as a percentage of the median travel time)
$BMI$	=	[-] bad minutes index (=percentage of minutes exceeding a threshold indicating a "bad travel time")
$C$	=	[-] constant in the estimation model for a user judgment grade
$COV$	=	[-] coefficient of variation (=standard deviation of travel times normalized by the mean of travel times)
$G$	=	[-] road user judgment grade for an outcome of the new performance indicator
$i$	=	[-] index of a single measurement within a minute
$K$	=	[-] total number of measurements that are observed
$k$	=	[-] index of the measurement
$L$	=	[km] length of a route
$M$	=	[-] total number of minutes in the considered period of the day
$MI$	=	[-] misery index (=the average of the highest five percent of travel times divided by the free-flow travel time)
$m$	=	[-] index of the minute for which the average travel time is calculated
$N$	=	[-] total number of measurements in the considered minute
$n$	=	[-] number of measurements in a variable
$NLP$	=	[-] not long probability (=the probability that a traveler will experience a travel time that is not "too long", which is defined as not more than $x$ minutes longer than the median travel time.)
$OTP$	=	[-] on time probability (=the probability that a traveler will experience a travel time that is less than $x$ minutes different from the median travel time.)
$PTI$	=	[-] planning time index (=the ratio of the 95th percentile travel time to the free flow travel time)
$R^2$	=	[-] the percentage of the response variable variation that is explained by a linear model
$r_{xy}$	=	[-] Pearson sample correlation coefficient
$s$	=	[-] standard deviation
$t$	=	[min] travel time
$\bar{t}$	=	[min] average travel time on a route in a period (quarter or month)
$\bar{t}_{year}$	=	[min] average travel time on a route for a period of the day in a complete year
$t'$	=	[min] average of the highest five percent of travel times measured in a period
$t^{10\%}$	=	[min] 10th percentile of measured travel times within a period
$t^{50\%}$	=	[min] median of measured travel times within a period
$t^{90\%}$	=	[min] 90th percentile of measured travel times within a period
$t^{95\%}$	=	[min] 95th percentile of measured travel times within a period
$t^f$	=	[min] free flow travel time
$UI$	=	[-] unreliability index (=a measure of the likelihood of experiencing a very long travel time)
$\bar{v}$	=	[km/h] mean speed
$w$	=	[-] multiplication factor to set the bad travel time threshold
$X$	=	[-] predictor in a linear model
$x$	=	[-] variable, consisting of $n$ elements
$\bar{x}$	=	[-] mean of a variable
$Y$	=	[-] response of a linear model

$y$	=	[-] variable, consisting of n elements
$\bar{y}$	=	[-] mean of a variable
$\beta$	=	[-] coefficient for the linear estimation model
$\lambda^{skew}$	=	[-] skew statistic (SS) (=ratio of the difference between the 90th percentile travel time and the median travel time to the difference between the median travel time and the 10th percentile travel time)
$\lambda^{width}$	=	[-] width statistic (WS) (=difference between the 90 th percentile travel time and the 10th percentile travel time, normalized by the median travel time)
$\sigma$	=	[min] standard deviation (STD)

# Bibliography

- A. König and K. W. Axhausen, *The reliability of the transportation system and its influence on the choice behaviour*, in *Swiss Transport Research Conference (STRC), Monte Verità/Ascona* (2002).
- E. A. Bogers, *Traffic information and learning in day-to-day route choice*, T2009/5 (Netherlands TRAIL Research School, 2009).
- O. E. Dictionary, *Oxford english dictionary*, (2013).
- Federal Highway Administration (FHWA), *Traffic Congestion and Reliability: Trends and advanced strategies for congestion mitigation*, Tech. Rep. (Cambridge Systematics Inc. and Texas Transportation Institute, 2005).
- OECD, *Improving reliability of surface transport network*, Tech. Rep. (Transport Research Centre of the Organization for Economic Co-Operation and Development, 2010).
- M. Martchouk, F. L. Mannering, and C. NEXTRANS, *Analysis of Travel Time Reliability on Indiana Interstates*, Tech. Rep. (NEXTRANS, 2009).
- D. Bremmer, K. C. Cotton, D. Cotey, C. E. Prestrud, and G. Westby, *Measuring congestion: Learning from operational data*, Transportation Research Record: Journal of the Transportation Research Board **1895**, 188 (2004).
- Gemeente Rotterdam, *Verkeers- en Vervoerplan Rotterdam 2003-2020: Open stad duurzaam bereikbaar* (2003).
- B. Hellinga, *Defining, Measuring, and Modeling Transportation Network Reliability*, Tech. Rep. (unknown, 2011).
- Vialis, *Systeem/subsysteem ontwerp beschrijving (SSDD), Monitoring Rotterdam - Perceel 1*, Tech. Rep. (Vialis Traffic bv, 2007).
- J. Bates, J. Polak, P. Jones, and A. Cook, *The valuation of reliability for personal travel*, Transportation Research Part E: Logistics and Transportation Review **37**, 191, 229 (2001).
- T. Lomax, D. Schrank, S. Turner, and R. Margiotta, *Selecting travel reliability measures*, Texas Transportation Institute monograph (May 2003) -, (2003).
- Strategic Highway Research Program (SHRP), *Analytical procedures for determining the impacts of reliability mitigation strategies (final report)*, Tech. Rep. (SHRP2 Project L03, 2010).
- M. Kouwenhoven, A. Schoemakers, R. Grol, and E. Kroes, *Development of a tool to assess the reliability of dutch road networks*, in *Proceedings of the Association for European Transport* (2005).
- J. v. Lint, H. v. Zuylen, and H. Tu, *Travel time unreliability on freeways; why measures based on variance tell only half the story*, Transportation Research Part A: Policy and Practice **42**, 258 (2008).
- H. Tu, *Monitoring Travel Time Reliability on Freeways*, Ph.D. thesis, TU Delft (2008).
- K. Pearson, *Liii. on lines and planes of closest fit to systems of points in space*, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science **2**, 559 (1901).
- C. Metrics, *Ngene 1.1. 1 user manual and reference guide*, Download fra: <http://www.choice-metrics.com/index.html> (2012).
- N. R. Draper and H. Smith, *Applied regression analysis 2nd ed.* (1981).







## Calculation procedure of the Average Speed Performance Indicator

This section describes how the *Gemeente Rotterdam* calculates the average speed of the main routes, which is currently used as a performance indicator.

The calculation is executed as follows:

$$\bar{v}_{r,k} = \frac{5 * \frac{\bar{v}_{wd-mp,r,k} + \bar{v}_{wd-ep,r,k} + \bar{v}_{wd-op,r,k}}{3} + 2 * \frac{\bar{v}_{sat,r,k} + \bar{v}_{sun,r,k}}{2}}{7} \quad (A.1)$$

Which equals:

$$\bar{v}_{r,k} = \frac{5}{21} * (\bar{v}_{wd-mp,r,k} + \bar{v}_{wd-ep,r,k} + \bar{v}_{wd-op,r,k}) + \frac{1}{7} * (\bar{v}_{sat,r,k} + \bar{v}_{sun,r,k}) \quad (A.2)$$

In which:

- $\bar{v}_{r,k}$  is the mean speed on a main route  $r$  in direction  $k$  in a certain quarter of the year
- $\bar{v}_{wd-mp,r,k}$  being the mean speed on a main route  $r$  in direction  $k$  in a certain quarter of the year on working days in the morning peak (07:00h to 09:00h)
- $\bar{v}_{wd-ep,r,k}$  is the mean speed on a main route  $r$  in direction  $k$  in a certain quarter of the year on working days in the evening peak (16:00h to 18:00h)
- $\bar{v}_{wd-op,r,k}$  is the mean speed on a main route  $r$  in direction  $k$  in a certain quarter of the year on working days in the off-peak period (09:00h to 16:00h)
- $\bar{v}_{sat,r,k}$  is the mean speed on a main route  $r$  in direction  $k$  in a certain quarter of the year on Saturdays (07:00h to 19:00h)
- $\bar{v}_{sun,r,k}$  is the mean speed on a main route  $r$  in direction  $k$  in a certain quarter of the year on Sundays (12:00h to 19:00h)

The mean speeds which are inserted in equation A.2 are based on average speeds per 5 minutes. These are derived from travel time measurements by means of license plate recognition. This means that only in the first calculation of mean speeds per 5 minutes the weight of the intensity is included. When calculating the mean speed in, for example, a morning peak, this weight is not included. And this also applies to further calculations.

This calculation is performed after each quarter of the year. After performing the calculation, the result of equation A.2 is averaged with the results of the 3 previous quarters, so that the average covers the past year. When this is done, there are 14 outcomes in total. That is, 7 main routes which all have 2 directions. These 14 values are tested against the flow objective, which states that the average speed on a route should be at least 25 km/h.



# B

## Survey

This appendix shows the setup of the survey, which was used to estimate the road user judgment model (see chapter 4). The survey is in Dutch, because the mother tongue of all respondents is Dutch. All the images that were used in the survey can be found on the CD that is attached to this report.

### Uitleg

Op de volgende pagina's krijgt u 25 combinaties van 40 reistijden te zien, over een vaste route.

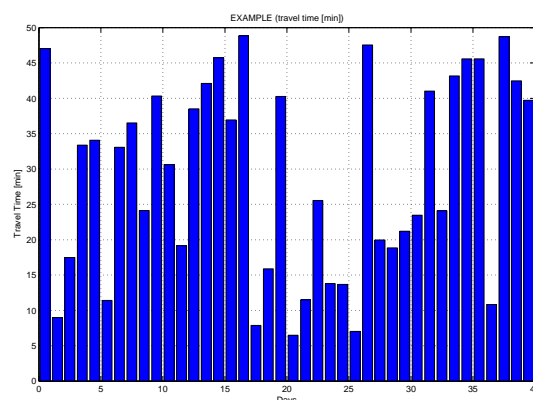
U dient zich bij elke combinatie voor te stellen dat u op 40 werkdagen in de ochtendspits de gegeven reistijden meemaakt, als automobilist. Bij elk van de combinaties wordt u gevraagd aan te geven hoe u deze waardeert.

Beoordeel de combinaties met een cijfer op een schaal van 1 tot 10, waarbij: 1 = zeer slecht: slechter kan haast niet er zou direct iets moeten gebeuren om de situatie drastisch te verbeteren 5 = twijfelachtig: nog iets slechter en het is een onvoldoende; met lichte verbeteringen is een acceptabele situatie te bereiken 6 = voldoende: er is genoeg ruimte voor verbetering; het mag zeker niet minder dan dit 10 = uitstekend: verbeteringen zijn onmogelijk of dragen niets meer bij aan mijn waardering

Karakteristieken: - De route heeft een lengte van 5 kilometer. Omdat dit bekend is, kunnen de gemiddelde snelheden behorend bij de reistijden worden berekend. Ter indicatie staan bij elk plaatje enkele kengetallen. - Het gaat om een stadsroute met twee rijstroken per richting, waar een maximale snelheid van 50 km/u geldt.

N.B. Het kan zijn dat u gedurende het invullen eerder gegeven antwoorden wilt wijzigen, om redenen van voortschrijdend inzicht. Het is mogelijk om terug te klikken en wijzigingen aan te brengen. Ingevulde antwoorden blijven dan staan.

### Voorbeeld



Ter indicatie: 6 min = 50 km/u, 7,5 min = 40 km/u, 10 min = 30 km/u, 15 min = 20 km/u, 30 min = 10 km/u, 60 min = 5 km/u

Geef een beoordeling tussen 1 en 10, waarbij 1 = zeer slecht en 10 = uitstekend.



# C

## **Visualization of Analysis Results**

This appendix contains bar graph plots and bandwidth graphs of the outcome of the data analysis in chapter 5. These were not placed in that chapter for reasons of conciseness. The graphs are sorted per route and direction.

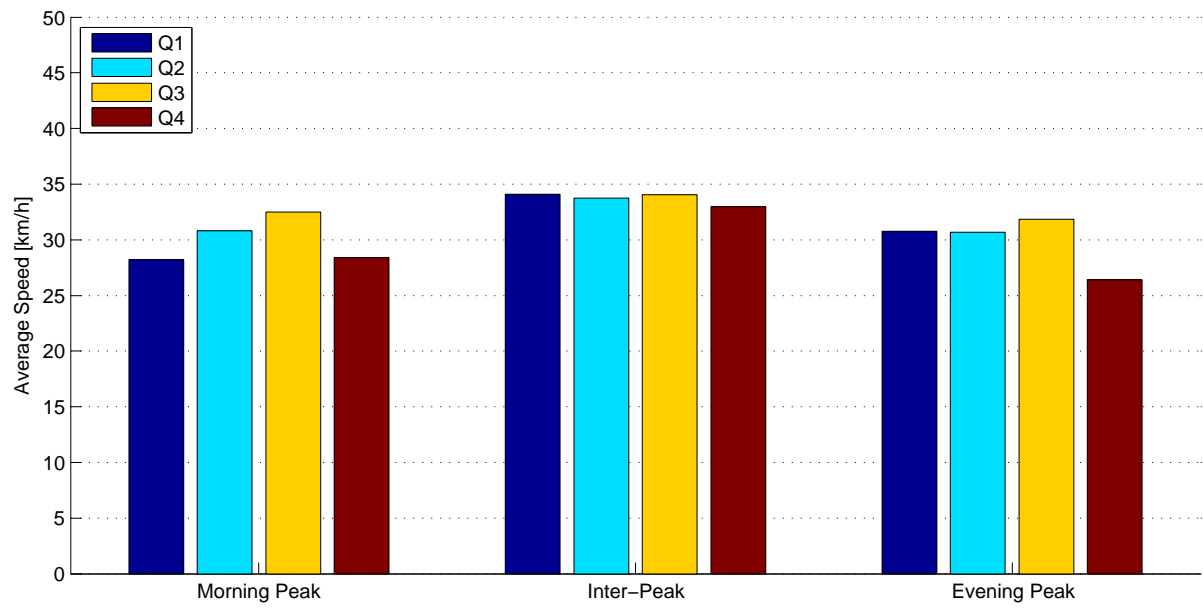
**Route B: Vaanweg – Pleinweg (Inbound) Project Method**

Figure C.1: Mean speed on route B inbound in three periods of the day and per quarter of the year 2013.

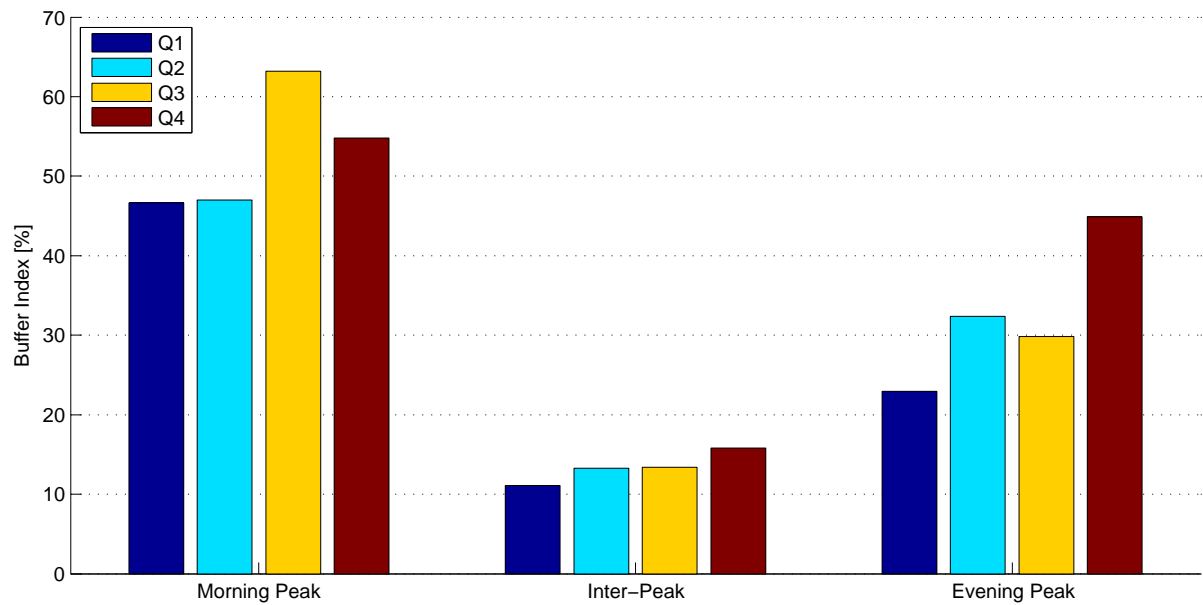


Figure C.2: Buffer Index on route B inbound in three periods of the day and per quarter of the year 2013.

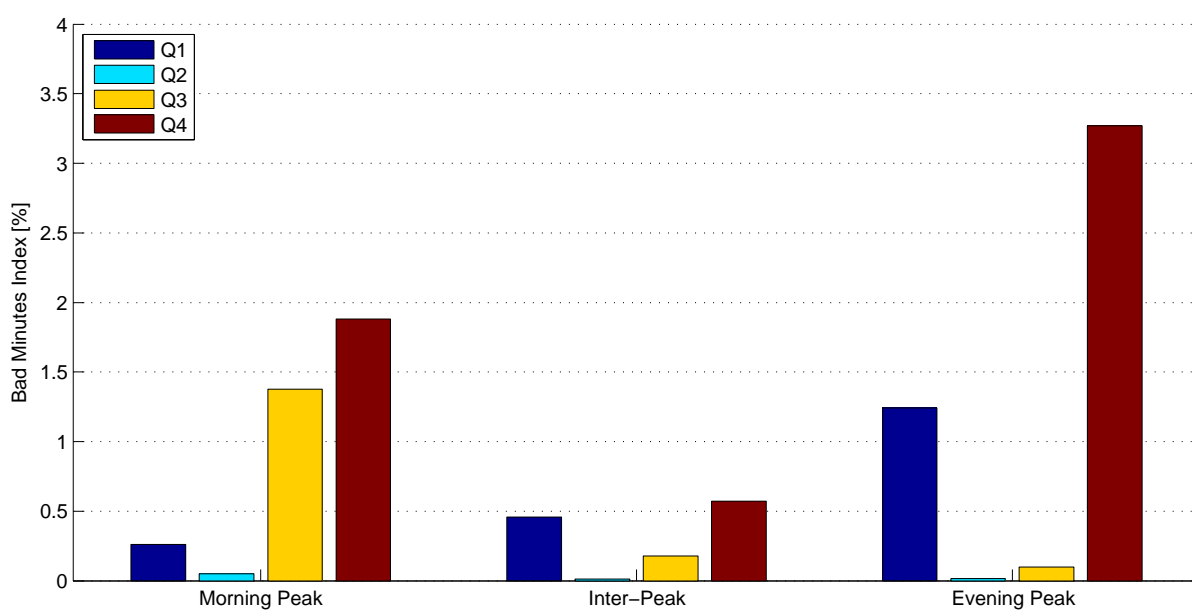


Figure C.3: Bad Minutes Index on route B inbound in three periods of the day and per quarter of the year 2013.

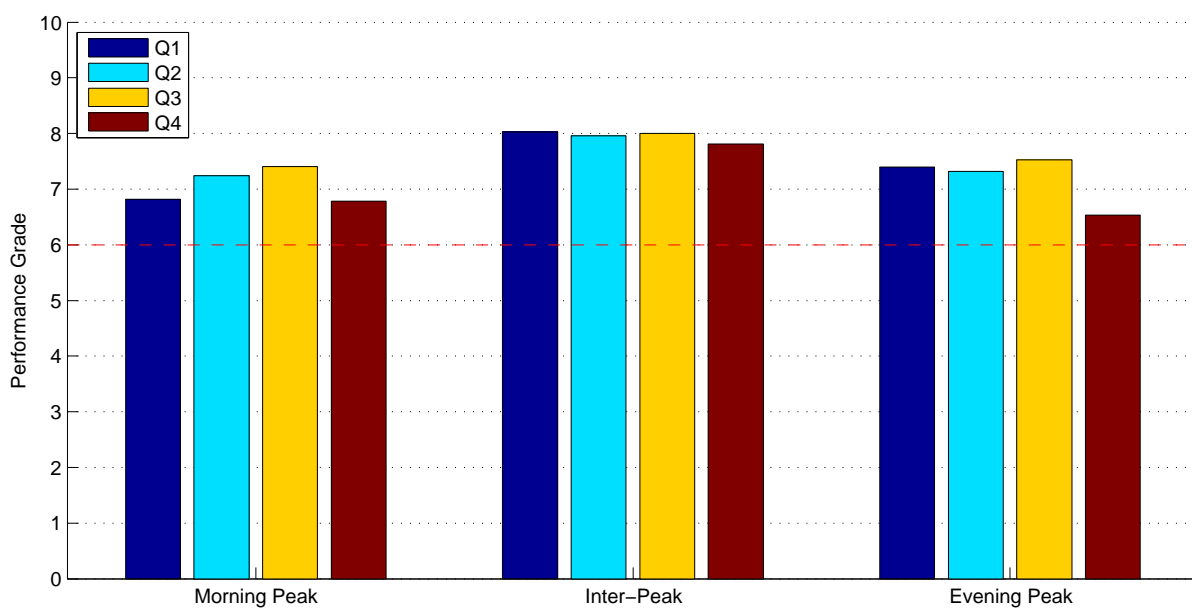


Figure C.4: Performance Grade on route B inbound in three periods of the day and per quarter of the year 2013.

### Route B: Vaanweg – Pleinweg (Inbound) Bandwidth Graphs

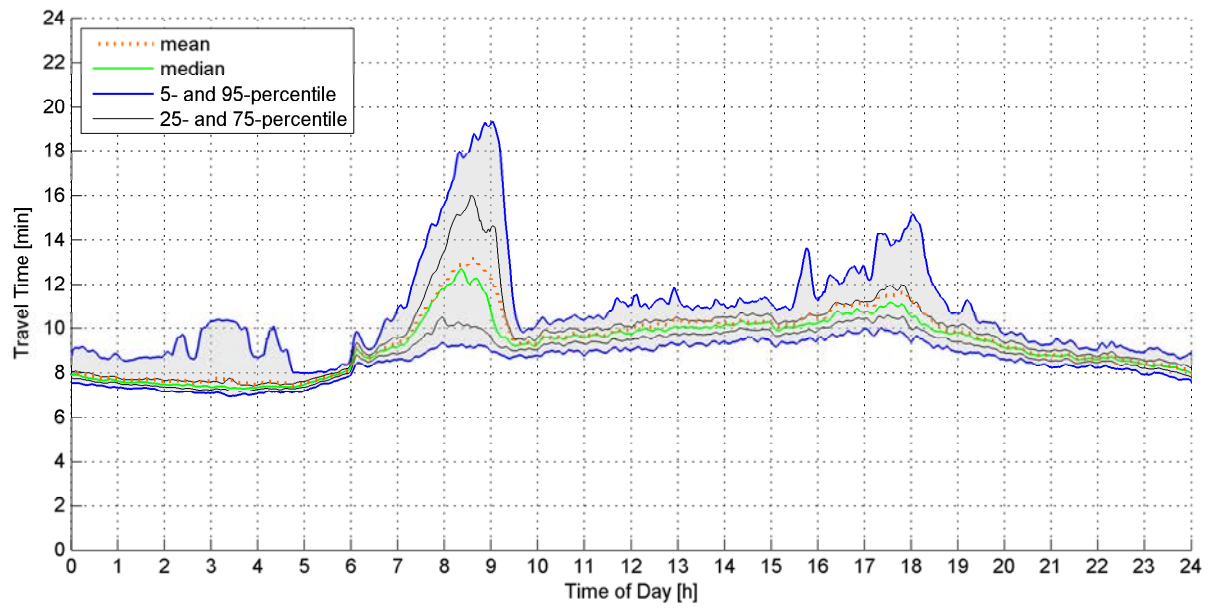


Figure C.5: Bandwidth graph of travel times on workdays on route B inbound in Q1 of 2013.

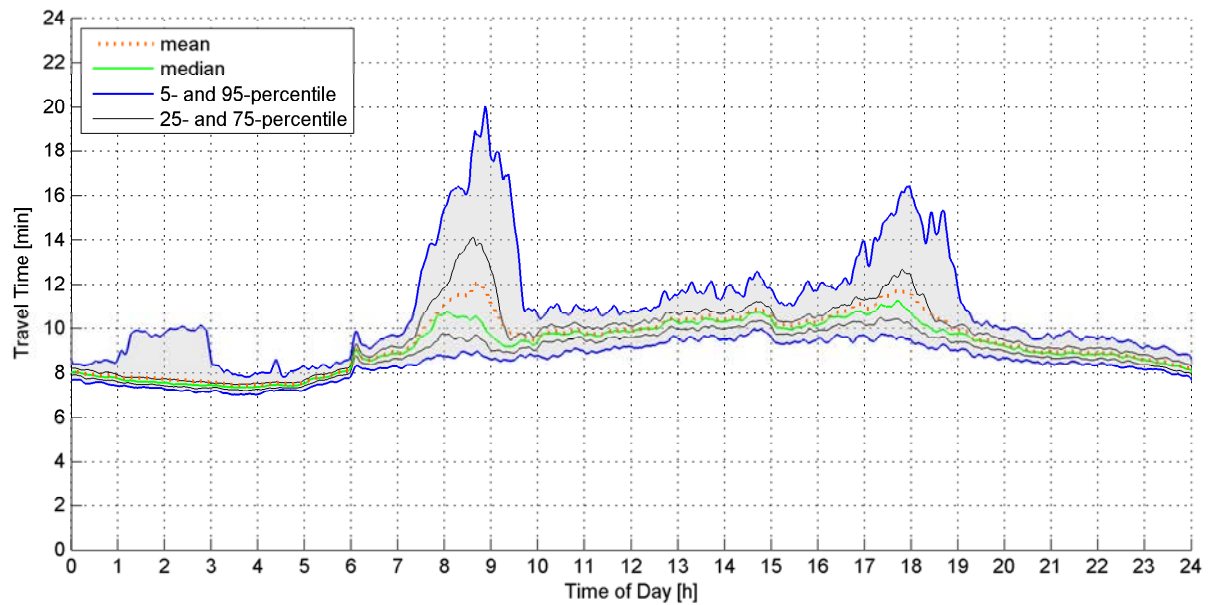


Figure C.6: Bandwidth graph of travel times on workdays on route B inbound in Q2 of 2013.



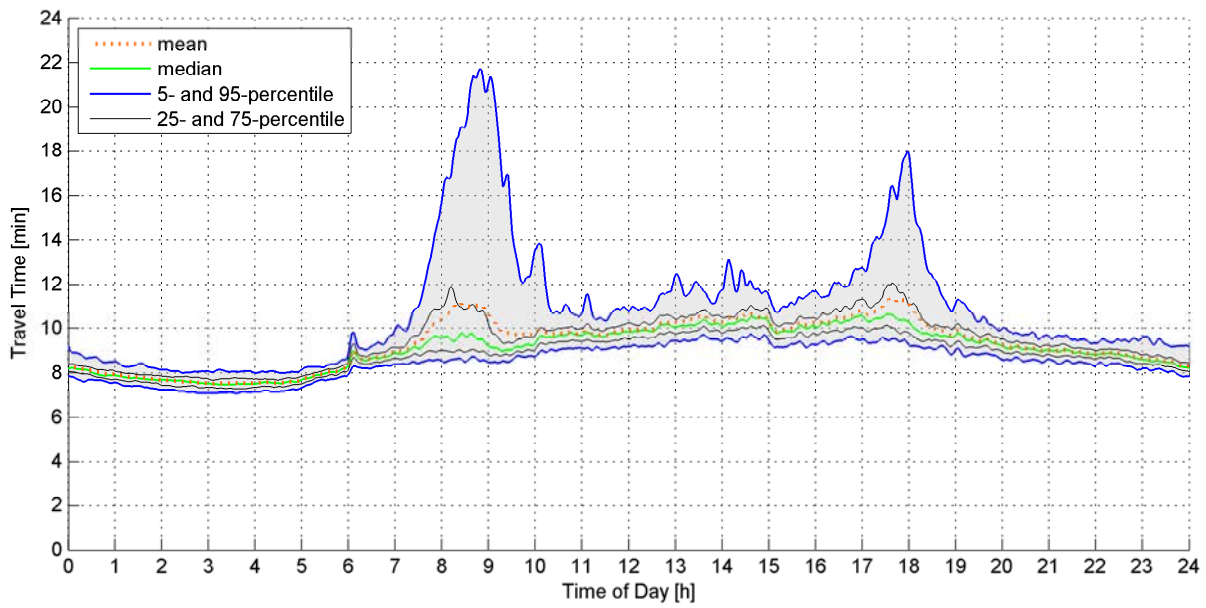


Figure C.7: Bandwidth graph of travel times on workdays on route B inbound in Q3 of 2013.

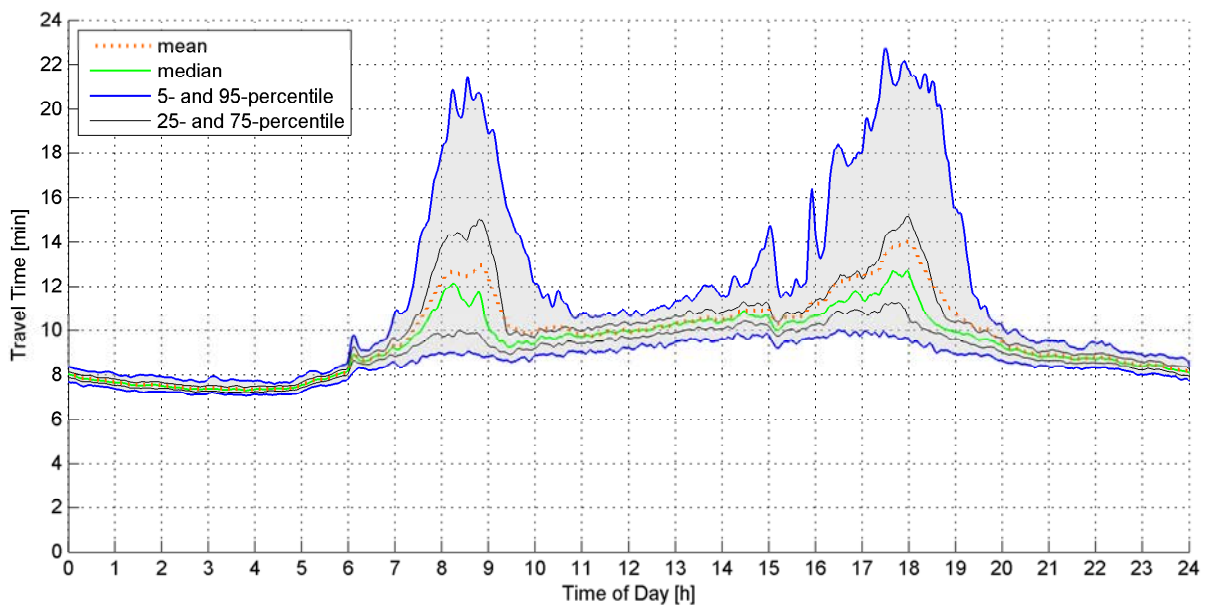


Figure C.8: Bandwidth graph of travel times on workdays on route B inbound in Q4 of 2013.

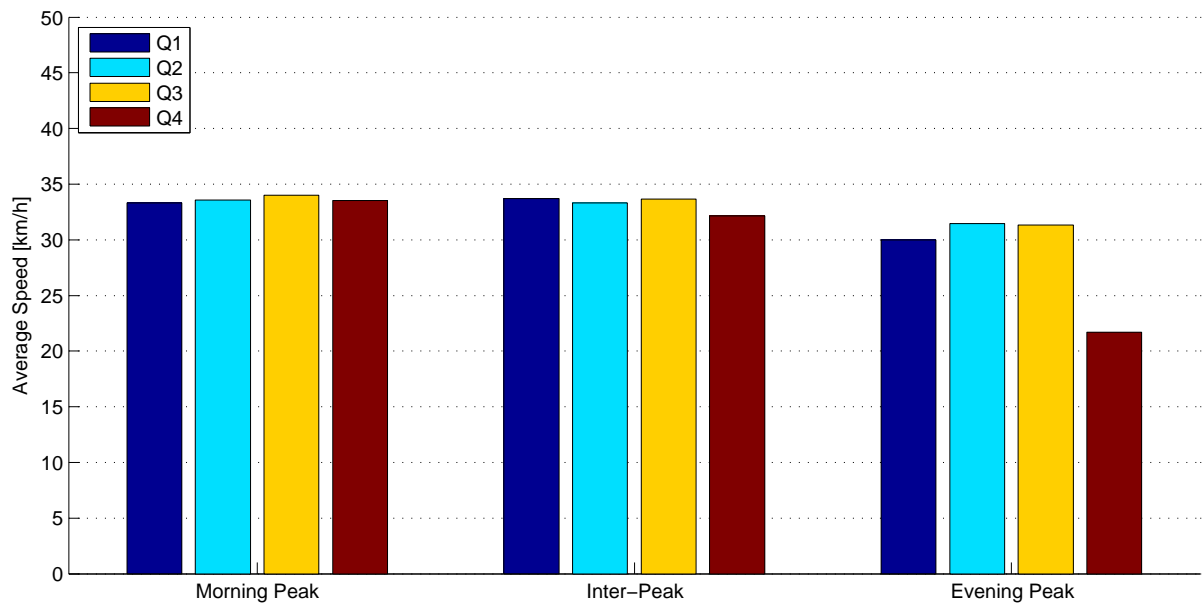
**Route B: Vaanweg – Pleinweg (Outbound) Project Method**

Figure C.9: Mean speed on route B outbound in three periods of the day and per quarter of the year 2013.

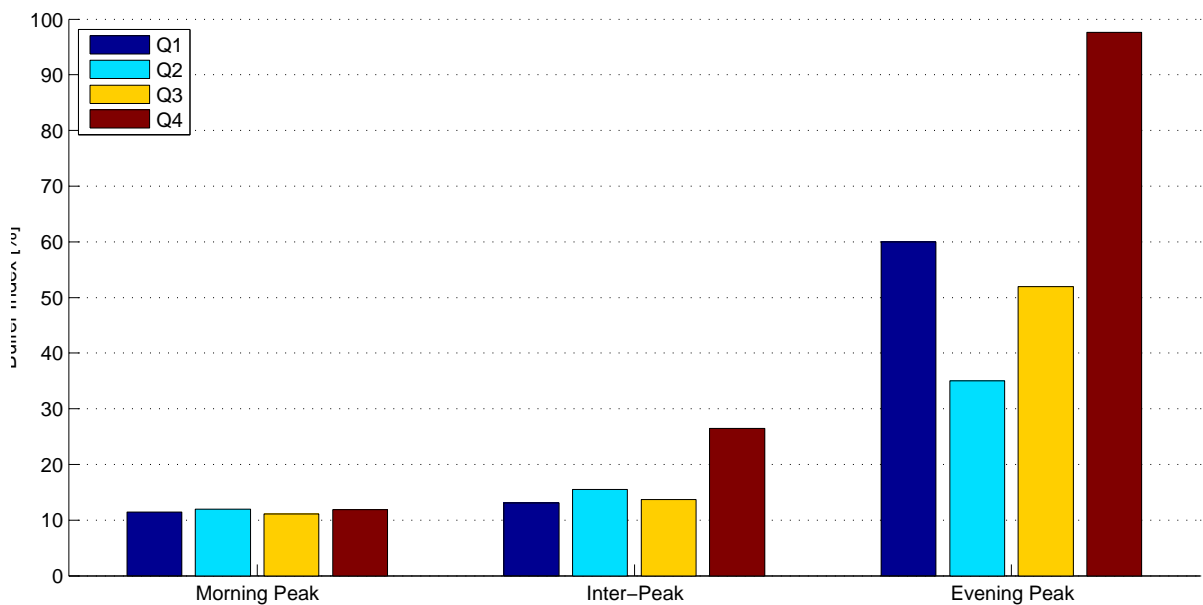


Figure C.10: Buffer Index on route B outbound in three periods of the day and per quarter of the year 2013.

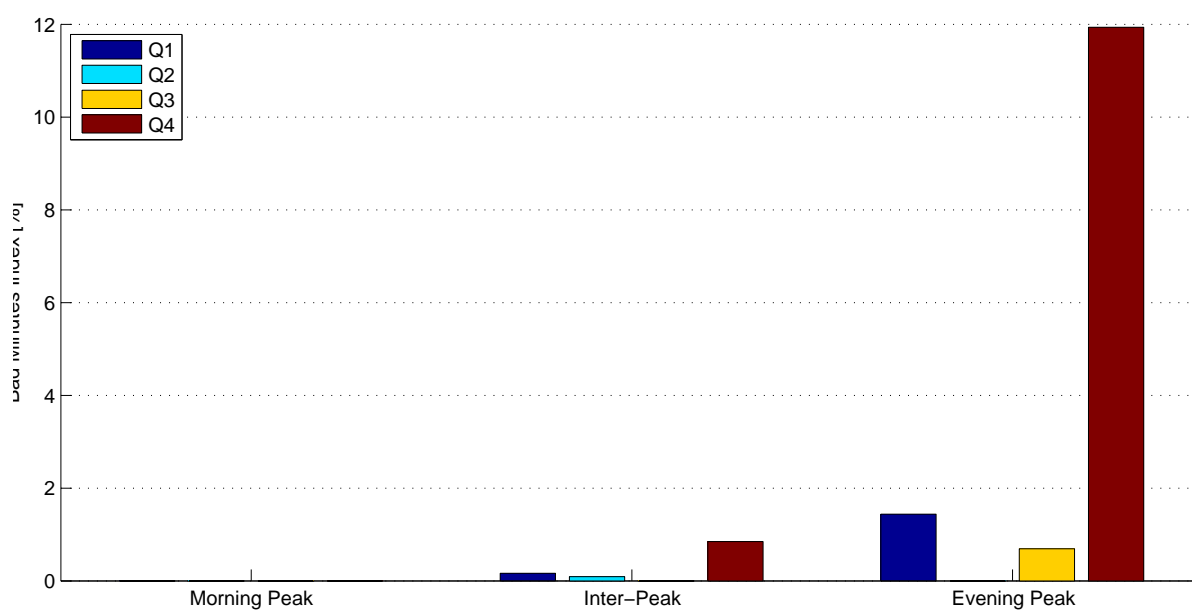


Figure C.11: Bad Minutes Index on route B outbound in three periods of the day and per quarter of the year 2013.

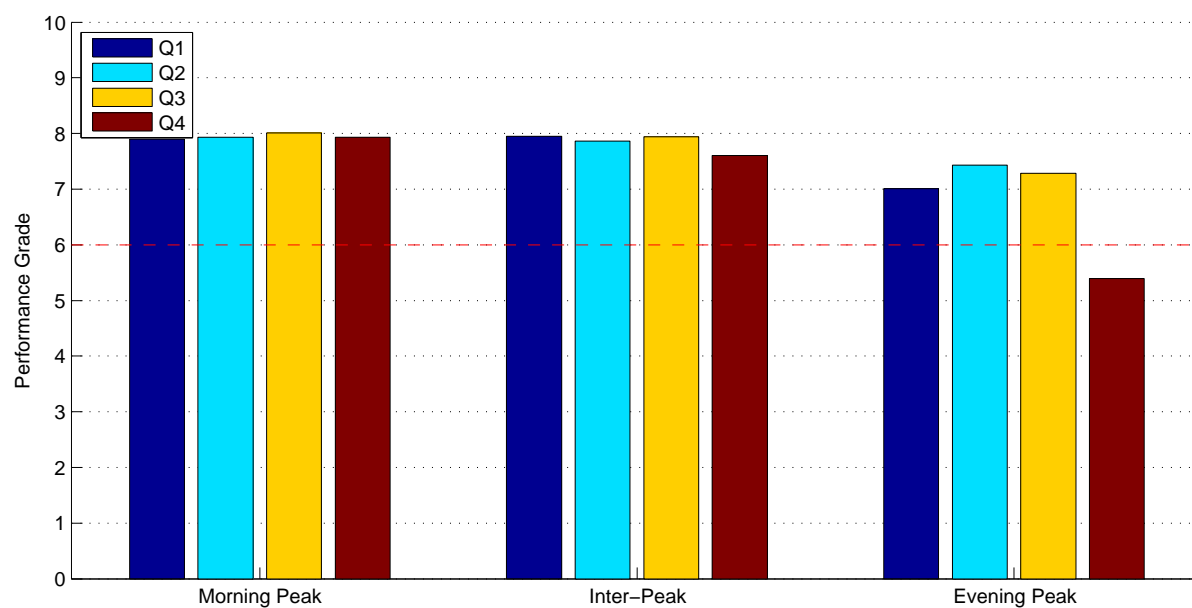


Figure C.12: Performance Grade on route B outbound in three periods of the day and per quarter of the year 2013.

### Route B: Vaanweg – Pleinweg (Outbound) Bandwidth Graphs

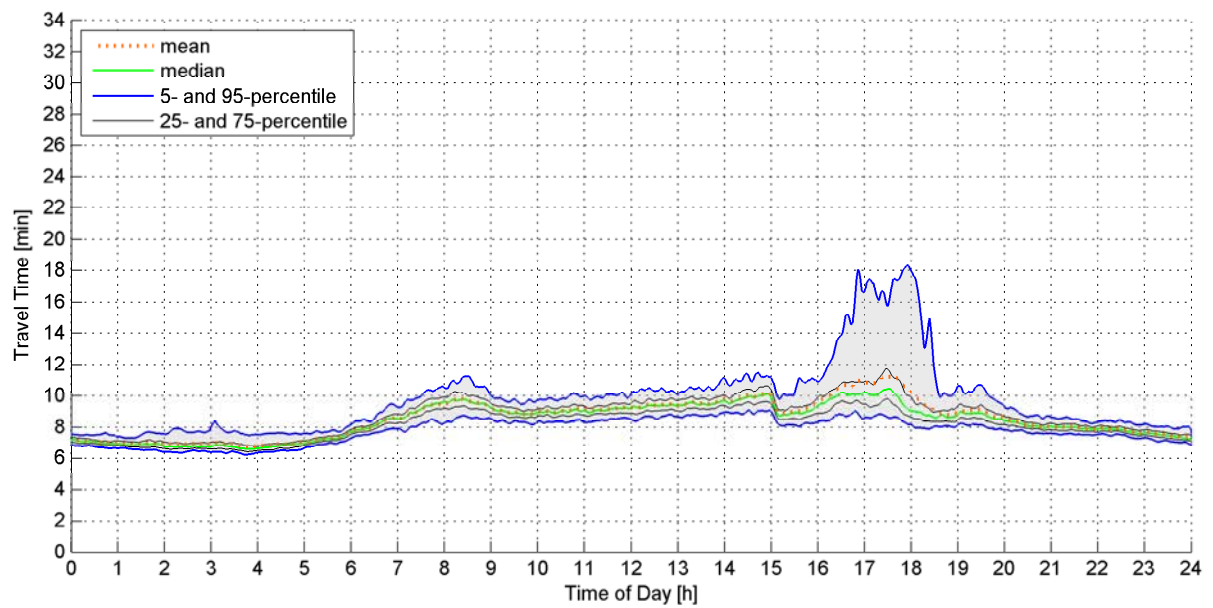


Figure C.13: Bandwidth graph of travel times on workdays on route B outbound in Q1 of 2013.

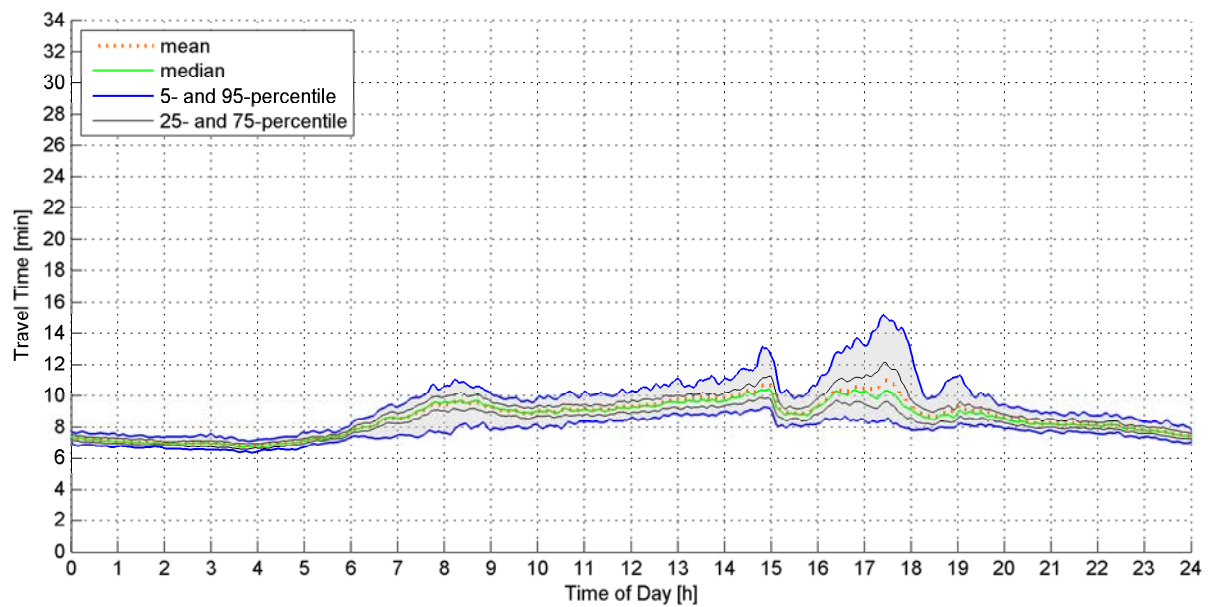


Figure C.14: Bandwidth graph of travel times on workdays on route B outbound in Q2 of 2013.

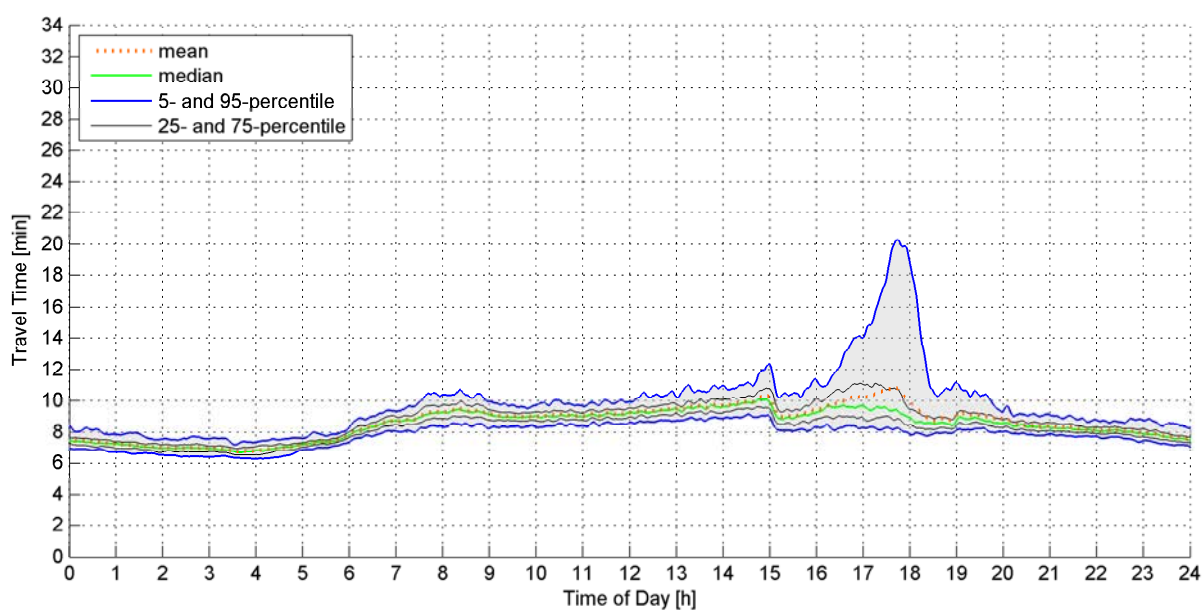


Figure C.15: Bandwidth graph of travel times on workdays on route B outbound in Q3 of 2013.

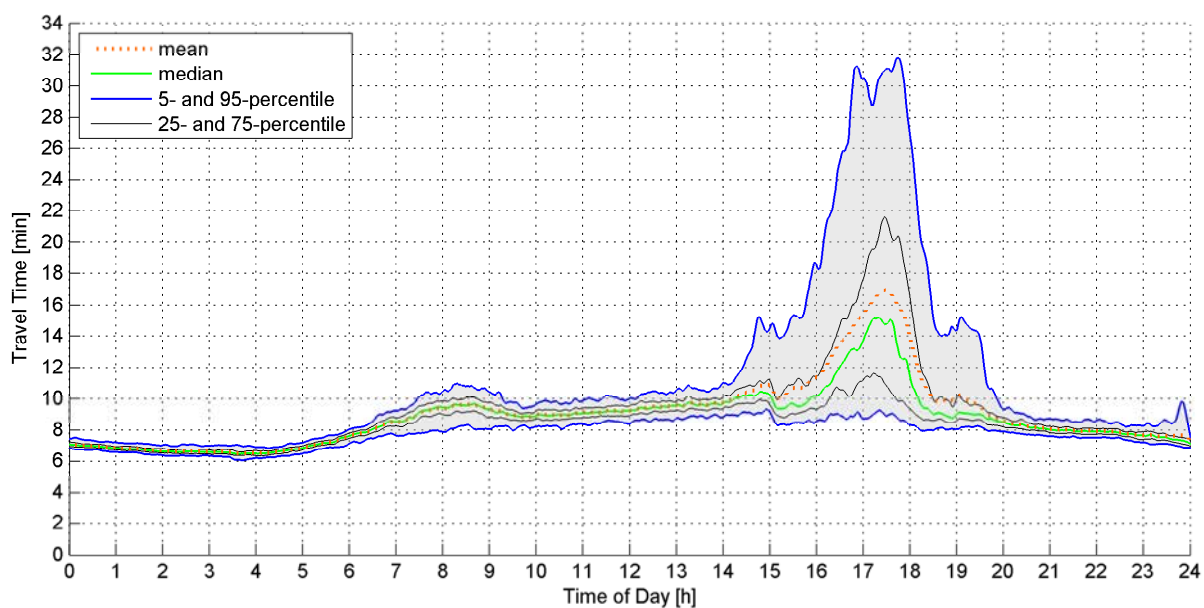


Figure C.16: Bandwidth graph of travel times on workdays on route B outbound in Q4 of 2013.

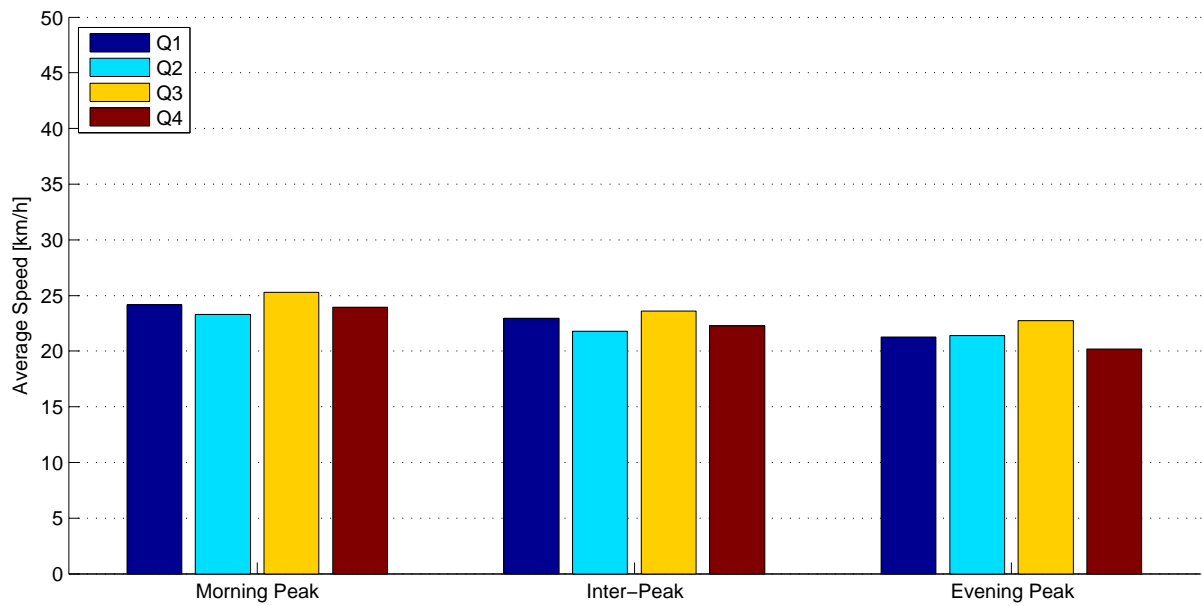
**Route E: Schieweg – Schiekade (Inbound) Project Method**

Figure C.17: Mean speed on route E inbound in three periods of the day and per quarter of the year 2013.

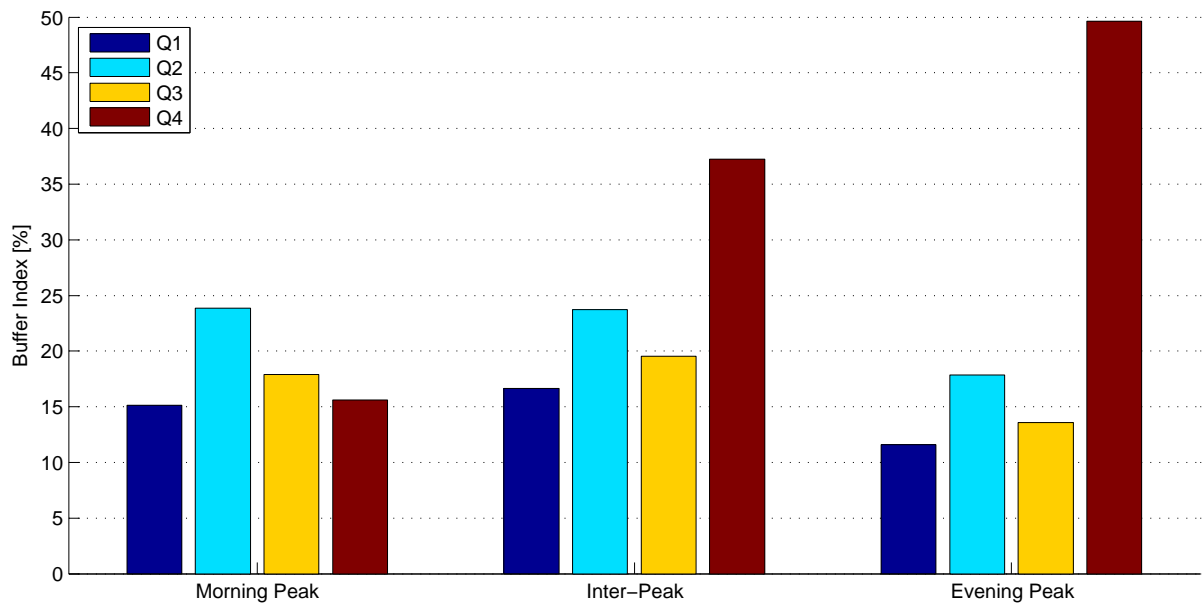


Figure C.18: Buffer Index on route E inbound in three periods of the day and per quarter of the year 2013.

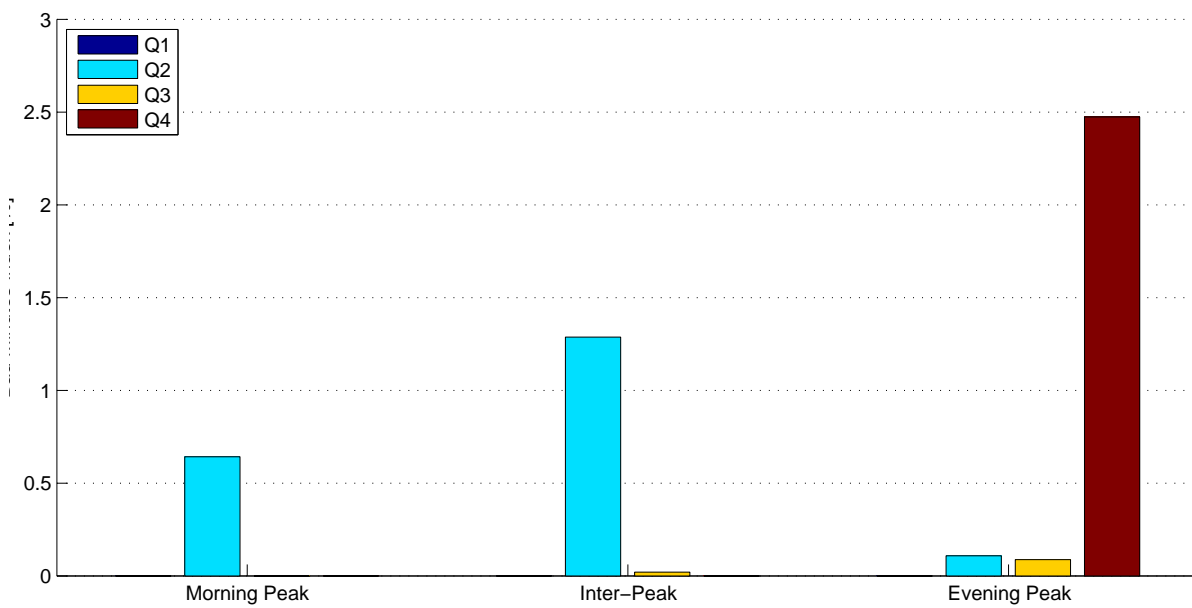


Figure C.19: Bad Minutes Index on route E inbound in three periods of the day and per quarter of the year 2013.

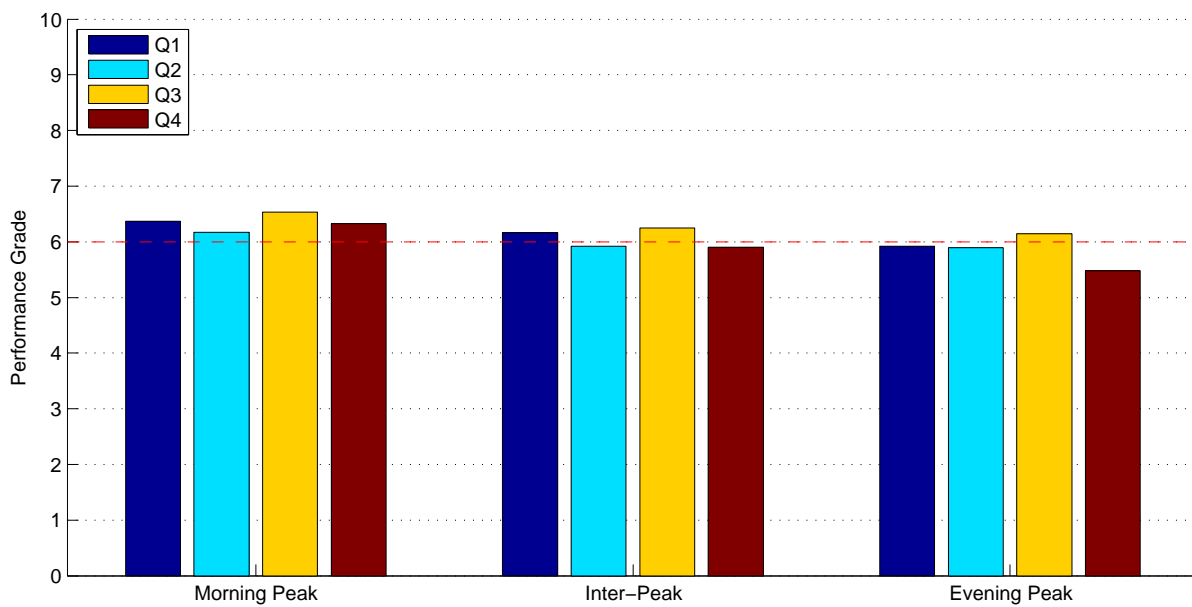


Figure C.20: Performance Grade on route E inbound in three periods of the day and per quarter of the year 2013.

### Route E: Schieweg – Schiekade (Inbound) Bandwidth Graphs

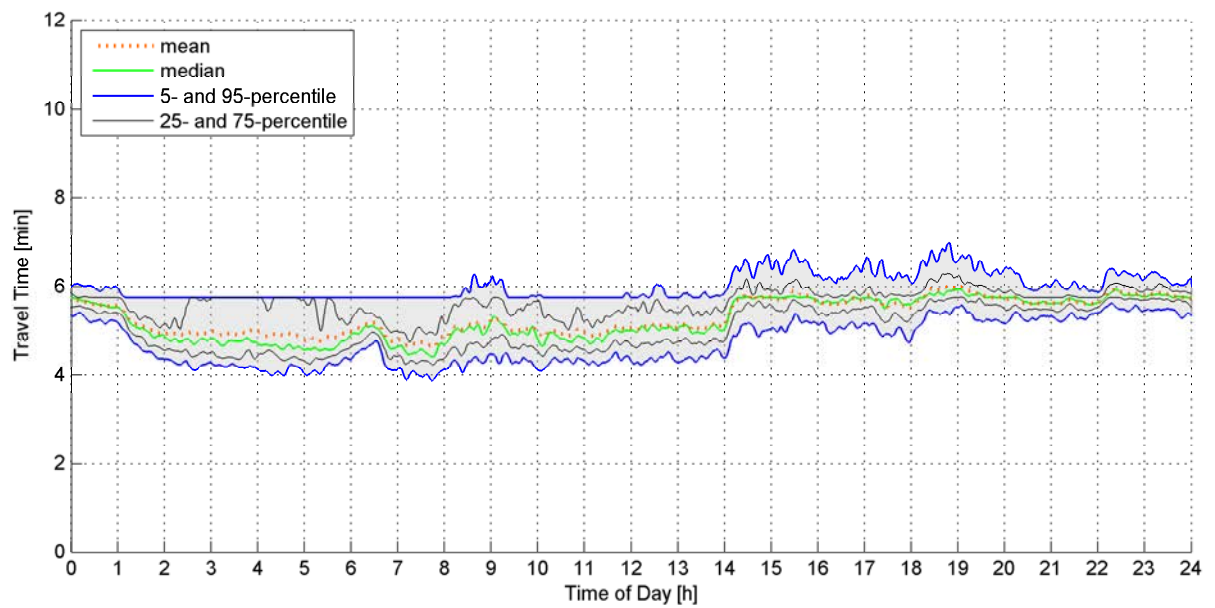


Figure C.21: Bandwidth graph of travel times on workdays on route E inbound in Q1 of 2013.

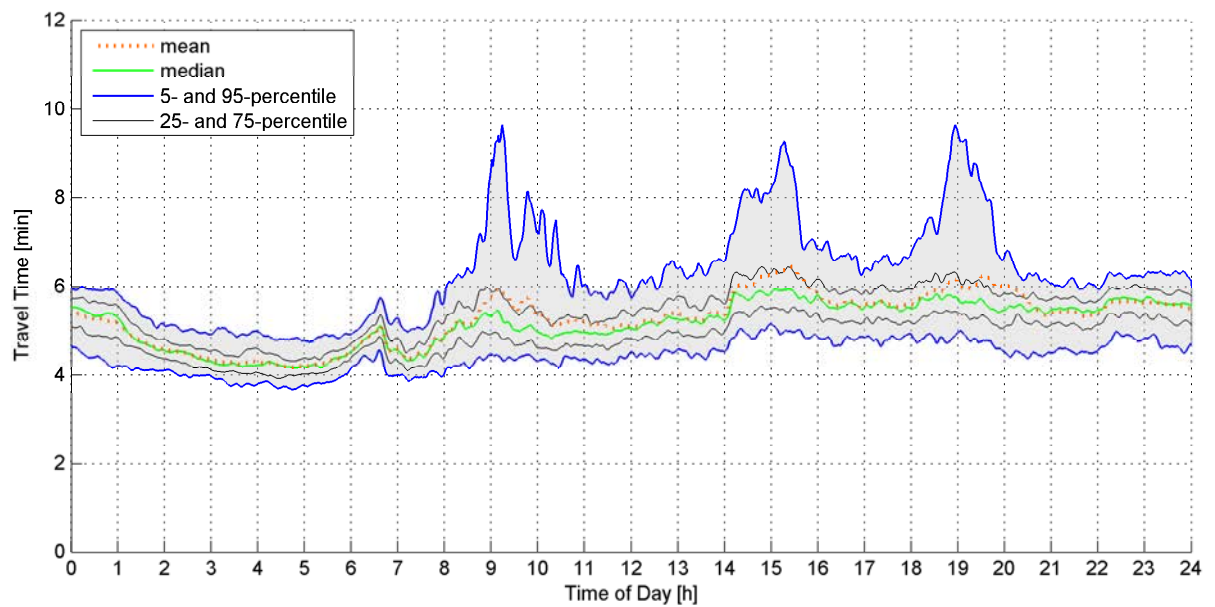


Figure C.22: Bandwidth graph of travel times on workdays on route E inbound in Q2 of 2013.



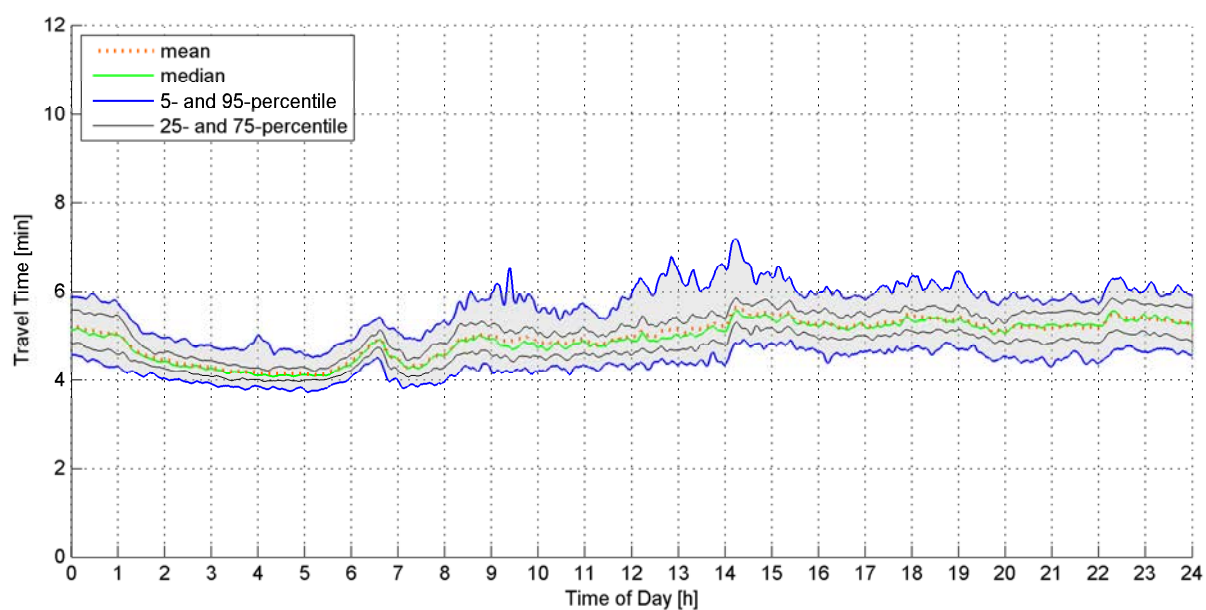


Figure C.23: Bandwidth graph of travel times on workdays on route E inbound in Q3 of 2013.

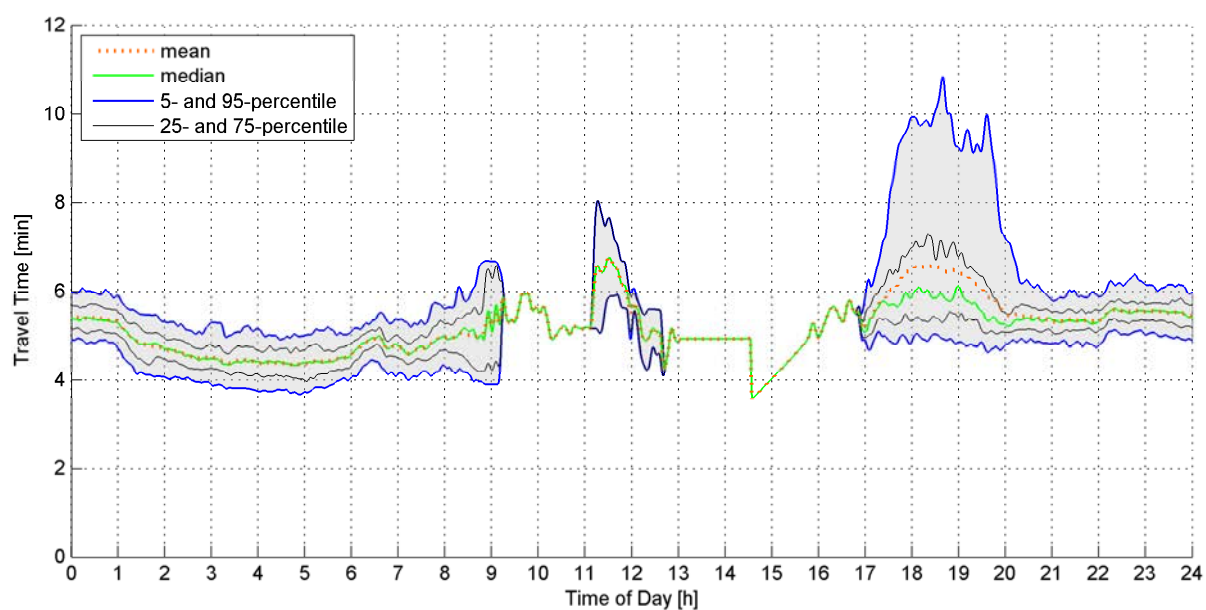


Figure C.24: Bandwidth graph of travel times on workdays on route E inbound in Q4 of 2013.

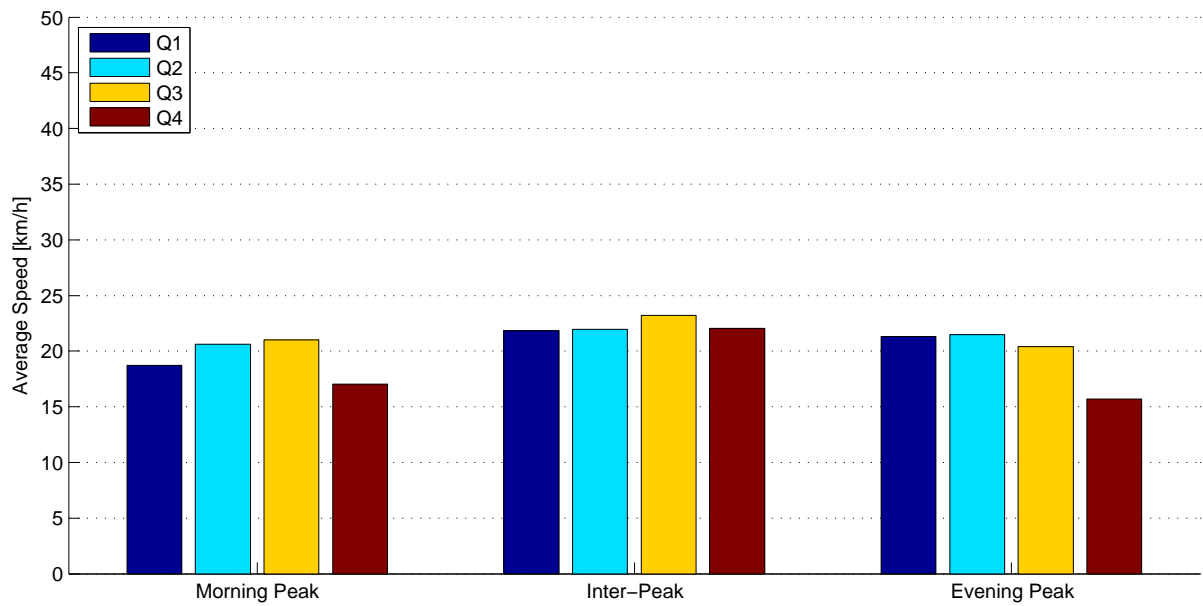
**Route E: Schieweg – Schiekade (Outbound) Project Method**

Figure C.25: Mean speed on route E outbound in three periods of the day and per quarter of the year 2013.

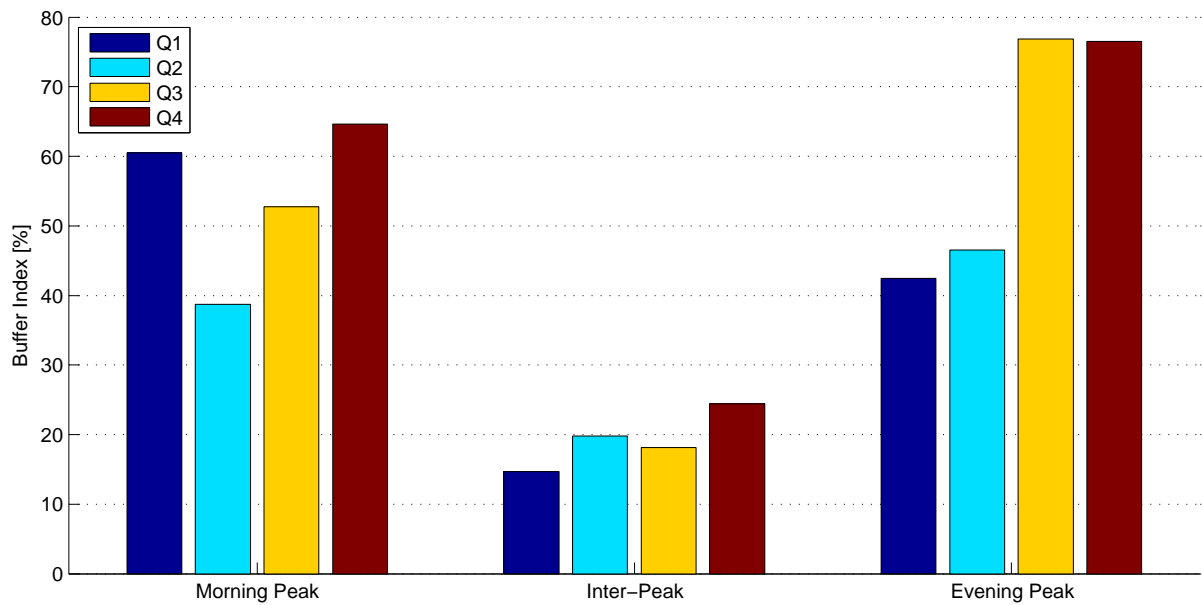


Figure C.26: Buffer Index on route E outbound in three periods of the day and per quarter of the year 2013.

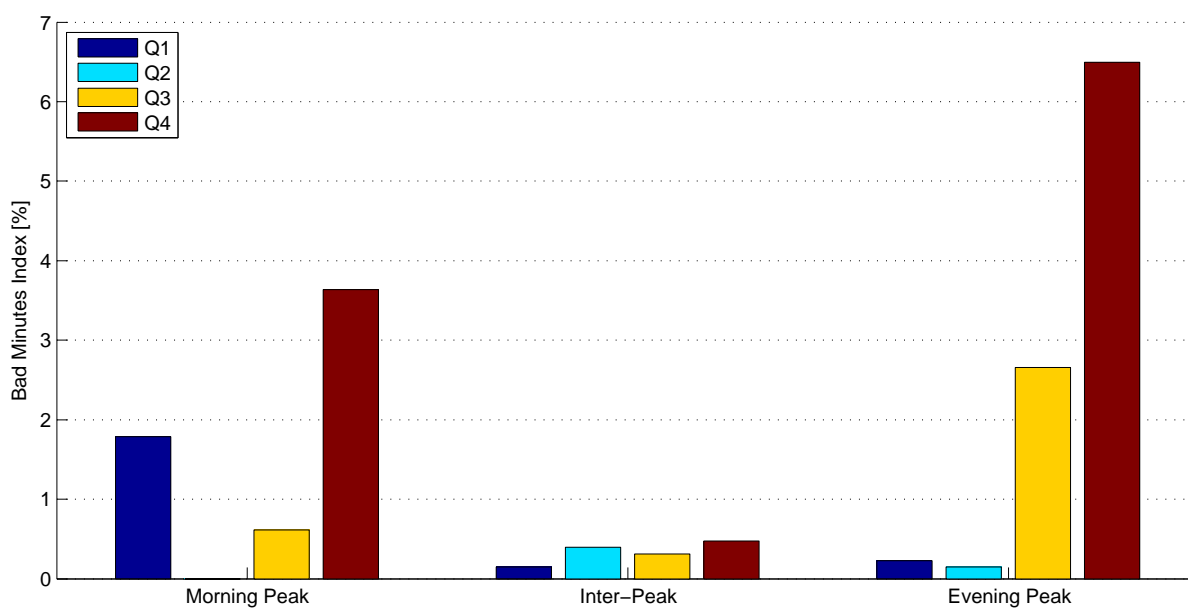


Figure C.27: Bad Minutes Index on route E outbound in three periods of the day and per quarter of the year 2013.

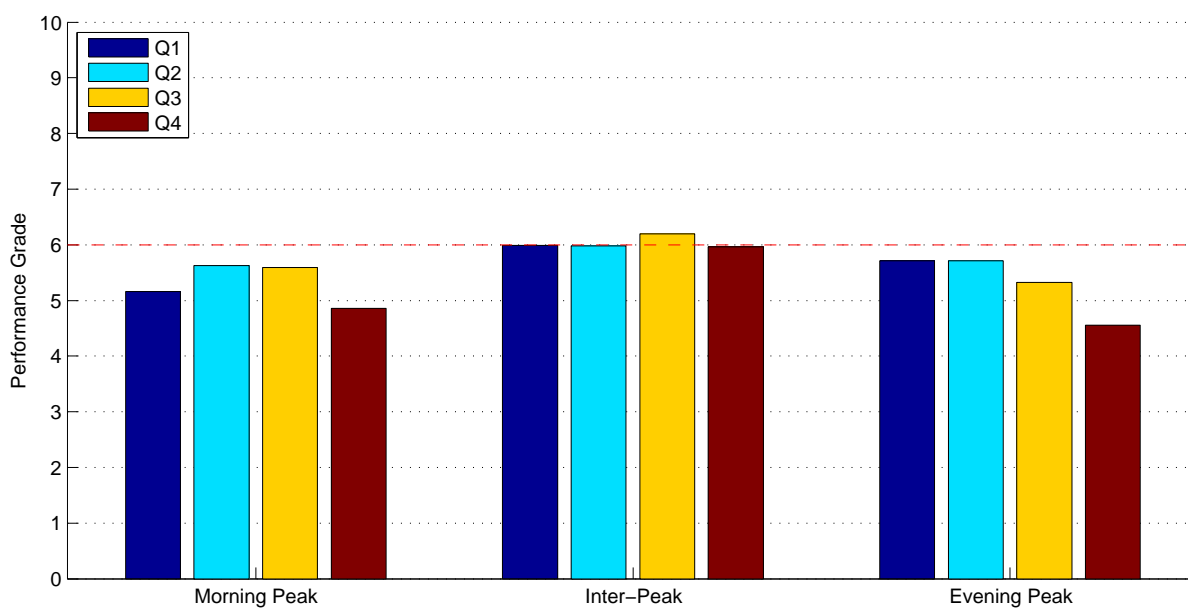


Figure C.28: Performance Grade on route E outbound in three periods of the day and per quarter of the year 2013.

### Route E: Schieweg – Schiekade (Outbound) Bandwidth Graphs

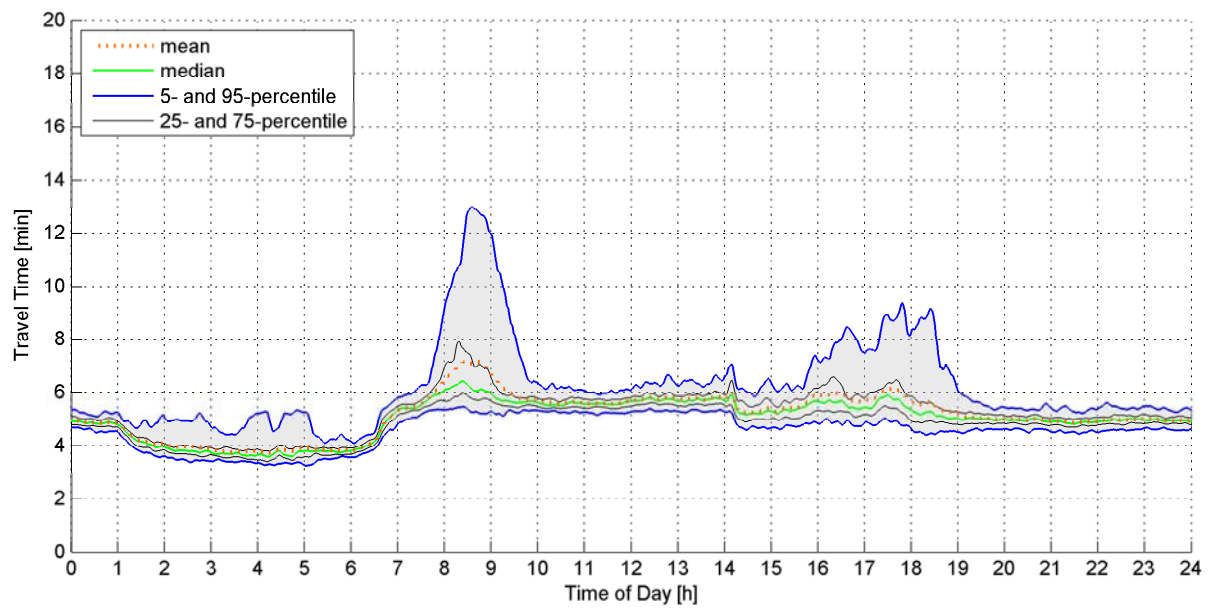


Figure C.29: Bandwidth graph of travel times on workdays on route E outbound in Q1 of 2013.

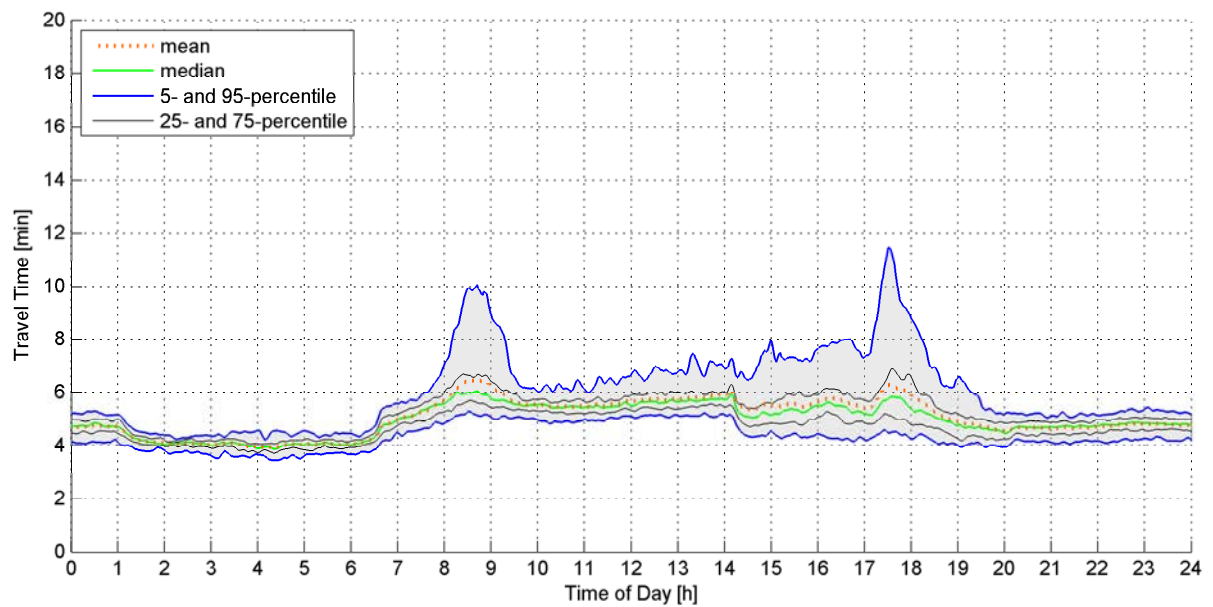


Figure C.30: Bandwidth graph of travel times on workdays on route E outbound in Q2 of 2013.

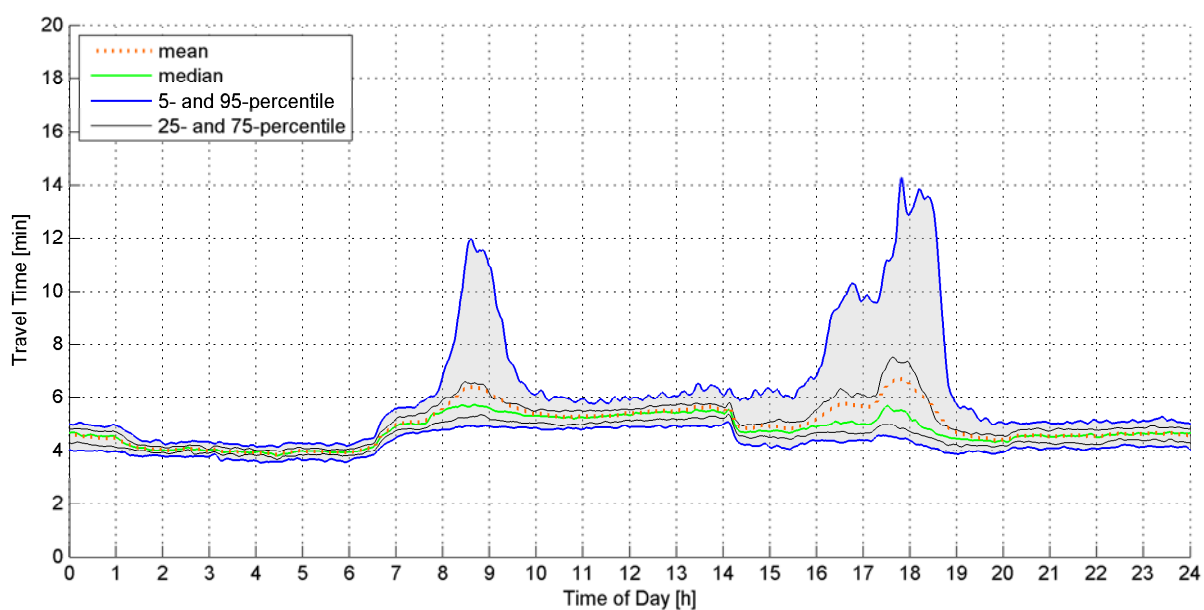


Figure C.31: Bandwidth graph of travel times on workdays on route E outbound in Q3 of 2013.

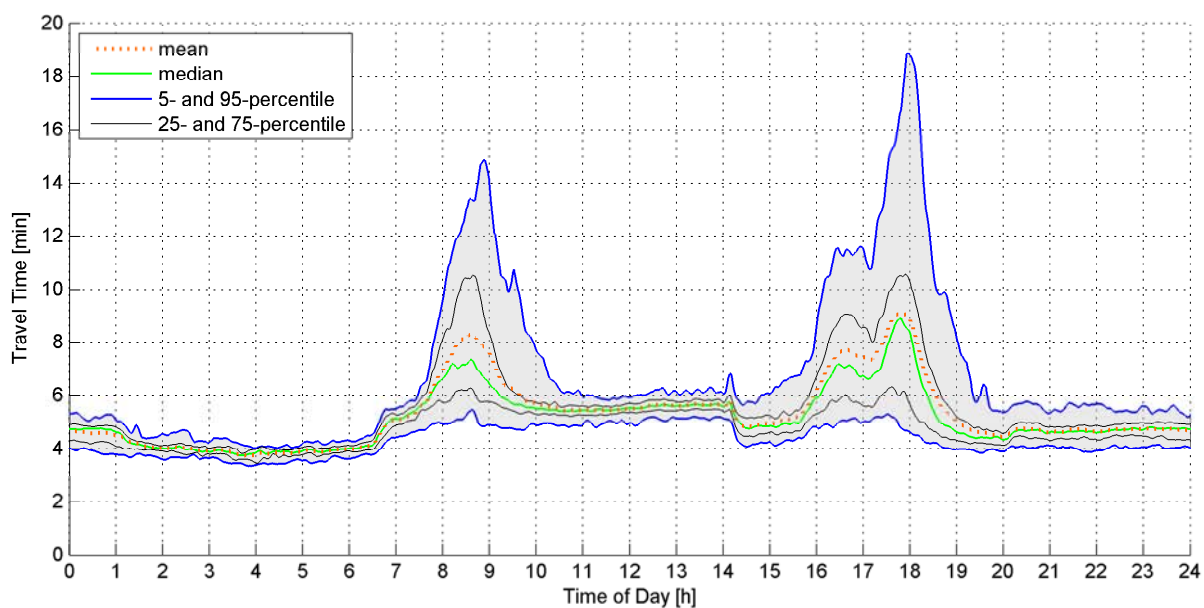


Figure C.32: Bandwidth graph of travel times on workdays on route E outbound in Q4 of 2013.