QUALITY OF REAL-TIME TRAVEL TIME INFORMATION

A research to travel times presented to drivers in the Netherlands

19 September 2012

Master thesis, final report

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Summary

Real-time travel time information becomes more and more important in nowadays' busy traffic situations. For a driver to choose the shortest route, for a traffic manager to improve the traffic flow. Therefore both public and private information providers offer traffic information services.
This research compares travel time information presented by Rijkswaterstaat (RWS), TomTom and Bluetooth services in the Netherlands. To measure the quality of the presented travel times the research contains a qualitative and a quantitative analysis. The first part creates insight in the operations of RWS and TomTom and describes the strengths and weaknesses related to accuracy, variety of data sources, relevancy, timeliness and accessibility. This second part contains a data-analysis to compare travel times of both providers at free flow and congested conditions. The analysis contains a description of trends in performances and measurements of accuracy by using the Mean Absolute Percentage Error (MAPE) and a two and one tailed paired student's t-test.

Rijkswaterstaat, the national traffic manager of the Dutch freeways, presents travel times on Variable Messages Signs (VMS) and uses loop detector data to calculate a travel time. Loop detectors however only measure speeds and intensities at certain points and a linear speed distribution between those measurement points is assumed to calculate an instantaneous travel time. Hereby the presented information could contain inaccuracies since changes of traffic flow between two loops are difficult to monitor, especially in congested conditions (for example with stop and go movements). The information is presented on VMS, which is freely accessible for all drivers on the road, but will only be relevant to the freeway part of a route. Next to that the used communication channel has some weaknesses; information should be read while driving at high speeds and after having passed the VMS the driver does not receive any updates.
TomTom, the leading producer of navigation systems, also provides real-time travel time information, which is presented at in-car navigation systems. This navigation product is called TomTom HD Traffic. The company uses both historical and real-time traffic data, combined by data fusion, to calculate a travel time. Real-time travel times are directly measured by floating car data of GPS receivers in their navigation systems and location data of cell phones using the Vodafone network. This latter data source of GSM location data requires extensive filtering to use only active cell phones located in a vehicle. A weakness of the measurement methods is the penetration rate of the equipped vehicles. Both GPS and GSM data sources only measure a selection of the total traffic flow. Furthermore, due to the limited bandwidth only real-time data is used in case of real delays. If the measurements exceed the historical values and the real-time data source gets priority in de data fusion. Strengths of TomTom's system are the travel time information is applied to the whole route including all type of roads, and up-to-date information is continuously accessible at the in-car device.
Bluetooth travel times are measured by monitoring active Bluetooth devices. Matching MAC-addresses at different locations leads to a direct measurement of travel time. However the method is dependent on a penetration rate and only measures a travel time at the end of a section. This results in delayed detection of increasing travel times during congestion, which is a major drawback for accurate real-time information.
In short, the qualitative analysis shows the travel time of TomTom is based on travel time measurements, relevant for the user-specified route and always accessible. In contrast, the indirect travel time calculation method of RWS uses average speeds at measurements points and assumes a linear speed distribution between those points to produce a travel time. Due to the characteristics of the communication channel the travel time information of RWS is only relevant to freeways and not accessible after passing the VMS.

The second part of this research include five scenarios to evaluate the accuracy of presented travel times during different traffic conditions. The scenarios contain a variation of different types of roads and monitoring systems to show the influence of the quality of the data collection on the presented travel time.

- *Scenario 0: Nijkerk - Nunspeet (via A28 both directions)*
- *Scenario 1: Hoevelaken to Utrecht (via A28 and A1/A27)*
- *Scenario 2: Gouda to Den Haag and Rotterdam (via A12 and A20)*
- *Scenario 3: Leiderdorp to Bodengraven (via A4/A12 and N11)*
- *Scenario 4: Ede to Lunetten (via A12)*

Based on an users' perspective, the travel times of Rijkswaterstaat are compared to TomTom HD Traffic travel times (in scenario 1, 2, 3 and 4) and/or to Bluetooth travel times (in scenario 0 and 4). In this way the available real-time information services are compared to determine whether differences appear. In scenario 0 and 1 also experienced travel times of individual TomTom users are added to check whether the presented information matches the experiences of drivers. In the data-analysis three types of days (free flow, medium congested and heavy congested days) are distinguished to check whether the performances of the travel time information systems are depending on the degree of delay. Furthermore the congested days are further divided in periods of free flow, increasing and decreasing congestion to determine the quality of the systems in encountering changes of traffic conditions.

The data-analysis shows that despite the theoretically weaknesses of indirect travel time calculation based on loop data, the travel times of RWS compete with the travel times of TomTom regarding accuracy. The travel times are comparable for road sections with high density of good performing loop detectors. For other sections differences are found between travel times of RWS and TomTom during both free flow and congested conditions.
Firstly, during free flow conditions the travel time of TomTom is smaller than RWS in all scenarios. The difference varies from less than 1 minutes to more than 3 minutes, depending on the specific route. The deviating travel times could be caused by an incorrect alignment of the routes, by the various performances of loop detectors or by ignoring or including slow trucks. Remarkable, the free flow values of TomTom does not match the experienced travel times of TomTom users. Next to that, for the non-freeway N11 the free flow travel time of TomTom is larger than the loop based travel time and does not confirm the results at freeways.
Secondly, during increasing congestion the difference between TomTom and RWS is bigger than during decreasing congestion. Several trends are observed in the comparisons of the travel time peaks during all scenarios. For example, because a threshold is use to switch between historical and real-time traffic data in the data fusion of TomTom, the travel time of RWS starts showing delay slightly earlier than TomTom. Next to that, the increase of RWS' travel time is smaller than TomTom whereby at high delays TomTom's travel time become comparable or even exceeds the values of RWS. During decreasing congestion the performance could be divided in two trends. The travel times decline comparable or the peak of TomTom decreases faster than RWS.
Next to these comparisons of RWS and TomTom travel times, this research shows among others the weaknesses of delayed detection of changes in travel time by Bluetooth detectors. This result suggest timeliness is a clear problem for these type of traffic data, whereby it is less useful for real-time travel time information provision.

Finally, although the results of the qualitative analysis indicate clear advantages of the TomTom system, the data-analysis refines this conclusion. The RWS system is able to deliver accurate travel time information if a high density of loop detectors is available and no disturbing factors (like roadworks) are present.

Preface

This report is the result of my graduation project to the quality of travel time information. This research studied the operation of the travel time systems of Rijkswaterstaat and TomTom, by analysing the strengths and weaknesses. And compares the travel times in five scenarios, measuring the accuracy of the presented information. The research is the final assignment of my education Civil Engineering and Management, track Traffic Engineering at the University of Twente. The past six months I have worked at ARCADIS in Arnhem and learn a lot about the topic. Studying the theoretical strengths and weaknesses of the data sources and recognizing these characteristics is the real data was a nice job. Next to that contacting the related companies and convincing them to join this research was instructive.

At the start of this report I like to thank all the people who have supported this research. Firstly my supervisors at ARCADIS for the very useful feedback during the whole project. Patrick Broeren for the daily support and the critical view on the structure of the report. Martijn Loot for the connections to Rijkswaterstaat and the input during the data-analysis. Secondly, the supervisors of the University of Twente. Eric van Berkum for his general supervision, and Jing Bie for the input during writing the research proposal and the frequently feedback on the progress reports.
Subsequently, I like to thank Rijkswaterstaat for the access to all data sources. The performed research was impossible without this cooperation. Furthermore I like to thank Jolanda van Gool for the nice discussion about the operation of the RWS processes. Next to that I am thankful for the cooperation with TomTom. Due to the delivered travel time data this research contains an interesting comparison between two information providers. Peter Krootjes and George de Boer, thanks for the meetings and explanation about products of TomTom.

Finally, I like to thank all my colleagues at ARCADIS. I appreciate the interested questions to my progress and delivered ideas to improve the research. Furthermore the good atmosphere and nice conversations made my graduation project a pleasant period.

Joost de Jong
Arnhem, 31th August 2012

Contents

Glossary

ABBREVIATIONS

ATIS	Advanced Traffic Information System
CDMS	Central DRIP Management System
D4T	Data4Traffic, consortium who collects traffic data for NDW
DRIP	Dynamic Route Information Panel
GRIP	Graphic Route Information Panel
GPS	Global Positioning System
GSM	Global System for Mobile communications
MAPE	Mean Absolute Percentage Error, statistical test
MoniBas	MONItoring BASic applications, part of travel time system of Rijkswaterstaat
MoniCa	MONItoring CAsco, part of travel time system of Rijkswaterstaat
NDW	National Data Warehouse for traffic information (Nationale Databank Wegverkeersgegevens)
RWS	Rijkswaterstaat
TMC	Traffic Message Channel
TREFI	Traffic information centre travel times and congestion information (TIC Reistijden en File Informatie)
VID	VerkeersInformatie Dienst
VILD	Traffic (Verkeer) Information Location Database
VMS	Variable Messages Sign

DEFINITIONS

Historical travel time	A aggregated travel time collected in previous periods. Used by service providers to estimate an expected travel time, based on route, type of day and point of time.
Instantaneous travel time	A travel time calculated by summing the real-time measurements of all route sections at the same time (t_{origin}). This type of travel time is presented by real-time travel time services at the origin of a route.
Predicted travel time	A predicted travel time based on real-time measurements, including expected changes of traffic conditions in the future.
Experienced travel time	A travel time experienced by an individual road user, measured after reaching the destination ($t_{destination}$).

1 Introduction

This chapter introduces the topic and explains the relevancy of this research. Firstly the background is described, explaining the important actors in the field of traffic information. Subsequently the research goal and questions are defined and the structure of this document is described.

1.1 BACKGROUND

Real-time traffic information becomes more important in nowadays complex and busy traffic conditions. The growth of traffic demand in dense road networks requires accurate up-to-date information provision which gives insight in the traffic situation for the traffic manager, who tries to improve the network performances, and the car drivers, who try to minimize travel times. Therefore both public and private companies offer services which deliver traffic information. Figure 1 shows the relations between actors of traffic information provision.

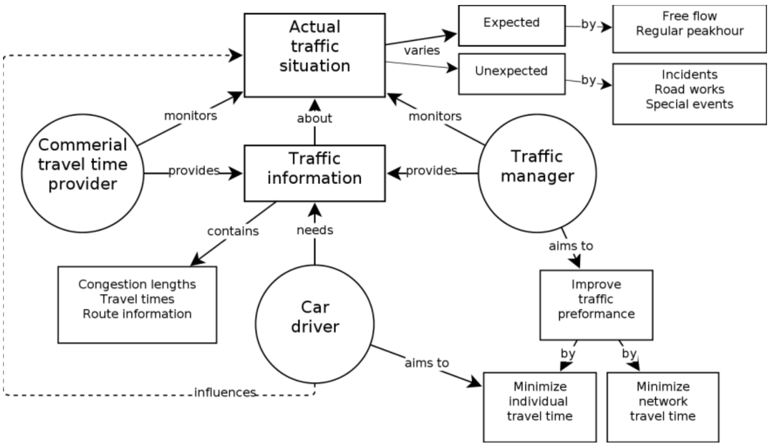


Figure 1 Interaction between car driver, traffic manager and travel time provider

The content of traffic information can vary widely. Mostly, information services contain travel times, route information, congestion lengths or combinations of those three. However messages could also contain information about weather conditions, road closures, roadworks, accidents or other special events. In the past years the information provision is further developed by real-time traffic information including travel times. In the Dutch situation, the road authority and traffic manager, Rijkswaterstaat, is investing in comprehensive data-collection and information provision by VMS systems in order to improve the traffic flow. Other travel time service providers however invest in more innovative data sources and use more flexible communication channels. Therefore the question rises what the quality of these traffic information services is. Imagine a vehicle equipped with a navigation system and a radio is driving at the freeway along a VMS. The information received via these Advanced Traffic Information Systems (ATIS) are likely to differ. Each system has its own data source, calculation method and update frequency, which could end in contradicting information and a confused driver. This indicates a need for a quality analysis of travel times services in the Netherlands. Based on the users (car driver) point of view, quality could be measured in accuracy, relevancy, representation and accessibility of the information (Wang & Strong, 1996). A comparison of the quality of the travel times from those providers could therefore be used to determine a fitting strategy for the future and furthermore create insight in the current state of travel time calculation.

> A general misconception is assuming the presented real-time travel time is the same as a travel time prediction. Most car drivers do not know the operation of the information systems and interpret the travel time as a prediction of their arrival time. However travel time information providers emphasize the provided information is only an estimation based on the current measurement and the assumption that the traffic conditions remain unchanged. This instantaneous travel time prediction is theoretically a way of prediction, but has limited predicting value in the reality of a dynamic traffic situation. The difference between real-time and predicted travel times is described in section 2.2 and 2.3.

The quality of the provided information can be measured by different aspects, as will be described in section 2.3. Accuracy is widely-used to evaluate the quality of the travel times. Since real-time traffic data enables possibilities for more accurate travel time calculation, it is interesting to determine how the current providers preform. Real-time travel time calculation is still quite difficult due to the high number of unknown or unpredictable factors. Besides accuracy, also qualitative indictors could be used to determine the quality of the services. These indicators could include other aspects of data quality, for example timeliness, false alarm rate or characteristics of data source and calculation method (like described by Wang & Strong (1996), Bogenberger (2003) and Fontan, Grullon, & Robbins (2010). Due to the limited time and resources, it is not possible to include all those quality indicators. Therefore this research will focus on the accuracy of instantaneous travel times presented to road users by different information providers in the Netherlands. Furthermore to explain the possible differences in these real-time travel times, the characteristics of data collection and processing will be studied.

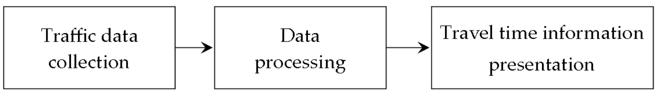


Figure 2 Chain from raw data to end-product

1.2 RESEARCH OBJECTIVE

This research will compare different travel time services in the Netherlands by measuring the quality. The goal of this study is defined as:

> Assessing the quality of real-time travel time information presented by different information providers in the Netherlands, by comparing presented instantaneous travel times to each other and to travel times experienced by individual drivers.

1.3 RESEARCH QUESTIONS

Based on this objective, the research question is formulated as:

> What is the quality of real-time travel times of RWS, TomTom and Bluetooth based services in the Netherlands, measured in mutually differences and differences to experienced travel times?

This question will be elaborated by studying the following sub-questions:

- How do the travel time services operate, including data sources, parameters and assumptions?
- How do the travel time information services perform during free flow and congested conditions?
- Which travel time information service is preferable combining the results of the first and second sub-question?

1.4 BRIEF EXPLANATION OF THE RESEARCH QUESTIONS

The research method will be elaborated in chapter 3, but in this section the questions are already shortly explained. The first sub-question focusses on the operation of the travel time information services of Rijkswaterstaat and TomTom (selection explained in section 3.2). Currently, an overview of the algorithms is missing and calculations are unclear or even a black box. A qualitative analysis will describe the characteristics of these travel time services to provide more insight in the quality of the predicted values, related to accuracy and other quality indicators, like timeliness, relevancy and accessibility. This qualitative analysis serves the quantitative analysis and could be used to explain the differences in accuracy even more.
The second sub-question contains the main part of this research and focusses on the accuracy of the presented travel times by performing an data analysis. This real-time travel time information will be compared to each other to determine whether differences appear. And next to that compared to an experienced travel time; a travel time measured after a driver has finished the route.
The third sub-question compares the results of the data analysis and adds qualitative indicators, studied in the first question, to the assessment. This generates an overview of the performances of the systems under different conditions and a possible explanation for the differences.

1.5 REPORT OUTLINE

This first chapter is an introduction to the subject of real-time travel time information provision. The second chapter further elaborates the topic and describes the possibilities of advanced traffic information systems. Next to that the chapter an overview of earlier researches to travel time estimation and prediction, also explaining the different definitions. The second chapter ends with some literature about data quality indicators and an overview of traffic data sources. Subsequently the research method is defined in the third chapter. The made assumptions are described and an overview of the work packages is presented. Furthermore the scenarios and qualitative/quantitative indictors are defined in the research methodology. Chapter 4 and 5 subsequently contain the qualitative analysis. Firstly describing the operation of both the travel time systems of RWS and TomTom. This contains i.a. the used travel time calculation method and data sources. Secondly, the sixth chapter, analysis the theoretical strengths and weaknesses regarding accuracy, variety of the data sources, relevancy, timeliness and accessibility. Chapter 6 contains all the results of the data analysis, presented for each scenario. The seventh chapter summarizes all the results; explaining the quantitative outcomes by using the results of the qualitative analysis and evaluating performances of the travel time services in the drivers' perspective. Chapter 8 shortly recalls the results of the research to answer the research questions and contains the discussion indicating which nuances could be made at the performed research.
Notice, since the data analysis produces a high amount of plots, this research comes with an electronic appendix containing plots of all studied days (see Appendix 9). These figures could be used to verify the described results or study the comparisons in detail.

2 Theoretical framework

In this chapter an extensive overview is presented of all subjects related to the quality of travel time information. The chapter starts with describing the commonly used traffic information systems. Subsequently the definitions and theories of travel time calculation and prediction methods are described. Next to that different indicators of measuring (traffic) data quality are elaborated. The chapter ends with a presentation of different types of traffic data sources and their limitations. In addition to this theoretical framework Appendix 1 presents the results of earlier researches regarding the effects of VMS.

2.1 ADVANCED TRAFFIC INFORMATION SYSTEMS

Radio, television, variable messages signs (VMS), on-board navigation systems, mobile phones etc. are used to deliver traffic information and called Advanced Traffic Information Systems (ATIS). The goal of these systems is influencing drivers' travel behaviour to improve network performance, in terms of less congestion and delays (Chorus, Molin, & Van Wee, 2006; Khattak, Pan, Williams, Rouphail, & Fan, 2007; Kattan, Nurul Habib, Tazul, & Shahid, 2011). Based on this traffic information, drivers are able to select a destination, travel mode, optimal route and departure time or even cancel their trip. Two information strategies are distinguished; The strategy could be informing about the possible routes and current conditions (descriptive information) or a steering strategy could be used by advising a certain route (prescriptive information) (Van der Mede & Van Berkum, 1993).

The development of the next generation ATIS is stimulated by real-time data gathering and fast growing development of mobile internet (Chorus, Molin, & Van Wee, 2006). Real-time traffic data is important to improve the accuracy of the information. The traffic information services become more accurate and therefore more reliable. The presented information on i.e. VMS or radio seems to match the traffic situation which the driver experience on his route. Furthermore due to the rapid developments of mobile internet and smart phones, the driver can receive relevant traffic information for his position at any time, requested or unrequested.

Due to the multiplicity of ATIS the driver can search information on various media. The interaction between these systems could enlarge the effects of traffic information systems. An example is shown by Kattan, Nurul Habib, Tazul, & Shahid (2011) where commuters who sought information via various traffic information sources are more likely to respond on VMS traffic information. Emmerink, Nijkamp, Rietveld, & Van Ommeren (1996) indicate a similar correlation between the use of radio and VMS traffic information. The characteristics of the widely used ATIS will be explained in the following subsections.

2.1.1 VARIABLE MESSAGE SIGNS

Variable messages Signs (VMS) are used to provide en-route information. This information contains congestion level, incident warnings, special event messages, recommendations of alternative routes, etc. (Zhenlong & Chonglun, 2011). The first generation of signs contain three lines of text and are mono-colour.

The newest VMS are full-colour and are able to present not only text, but also symbols or maps. These new developments serve the need for improved travel information provision. The growing amounts of traffic and increased demand for fast connections ask for improved use of the road networks. Since space is limited and network expansion is expensive, dynamic traffic management plays an important role in solving congestion, improving travel times and creating a balanced use of all the routes in the network. In this situation VMS is a useful tool and should be used effectively.

The effectiveness of travel times and route information on VMS is a complex subject. The effects can be measured in individual travel times, network travel times, route choices, intensities, speeds, etc., and depends on the response of drivers, the content of the messages and situation specific factors such as characteristics of the network, traffic situation, etc.. The response of drivers is based on preferences and behaviour. The content of the messages is related to types of information, accuracy, reliability, etc.

Figure 3 Mono-coloured VMS with text: congestion information (top left) and campaign information (top right). Duo-coloured VMS with text and graphics: congestion information (bottom left) and travel times of public transport and car (bottom right)

DRIPS IN THE NETHERLANDS

The general term for electronic signs in literature is Variable Message Signs (VMS). However, in the Netherlands different types are distinguished, for example Matrix Signal Installation (MSI), Dynamic Route Information Panel (DRIP), Graphic Route Information Panels (GRIP). Most of the electronic signs on the Dutch freeways are MSIs. Electronic signs, located above each lane of the Dutch freeway, inform the drivers about (dynamic) speed limits, for example in case of congestion, or lane closures. The number of DRIPs is lower; in 2004 around 100 (SWOV, 2006). During the last years the number of DRIP grows fast, not only on freeways but also on rural and urban roads. The first DRIP at the Dutch freeway networks was installed around 1990. Initially, the messages contain congestion information and was located above the road at decision points between two alternative routes (see figure 2). Since 1996 the DRIPs were also used to display (expected) travel times (Westerman & Hoeve, 1996). Nowadays traffic managers use the signs also for other purposes, like Park&Ride services, special events or safety campaigns. The newest generation therefore also displays pictures and maps, and is located at the roadside (in Dutch ‘bermDRIP’). The used displays are based on Motorway Signal 4; a commonly used information panel in Great Britain. This displays are 3x4 meters, freely programmable and contain two colours of LEDs. The newest pilots research the possibilities of GRIP using variable congestion indication on fixed map signs or using the newest generation of DRIP.

2.1.2 RADIO AND TELEVISION BROADCASTS

Television broadcasts plays an important role in pre-trip trip choices. The information provision can influence the departure time, the route, the travel mode or even the destination. Radio broadcasts are more flexible and can provide, besides pre-trip, also en-route information. The traffic information on both media is normally broadcasted in frequent bulletins, for example every hour. This way of distribution has however disadvantages. Due to the fixed programming, the timeliness of the information is quite difficult to ensure. Next to that the services providers decide which information is included in the presentation. This is a clear shortcoming for the level of detail. Not all congested areas are mentioned and the information tends to be more generalized (Khattak, Pan, Williams, Rouphail, & Fan, 2007).

2.1.3 NAVIGATION SYSTEMS

Navigation systems could be divided in two categories: fixed in-car systems and mobile (handheld) devices (Katteler, Sombekke, & Van Mieghem, 2009). The first generation of navigation systems were implemented in the vehicle and uses the Radio Data System(RDS)/Traffic Message Channel (TMC) to update the navigation information and were quite expensive. Further developments in navigation products and a reduced price resulted in a fast growth of mobile devices, the second generation of navigation systems. Handheld navigation systems and navigation software installed on PDA or smartphone are more flexible in use; not limited to one vehicle and easier to replace/update when newer versions and technologies are available. The latest versions of navigation systems offer not only static route information, but are also dynamic systems which are equipped with a mobile phone connection to receive frequently updates of real-time traffic data. Next to that the navigation systems provide extensive information: route instructions, travel time, estimated time of arrival, (average) speed, points of interest, etc. A key characteristic of navigation systems is the voice and visual based support. This type of ATIS has a significant influence on en-route travel behaviour.

2.1.4 INTERNET SERVICES

Multiple internet sites offer traffic information services. The fast developments in online applications have resulted in a multiplicity of online applications with various qualities. The quality of the information strongly depends on the supporting company or authority. In general, internet services have however some clear advantages. Flexibility is the most important one (Khattak, Pan, Williams, Rouphail, & Fan, 2007). Information can be provided about i.e. travel times, congestion, accidents, roadworks, weather conditions by using multiple formats, i.e. text, maps, photos or videos. Next to that the user interacts with the system and selects only relevant information. Several sites stimulate this even more by providing a planning tool which determines the optimal route including all relevant information based on origin and destination. Due to the low cost of operating a website, internet services seem to be one of the most cost effective methods of providing traffic information. Since an internet connection is required to access the information, these services mainly contribute to pre-trip traffic information. However the development of mobile internet enables also en-route information provision.

2.1.5 MOBILE PHONE SERVICES

Telephone advisory services originally contain special phone numbers which give access to traffic information. Automated systems provide easy access to information at any time, generalized for the whole network or only for users' specified routes (Khattak, Pan, Williams, Rouphail, & Fan, 2007). However, the fast development of mobile phone technology and wireless internet connections enables a new generation of mobile phone services. Smartphone applications are available in various types and can offer all types of traffic information (like internet services) or can function as navigation systems (Manolopoulos, Tao, Rusu, & Papadimitratos, 2012). Furthermore, since a smartphones also contain a GPS-receiver, the position of the driver is known and the information could specified automatically. The easy accessible apps improve the traffic information distribution and could enlarge the use of real-time traffic information.

2.2 TRAVEL TIME ESTIMATION

One major subject of traffic information is travel times. These times could be measured direct or indirect, depending on the used traffic monitoring source, and used to provide travel time information (elaborated in the next section).

> A travel time is the time needed to travel between two points, mostly origin and destination. The travel time could be calculated based on the distance between those points and the (mean) speed. An online travel time is provided to a driver by forecasting the travel time, based on real-time data, on a certain link before he enters that link. An offline travel time uses historical data from a link to estimate the travel time of a vehicle after he passed through that link (Feng, Bigazzi, Kothuri, & Bertini, 2010)

2.2.1 DIRECT TRAVEL TIME ESTIMATION

Travel time of individual vehicles can directly been measured. Two categories of methods are distinguished: Automatic Vehicle Identification (AVI) and Vehicle tracking. The first category uses an unique vehicle ID to recognize a vehicle. Detectors installed along the road scan license plates or detect i.e. RFID tags or Bluetooth signals. A matching vehicle ID scanned by two detectors results directly in a travel time of the road section in between. The accuracy of travel time depends on the detection rate of vehicle IDs. If only a small amount of vehicles is equipped with for example Bluetooth devices, the detectors are not able to monitor the total traffic flow. Therefore the penetration rate (level of equipped vehicles with respect to the total flow) should be sufficiently high to ensure a significant amount of data is produced. If the number of equipped vehicle is low or an incorrect representation of the total traffic flow, the measurements could be present an incorrect travel time. Furthermore this measurement system is infrastructure related and the coverage is limited to the presence of detectors. A variation of this AVI method is using loop detectors to recognize vehicles by the length of the vehicle or platoon, or a unique inductive profile. This method operate fully anonymous, but the accuracy is limited due to low sampling rates. Next to that the method are not yet widely implemented, since it still requires investments in additional hardware (in case of inductive signature) or delivers errors (i.e. when a vehicle changes lanes at a loop detector).

The second category is based on floating car data (FCD); it follows the position of the car in time by collecting location data. Currently two types of FCD are commonly used to monitor traffic. Firstly, GPS data received from vehicles equipped with a GPS receiver. These vehicles continuously sending their position, which could be used to track the route, speed and travel time of individual vehicles. This method is not infrastructure related and therefore able to cover a high amount of roads (including local roads). The accuracy of travel time depends on the accuracy of the GPS signal and also on the penetration rate of GPS equipped vehicles. The second location data method to tracks vehicles by using the locations of active cell phones. Data logged by the telecommunication providers contain positions of cell phones to ensure a connection with the nearest base station. After extensive filtering, the non-car users are removed and the positions of active cell phones located in vehicles remain. The accuracy of the travel time is affected by the low accuracy of location estimation in telecommunication network and the required filtering to remove non-car users.

2.2.2 INDIRECT TRAVEL TIME ESTIMATION

Indirect travel time methods use data of fundamental traffic variables (flow, speed, density), mostly collected by loop detectors. By using traffic flow fundamentals and (inter/extrapolating) algorithms, this data is converted to travel times. Indirect travel time estimation method are divided in two categories: Spot Speed methods and Cumulative count curve methods. The first, and widely used method, calculates travel times on road sections based on the speeds measured by dual loop detectors. The speeds measured by the loops are interpolated over the road section between two measurement points by assuming i.e. a constant, linear or quadric speed profile. This indicates the clear weakness of the method; only the speeds on some points are known, so the traffic flow distribution between those points are unknown. In case of congestion, the system is not able to detect the precise start- and end-point of the queue, which leads to under- or overestimations of the travel time.
The second method uses only traffic intensities of in- and outflow and approaches a road section as a closed cell. The travel time of this section is estimated based on the amount of traffic within the cell. This method is applied in case of single loop detectors and contains obvious shortcoming regarding accuracy.

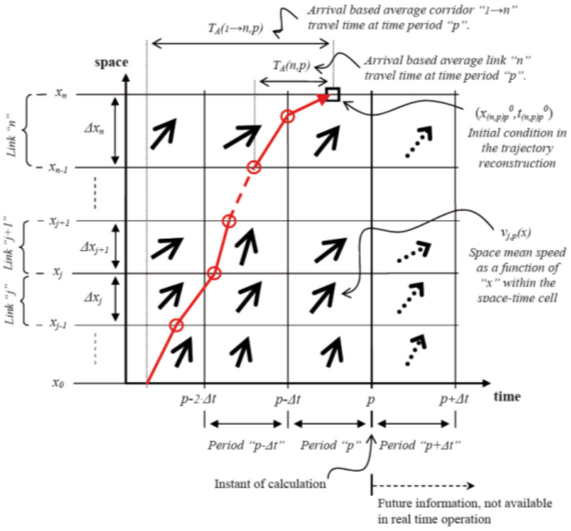


Figure 4 Indirect travel time estimation using spot speed (trajectory method).

2.3 TRAVEL TIME PREDICTION

A travel time prediction is quite complex since traffic and environmental conditions of the future are unknown. In order to predict a travel time, all those factors should however be known. Some factors could be determined based on historical data or theory of traffic processes, other factors are difficult or even impossible to predict (for example accidents). Besides the uncertainty due to the necessary assumptions in the travel time prediction, the predicted travel time is an average value for all drivers. However each individual driver experiences his own travel time caused by i.e. his driving style. Therefore individual travel times could deviate from this predicted travel time (TU Delft , 2006).

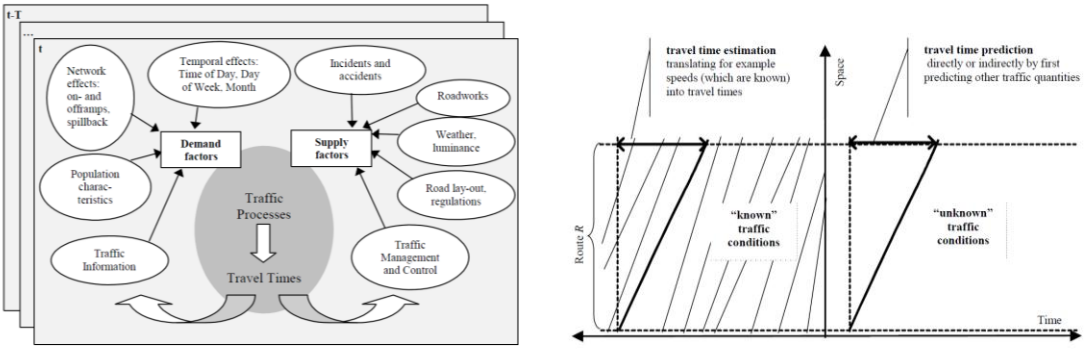


Figure 5 Influencing factors of travel times(left) and Prediction for unknown traffic conditions (right) (Van Lint, 2004)

In general, three categories of travel time predictors are distinguished:

- *Model based travel time predictors* determine traffic conditions for a defined time period ahead based on traffic processes. A traffic flow simulation model is used to predict the traffic conditions and deduce the mean travel times (Van Lint, Hoogendoorn, & Van Zuylen, 2005). Microscopic traffic flow models simulate individual vehicles and the results can be directly used in the mean travel time calculation. Macroscopic models focusses on a aggregated stream of vehicle. The model results, like intensity and mean speed, can be used indirectly to estimate the prediction of travel time (Van Lint, 2004) . A model based travel time prediction is a generic approach, applicable to all possible routes, and provides insight into the locations and causes of possible delay. However the required computational time and modelling expertise are disadvantages. Furthermore, the model in itself requires also predictions of traffic demands and supply as input.
- *Instantaneous travel time predictors* use current measurements and calculates travel times assuming the traffic conditions will remain stationary in the near future (Shen, 2008). Although this assumption in reality the seldom holds, this prediction method is currently widely used to determine travel time information. This approach requires a low computational time and exist of a simple algorithm, hereby this method is easy to implement. The route travel times are calculated by aggregating the predicted times for road segments. Van Lint (2004) shows an example of the systematic mismatch of travel times predicted by this approach. If congestion occurs, for example due to a bottleneck, the stationary conditions assume systematically lower congestion rates which leads to underestimation of the travel time. Inherently, if congestion disappears, the predicted travel times are overestimations. The real traffic conditions contain less congestion than measured data used in the instantaneous travel time prediction.
- *Data driven travel time predictors* do not use any traffic flow theories, but approaches traffic systems as a black boxes (Van Lint, 2004). The method predicts traffic flows, speeds and travel times based on the output of this black box. With the use of mathematical algorithms the models are able to learn the traffic processes directly from the data (Van Lint, 2008). As input the models can use road section traffic data or route travel times. However the latter is less usable for online travel time prediction, since this data is only available when the vehicle has arrived at the end of the route. Clear advantages of this prediction method are the ready-to-use software packages. Therefore expertise of traffic flow is not required, however for each location where these models are applied significant effort is required for calibration of the input parameters.

Travel time predictions are used to inform drivers and influence their travelling behaviour. If the predicted travel time lead to a route diversion, this will influence the travel time on the original and alternative route. Therefore the complexity of the travel time prediction increases. Since the traffic information is used to change the traffic conditions of the future (for example divert drivers to solve congestion), the response of drivers will influence the travel time. Hypothetical if all drivers change their route due to a small travel time on the alternative route, this will lead to a strong increase of the travel time on this route and a reduction of travel time on the original route. This trade-off is illustrated in the case presented below.

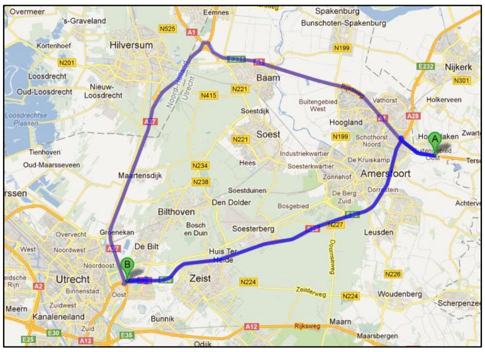


Figure 6 Two routes from A1 to Utrecht

To Utrecht
Via A28 27 min
Via A1/A27 33 min

1) Car drivers on the A1with destination Utrecht will choose the A28, since this route has the lowest travel time.

To Utrecht
Via A28 27 min + 6
Via A1/A27 33 min

2) More travellers will choose the A27, compared with the base situation. This could lead to an increase of travel time. So a difference between the prediction and the experience after passing this information sign.

To Utrecht
Via A28 27 min + 7
Via A1/A27 33 min + 2

3) Increased travel time on both routes. The changed route choice will influence the travel time on the A27. This information displays the traffic situation the drivers of situation 2 actually experience.

CASE: TRAVEL TIMES ON A27/A28 TO UTRECHT

To explain the operation of the VMS/DRIP system, the case of A1 to Utrecht will be elaborated. Two routes are available for a vehicle driving on the A1 with destination in Utrecht. The first route is via the A28 which is in free flow conditions 27 minutes. The second route is continuing on the A1 and subsequently to Utrecht via the A27 which is in free flow conditions 33 minutes, so 6 minutes longer. Due to high traffic demand the route via the A27 will become congested during peak hours. In these cases the travel time increases. After a certain time period, a delay time of 6 minutes is arisen on the A28, so the travel times on both route become equal. This will decrease the attractiveness of the A28, since this is no longer the shortest route, and lead to an increase of traffic loads on the A27. Due to this increase the traffic conditions on the A27 will change and result in an increase of travel time. The A28 will become more attractive again. This shows the complexity of real-time travel time information; the route choices are based on travel time information which is depending on the distribution of traffic among the routes. If car driver choose the A27-route, because the presented information tells this route is shorter, his route change and the diversion of other drivers will lead to an increase of experienced travel time and causes a mismatch compared with the presented information. So an accurate calculation should not only included the current traffic condition, but should actually estimate the travel time based on the route choices car drivers will make based on that information.

Most of the current dynamic travel time information services are non-predictive systems. The provide travel time information is based on the current traffic conditions instead of forecasting travel times based on future traffic conditions. Although traffic data is 'real-time', the moment of information delivery is always after a period of measurement and calculations. Just calculating the perceived mean travel times without using any prediction method is not a prediction (Papageorgiou, et al., 2007). The boundary between an offline travel time and an online instantaneous travel time is however small. If the traffic information service calculated the perceived travel time and assumes the traffic conditions will not change, the calculated offline travel time will be used as an instantaneous prediction.

2.4 DATA QUALITY INDICATORS

The quality of data is a complex subject, which is mostly narrowed to accuracy. Therefore Wang & Strong (1996) developed a conceptual framework of data quality. They distinguish intrinsic, contextual, representational and accessibility data quality with for each category several indicators. The framework is show in figure 5. In the context of traffic information; intrinsic means the traffic measurements and calculations are good, contextual means the information is presented at the right location and time, representational means good communication with the car driver, accessibility means the driver could receive the information.

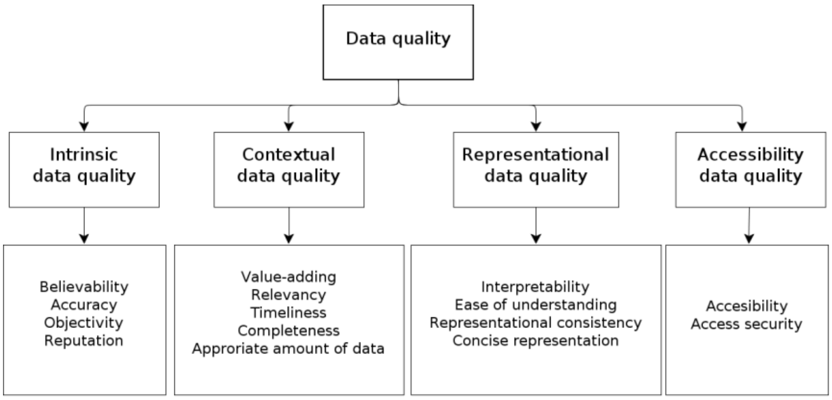


Figure 7 Conceptual framework data quality (Wang & Strong, 1996)

Bogenberger (2003) also states the quality of information should not only be measured in accuracy. He defines two qualitative indicators; the degree of overlap between the area of congestion and area of traffic message, and the proportion of the traffic message that is not covering the congestion area (false alarm rate). When the first quality indictor is high and the second is low, the quality of the traffic information is high. Fontan, Grullon, & Robbins (2010) evaluate ATIS of the Florida Department of Transportation, which provides real-time traffic information through internet and an interactive voice recognition system. They measure the usefulness for car drivers, based on accuracy and timeliness.
Besides these comprehensive quality approaches, most researchers do use only accuracy to evaluate the quality of traffic information services. For example, Zwahlen & Russ (2001) evaluate the travel time prediction service on VMS during road work and concludes that the accuracy of the prediction (about 88%) is an improvement over any static travel time system. Rakha & Van Aerde (1995) compared the accuracy of travel times based on respectively probe data and loop detectors. They conclude the standard loop detectors could provide accurate sources of real-time data and with high marker penetration rates, vehicle probes offer accurate link travel times. Quiroga (2000) recognizes less accurate travel time prediction during peak hours; a significant difference between the predicted and instantaneous travel time. His evaluation suggest that improvement of the predictive algorithm would result in lower discrepancies between those travel times.

2.5 DATA SOURCES: LIMITATIONS OF TRAFFIC MONITORING

The characteristics of the monitoring system are strongly related to the possibilities of the data sources. The systems are described in Appendix 2 and specific implications for travel time calculation will be elaborated in this section.

Dual loop detectors are not able to measure individual travel times, since vehicles are not uniquely identified. Therefore the travel times could only be derived from average speeds and intensities. The travel times are calculated based on the distance between two loop detector sets and the measured speeds on these locations. This method is therefore strongly dependent on the presence of loop detectors. This system is not able to monitor the traffic conditions on sections without loops or even between two loop sets and is not able to measure non-moving vehicles.

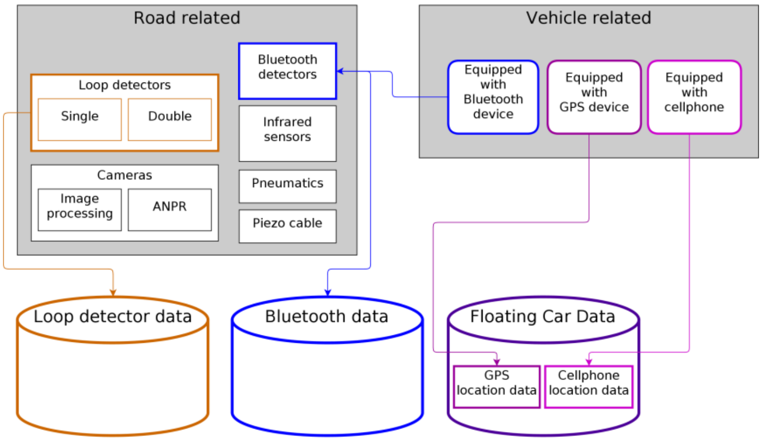


Figure 8 Overview of traffic data sources

Bluetooth data can be used to measure the travel time between two locations. The system could only measure the travel time when the same Bluetooth device is detected by two (or more) detectors. This means that the travel time is always offline calculated which will result in a delayed detection of changes in traffic conditions. Next to that only vehicles with an active Bluetooth devices are monitored. So the accuracy of this method is depending on the penetration rate of Bluetooth devices.

FCD could be used to measure traffic times, since the vehicles can be followed (in position and time). Telecommunication network and GPS instruments are not road-related and therefore covers the whole road network. The method is therefore not limited to certain locations or routes and is also able to monitor non-moving vehicles.

Table 1 Characteristics of traffic data sources

	Dual loop detector data	Bluetooth data	Floating car data
Coverage	Measurement points	Measurement points	Whole network
Travel time	No, only derived from speed data[1]	Yes, direct	Yes, direct
Speed	Yes, direct (at point)	Yes, direct (at route)	Yes, direct (at time period)
Intensity	Yes, direct (at point)	No[2]	No[2]
Detection rate	All vehicles	Only equipped vehicles	Only equipped vehicles
Non-moving traffic	No	No	Yes
Origin/Destination	No[1]	Yes	Yes
Vehicle classification	No[1]	No	No

1) Individual vehicles could be followed by recognizing vehicle lengths or inductive profiles. Currently these technologies are not widely used.
2) The intensity could be estimated if the penetration rate is known and stable.

3 Research methodology

In this chapter the methodology of the research is explained. The method consist of two analyses. A qualitative analysis describes the operation of the traffic information services to analyse the theoretical weaknesses and strengths of the travel time services. A quantitative analysis compares the instantaneous travel times by calculating the accuracy of those values compared to the experienced travel time. This data-analysis is the main part of this research. In Figure 9 a schematic overview is given of the work packages and relation within this research. Subsequently, this chapter describes the assumptions, selected travel time services and both analysis.

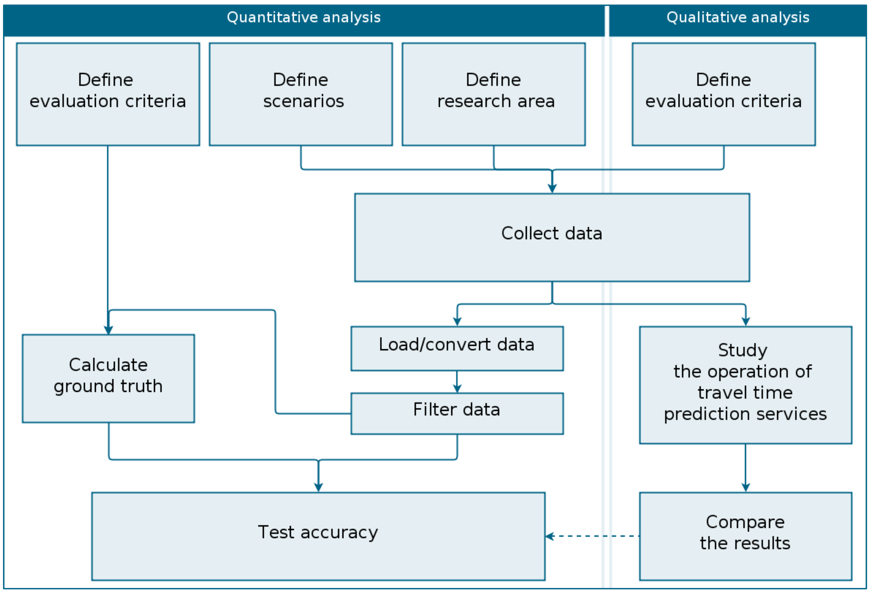


Figure 9 Research structure including qualitative and quantitative analysis

3.1 ASSUMPTIONS AND CHOICES TO DEFINE THE RESEARCH SCOPE

Assessing the quality of travel time information is a large subject, which should be reduced due to the limitations in time and research possibilities. Those limitations, visible in assumptions and choices are:

- Firstly, a relation between the accuracy of the real-time travel time and the quality of the traffic information is assumed as starting point of this research. This research tries to assess the quality of these information services by measuring the accuracy of the instantaneous travel times (and studying the qualitative characteristics). This accuracy is measured by the difference between the presented and experienced travel time. Underlying idea is that more accurate travel time information leads to more reliable travel time and thereby to a higher quality of traffic information.

- Secondly, the scope of the research will include only technology related issues regarding travel time information services. This means other aspects, like the human machine interaction (HMI) or human behavioural in general, will not be included. This is especially important for the definition of indicators in the qualitative analysis, since the quality of traffic information services could also be approached based on these aspects.
- Thirdly, this research focuses on the driver's perspective. The quality of the travel time information will be assessed by comparing the travel time information received by drivers. In this way the research objective and questions could be answered. Other perspectives could result in a different assessment of quality. Furthermore, the selected perspective clearly indicates which data will be compared. For example comparing the raw measurements of the monitoring system to determine which traffic monitoring system delivers the best quality of data will not be a goal of this research. Studying characteristics of different traffic data sources will only be partly included to explain the operation of the travel time information services.

3.2 SELECTION OF TRAVEL TIME SERVICES

There are multiple traffic information services available, as described in the first chapter. For this research the two most important travel time information providers are selected who both present real-time travel time information on the route.

- Rijkswaterstaat: The first information provider selected for this research is the Dutch road authority. This is the owner and traffic manager of the national wide freeway system. Like described in chapter 1, the aim of this research is to assess the quality of the travel time information provided at VMS/DRIP by RWS to evaluate whether investments in a comprehensive loop detector and DRIP systems result in accurate travel time information.
- TomTom: As leading producer of in-car navigation systems this information provider is a competitor of the on-route travel time information of the VMS system, since it presents an estimated time of arrival (ETA). The newest navigation system TomTom HD Traffic uses floating car data instead of RWS loop data, the travel time information could possibly been deviating from the information of RWS. This could lead to a dilemma for the driver which information to trust and an interesting research question which information is more accurate. See table 2 for a preliminary overview of characteristics of both travel time information providers.

Table 2 Characteristics of selected travel time information providers

	Rijkswaterstaat	TomTom
Real-time data source	Loop detectors/Bluetooth detectors[1]	Floating car data of GSM and GPS devices
Communication channel	VMS/DRIP	In-car navigation system
Coverage	Freeways (and some rural roads)	Freeways, rural and local roads
Type of travel time	Instantaneous travel time	Instantaneous travel time
Information strategy	Descriptive information	Prescriptive information
Dissemination	Publicly presented	Presented to only TomTom users

1) Bluetooth detectors operated by the VerkeersInformatie Dienst (VID) are used as alternative travel time data source by RWS. The VID is not included as travel time service in this research, so only the instantaneous travel times of the Bluetooth method will be studied as a data sources used by RWS.

3.3 QUALITATIVE ANALYSIS

A qualitative analysis is used to study the differences between the different traffic information services. Firstly, before assessing the selected systems in a qualitative way, the operations of Rijkswaterstaat, TomTom and Bluetooth services should be elaborated. Since the operation of the selected traffic information services is not completely documented, an important challenge of this research was to gain more insight in the 'black boxes' of these systems. The operations are described in the next chapter.
Secondly, after the operations were studied, the qualitative assessment is performed focussing on a broad context of quality. Like explained in the theoretical framework by different researchers (section 2.4), data quality should not be narrow to accuracy alone. The qualitative analysis therefore focuses on accuracy, variety of data sources, relevancy, timeliness and accessibility (selection explained in Appendix 3). Table 3 shows the selected quality indicators and adds the underlying question and system-related characteristics, which define the scope of the indicator. In Chapter 6 this indicator framework is applied on the selected travel time services to create insight in the strengths and weaknesses regarding the indicators.
Overall, this qualitative analysis is meant to support the quantitative analysis. Based on the theoretical knowledge about the operation, the performances of the travel time systems could be interpret and possible causes of differences could be explained (see Chapter 7).

Table 3 Qualitative indicator framework

Quality indicator	Underlying question	Specific characteristics
Accuracy	How accurate is the presented information, based on the operation of the travel time system?	Error free, Correct, Reliable, Precise (Wang & Strong, 1996)
Variety of data sources	Which data sources are used for the travel time calculation?	Data and data sources (Wang & Strong, 1996)
Relevancy	To what extent is the travel time information usable for a car driver?	Applicable, Relevant, Interesting, Usable (Wang & Strong, 1996); One way/two way communication, Collective/Individual dissemination (Papageaorgiou et al, 2007); Update rate, Computation time, Aggregation over time
Timeliness	How 'old' is the presented information?	Age of data (Wang & Strong, 1996); Message dissemination and guidance update intervals (Papageaorgiou et al, 2007)
Accessibility	How and when could a car driver receive the information?	Accessible, Retrievable, Speed of access, Available, Up-to-date (Wang & Strong, 1996); Local/area wide focus, Transmission range, Collective/Individual dissemination, Pre-trip/ en-route access to guidance (Papageaorgiou et al, 2007)

3.4 QUANTITATIVE ANALYSIS

The quantitative analysis focusses on the real-time presented information of instantaneous travel times by RWS and TomTom. The aim of this part of the research is assess the accuracy of the instantaneous travel times, compared to experienced travel times of individual drivers and to each other. Furthermore the data-analysis distinguishes the performances during free flow and congested periods. Although the aim of this research is on presented travel times (end products of real-time travel time services), also different datasets of travel times are included to create more insight in the quality of the traffic data sources and to assess the operation of travel time services.
This section describes which routes are studied(section 3.4.1), which datasets are compared(section 3.4.2), how the accuracy is measured (section 3.4.3) and how the studied periods are divided into categories (section 0).

3.4.1 SELECTION OF SCENARIOS

The quality of real-time travel time information depends on many factors. The selection of scenarios therefore contains different characteristics to show the relationships between accurate travel time information and the presence of the factors below.

- Monitoring systems — Roads with different loop detector systems (with low and high densities) and Bluetooth detectors are selected, to assess the performances of different infrastructure related monitoring systems.
- Traffic conditions — Although difficult to control, busy routes should be included to ensure free flow and congested conditions are both present.
- Roadworks — These activities could have clear impact on the monitoring systems and are included to assess whether it is possible to present accurate travel times if monitoring systems are frequently malfunctioned.
- Road types — Freeways and non-freeways are included, to assess the quality of floating car data of TomTom on different locations.
- VMS/DRIP — Logically since this research assess the real-time information presented by RWS, VMS/DRIP systems should be present at the selected roads.

Variations of the described factors created five scenarios with routes in the Netherlands. Due to the different characteristics of the scenarios this research is able to create a broad overview of performances of real-time travel time services under various conditions. The five scenarios are explained below.

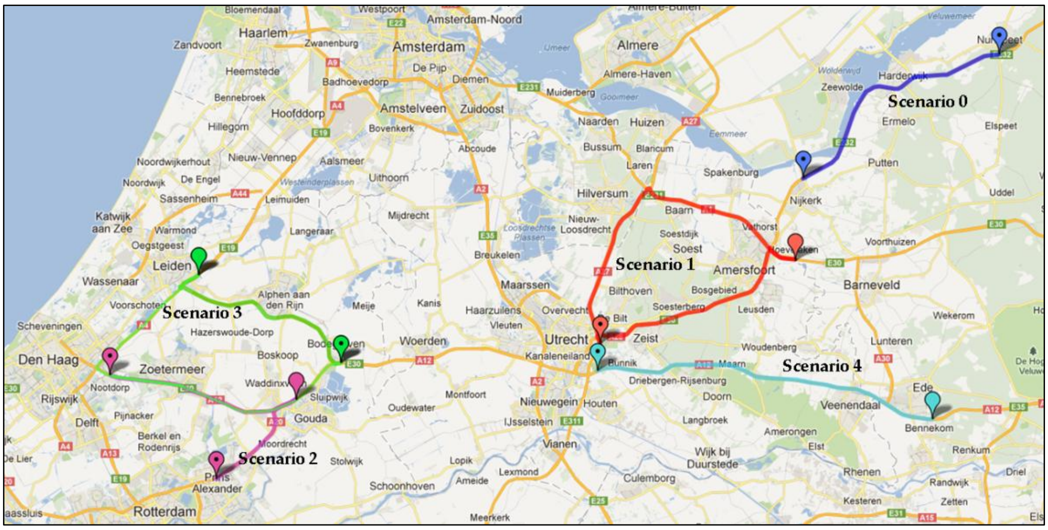


Figure 10 Selected routes of scenarios, Origin Destination

0. The study starts with a deviating preliminary scenario which do not assess on real-time travel time information but study the performances of two special monitoring systems; low density loop detectors and Bluetooth detectors. This scenario 0 focuses on the A28 between Nijkerk and Nunspeet in both directions. This section is a rare part of Dutch freeway with a low density of loop detectors (average distance around 4 kilometres). In contrast to the other scenarios, this traffic data is not used to present a travel time on a DRIP. However to improve the traffic monitoring on this 'blind spot' the NDW has contracted the consortium Data4Traffic to install and operate Bluetooth detectors. The presence of this new data source contributes to an interesting comparison to the qualities of different data sources. This data source is available since 27 January 2012 and so this scenario studies the months February and April 2012 to check whether the Bluetooth data differs from the loop data.

1. Scenario 1 contains two routes from the A1 near Hoevelaken to Utrecht, via the A28 and via the A1/A27, which have both comparable travel times and are frequently congested. Furthermore, roadworks on the A28 cause failure of the loop detectors. Despite this reduced performance of the traffic monitoring RWS does not use an alternative data source. Since TomTom uses floating car data, this system is not infrastructure dependent and the comparison could indicate whether the performances on both roads differ.
2. Scenario 2 studies two freeway sections with good conditions for accurate travel time information based on loops. The available loops at the A12 and A20 have a high density and deliver good quality of data. Therefore this scenario is useful to determine whether both floating car data and high quality of loop detectors data could deliver accurate travel times.
3. The third scenario studies a combination of a freeway and a 2x2 motorway. On the N11 loop detector of the NDW monitor the traffic flow and this data source is used by RWS to present a travel time on the DRIP. The comparison on this non-freeway is mainly interesting to assess the performances of TomTom. One of the major advantages of floating car data, claimed by this company, is the high network coverage, also including non-freeways.
4. The last scenario studies the A12 between Ede and Lunettten, where due to roadworks RWS uses an alternative data source (VID Bluetooth data) to present travel times. Because of the roadworks the loop detector data contains errors and therefore the motivation of RWS to switch to another data source for travel time information on this road is interesting, especially in relation to scenario 1 where despite reduced quality of data RWS does not use an alternative source.

Table 4 Overview of selected routes

	Origin	Route via	Destination	Datasets	Time period	Length [km]
0	Nijkerk	A28	Nunspeet	RWS TREFI NDW/D4T Bluetooth TomTom historic GPS	February 2012 April 2012	27.0
	Nunspeet	A28	Nijkerk			27.0
1	Hoevelaken	A1/A28	Utrecht, Rijnsweerd	RWS TREFI RWS DRIP logging TomTom HD Traffic TomTom historic GPS	December 2011 January 2012	27.1
	Hoevelaken	A1/A27	Utrecht, Rijnsweerd			36.8
2	Gouda	A12	Den Haag, Prins Clausplein	RWS TREFI RWS DRIP logging TomTom HD Traffic	16 June – 16 July 2012	20.8
	Gouda	A12/A20	Rotterdam, Terbregseplein			13.1
3	Leiderdorp	A4/A12	Bodengraven	RWS TREFI RWS DRIP logging TomTom HD Traffic	16 June – 16 July 2012	43.8
	Leiderdorp	A4/N11	Bodengraven			23.8
4	Ede	A12	Utrecht, Lunetten	RWS TREFI RWS/VID DRIP logging TomTom HD Traffic	16 June – 16 July 2012	37.2

At scenario 0: D4T operational since 27 January 2012.
At scenario 2: 13-07 and 15-07 are excluded due to technical error of the DRIP.
At scenario 4: DRIP travel time based on Bluetooth data of VID.

Besides the definition of routes, the scenarios are also restricted in time. Table 4 shows the time periods studied in each scenario. Scenario 0 analyses two months after the installation of Bluetooth detectors at the A28 which are operation since 27 January 2012. Comparing those months gives insight into the development of performances. For the other scenarios the presence of TomTom HD Traffic was leading in defining the time periods. This real-time product is not standardly collected on all routes. For this research TomTom started collecting this type of data at 16 June 2012 and collected the data for a period of four weeks. This length is chosen to ensure a significant amount of data could be analysed and to enlarge the change of interesting events, like incidents. Because the collection of this real-time data required a month of the available time, a different time period is selected for the A28 and A27 (scenario 1). For an earlier internal research TomTom HD Traffic was already collected for these roads at December 2011 and January 2012.

3.4.2 COMPARING TRAVEL TIMES

In order to understand the quality of a real-time travel time information, this section further explains the meaning of different types of travel time which will be compared. In this research instantaneous travel times presented by real-time information services are assessed. Since each service provider has its own data source, the characteristics of the traffic monitoring systems differ (i.e. the length of the road sections depends on location of the installed detectors). However in general, the figure below presents a schematic overview of the different types of travel times.

Figure 11 Timeline from origin to destination

Origin (O) *Destination (D)*

TT_1^t	TT_2^t	TT_3^t	…	…	TT_x^t

Travel time measurements on road segments (1)

$$TT_{RWS}^t = \sum_x^1 TT_x^t$$

$$TT_{TomTom}^t = \sum_x^1 TT_x^t$$

$$TT_{Bluetooth}^t = \sum_x^1 TT_x^t$$

(2) Instantaneous travel times of real-time information services

(3) Experienced travel time by drivers — TT

$$PTT^t = \sum_x^1 TT_x^t + C$$

(4) Predicted travel time

1. Each monitoring system calculates an average travel time per road section, aggregated for every minute. The location of the loops or Bluetooth detectors determine the length of a section and also within the system of TomTom different road segments are defined to calculate the travel time. RWS calculates a travel time by monitoring the vehicles who enter and leave the segment, TomTom monitors all vehicles in a segment and Bluetooth services measure only the travel time of vehicles leaving the segment.

2. Each service provider calculates an instantaneous travel time by summing the travel times of all the road segments at $t = t_O$. Notice this travel time in reality do not precisely match the experienced travel time, since a vehicle could not be present at all segments at the same time. Changing conditions between t_O and t_D will result in changes of the segment travel times and therefore cause deviations between the presented travel time and the experience of a driver. An instantaneous travel time is accurate if the traffic conditions of $t = t_O$ remain completely unchanged till $t = t_D$.
3. After passing all road segments and reaching the destination, the experienced travel time TT could be measured at $t = t_D$. This travel time value is unique for each individual driver, caused by i.e. driving behaviour and vehicle characteristics. Especially during free flow conditions the travel time variation is relatively high.
4. A predicted travel time is also based on real-time measurements and includes expected changes (C) in future to reduce the gap between the presented travel time information at t_O and the experienced travel time at t_D (see travel time prediction methods, section 2.3). None of the currently operational system provides predicted travel time, so this type of travel time will not be part of this research.

3.4.2.1 GROUND TRUTH: EXPERIENCED TRAVEL TIMES

To assess the accuracy of the traffic information services, the instantaneous travel times will be compared to a 'ground truth'. This ground truth is a travel time experienced by individual drivers on the road. Notice that travel time is influenced by several parameters, like drivers behaviour and vehicle performances. Especially under free flow conditions, when everyone could drive his personal desired speed, the variation of travel time is relatively high. However the presented instantaneous travel time is an average value (including all types of road users) or specified for one user group (i.e. car drivers).
Several technologies exist to measure travel times, as described in section 2.5. Each method has limitations and gives its own representation of reality. A ground truth travel time should measure travel times accurately, so preferably detect all vehicles (to guarantee a good representation) and monitor travel times directly (to prevent miscalculations). Loop detectors do not measure travel times and trajectory methods based on this data are not accurate enough (see appendix 4). Bluetooth detectors can be used to measure travel time, but are not widely present on Dutch freeways and do not detect all vehicles. Floating car data based on GSM data is dependent on the penetration rate and quality of the data filtering. Floating car data based on GPS data also depends on the level of equipped vehicles, but accurately measure the location of the vehicles in time. Other technologies, like number plate recognition, are not widely available and therefore less suitable for this study.
Based on the good characteristics and availability of GPS traffic data, the experienced travel times of individual TomTom users are used as ground truth. This travel time data is collected by GPS receivers within the navigation devices. This GPS device monitors the position of the vehicle in time. In this way TomTom collects anonymous travel time data of individual drivers, which accept the usage of their trip history, and creates a comprehensive historic database. However since the historic database contains raw travel time measurements, the data is infrequent and not aggregated. At some points (or periods) of time when intensity is low, the penetration rate could be zero and no TomTom data will be available. When intensity increases, the number of TomTom users will also increase, which could result in different travel times at the same point of time (due to travel time variation). Despite these implications the experienced travel time data (TomTom Experienced) could give a useful representation of the real traffic situation.

3.4.2.2 APPLIED COMPARISONS

To assesses the quality of real-time information services of RWS, TomTom and Bluetooth detectors in drivers' point of view, the differences between the instantaneous travel times and the experienced travel times should be measured. In other words, the real-time travel times, presented at $t = t_O$, will be compared to the experienced travel time, measured at $t = t_D$, to check whether these information services match reality. This leads to the following comparisons:

- *RWS DRIP and TREFI – TomTom HD Traffic – TomTom Experienced*
  Comparing these four dataset provides insight into the mutually differences of the real-time travel time services which tells whether the provided travel time information is different. Furthermore by comparing the instantaneous travel times to experienced travel times of individual drivers, the accuracy of the travel time services is measured. The difference between the provided information and the experiences of drivers indicate to what extent the different real-time travel time services are able to present an accurate travel time which matches the reality.
- *RWS MoniBas – D4T Bluetooth – TomTom Experienced*
  An alternative comparison is applied in scenario 0 since this scenario is an introduction to show the characteristics of different traffic data sources. The MoniBas data, the traffic data source of RWS, is compared to the new Bluetooth data source of D4T. In order to check the quality of the real-time data, experienced travel times are added as ground truth.

> After the period of data collection, it became clear that TomTom Experienced travel time data was only available for scenario 0 and 1. Studying a recent time period in the other scenarios was unavoidable, because TomTom HD Traffic is not standardly collected and had to be real-time collected. However it automatically generated a problem at collecting the experienced travel times. This type of data appears to be only available some months afterwards, since users of non-connected TomTom systems should manually send their travel history to the database to ensure a significant amount of data. Due to the limited available time for this research it was not possible to wait this period and therefore in scenario 2, 3 and 4 the comparison to experienced travel times is missing.

Since the ground truth travel times were not available for scenario 2, 3 and 4, the following comparison is applied in these scenarios:

- *RWS DRIP and TREFI – TomTom HD Traffic*
  The three available datasets all contain instantaneous travel times, whereby only the differences in performances of the travel time services can be determined. Unfortunately, a comparison to experienced travel times is missing. However even without this ground truth, the comparison is valuable because mutually comparing the real-time travel times will indicate the differences in performances. Furthermore based on the results of scenario 0 and 1 and the qualitative analysis, the differences could be explained. This means the accuracy of the presented travel times could also be assessed in scenario 2, 3 and 4, although a precise check to the experienced travel times lacks.
  Next to that, notice that the instantaneous travel time on the DRIP at scenario 4 is based on Bluetooth data of the VID. The TREFI data still presents values of the loop detector system.

3.4.3 EVALUATION CRITERIA: ACCURACY INDICATORS

The difference between the instantaneous travel time of TomTom and RWS will be used as a measure of accuracy. The difference to the ground truth is not measured by accuracy indicators, since this dataset is infrequent and not present in all scenarios. The ground truth just selected to present the individual travel times and variation and will therefore not be adapted. Appling these indicators requires (aggregation per minute to produce) a dataset with the same number of elements as the instantaneous travel time datasets.
Several statistical indicators are possible to measure accuracy. The selected indicators should measure the differences between two datasets and provided a clear score. The score should be meaningful by explaining the differences between the two travel time services. Therefore the Mean Absolute Percentage Error (MAPE) and student t-test are used in this research and are explained below.
Firstly, MAPE expresses the average deviation of the real-time travel times of the two sources, expressed in percentage of travel time. Since the absolute value of the difference is taken, negative and positive

scores do not balance. A low value of MAPE indicates high similarity of the two sources, a high value shows differences between the two. A drawback of this test is the inability to handle zero values, since this will result in dividing by zero. These values should therefore be filtered out.

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\frac{|x_i - y_i|}{y_i} \tag{1}$$

n	length of dataset
x_i	instantaneous travel time of RWS (DRIP)
y_i	instantaneous travel time of TomTom (HD Traffic)

Secondly, the student t-test is used to check whether two datasets are statically equal or different. A two tailed paired t-test is used to prove the equality of TomTom and RWS. The null-hypothesis is therefore the difference of the population means is equal to zero. However if one of the two data sets is bigger, the means are not comparable and the hypothesis will be rejected. Subsequently, a one tailed paired t-test is used to prove one of the two is indeed bigger than the other. Now the null-hypothesis is that one dataset is bigger than the other.

For both t-tests a confidence interval of 95% is applied. A normal distribution around the mean is assumed and values outsides the 95% range are resulting in rejecting the hypothesis. For the two-tailed t-test the confidence interval around the mean should contain zero, to prove the means are equal. Besides the results of whether or not rejecting the null-hypothesis, the boundaries of the confidence intervals could be used to present the difference between the travel times of TomTom and RWS. Furthermore, the spread of the boundaries expresses the variation of the differences.

$$T = \frac{\bar{X} - \bar{Y}}{S_d / \sqrt{n}} \tag{2}$$

n	length of dataset
S_d	standard variation of differences
$\bar{X}$	mean of instantaneous travel times TomTom (HD Traffic)
$\bar{Y}$	mean of instantaneous travel times RWS (DRIP)

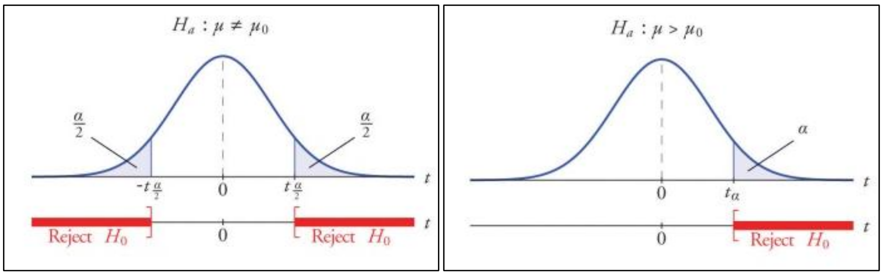


Figure 12 Two tailed (left) and one tailed (right) t-test (Shafer, n.d.)

3.4.4 CATEGORIZATION OF DAYS AND TRAFFIC CONDITIONS

Within each scenario (except the preliminary scenario 0) the travel times of RWS and TomTom are compared. To create insight into the relation between the traffic conditions and performances of the travel time systems, the comparisons are applied to periods with comparable conditions.

First of all, the studied days are categorized to compare the same type of days within each scenario. In this way, the qualitative analysis is able to interpret whether the quality of travel time information is influenced by different traffic conditions. The days are divided in the following three categories of days based on different amounts of delay. Notice the categorization is created based on the instantaneous travel time dataset of RWS and the free flow travel time is defined as the mode minimal travel time of all days in the scenario.

- *Free flow day:* No substantial changes of travel time occur during this type of day. The maximum travel time is lower than or equal to 125% of the free flow travel time.
- *Medium congested day:* This second category contains all days with moderate delays. The maximum travel time is lower than or equal to 200% of the free flow travel time.
- *Heavy congested day:* This last category contains all days with major delays, for example caused by incidents or routes with high amount of congestion during peak periods. The maximum travel time during these days is higher than 200% of the free flow travel time.

Secondly, the congested days are further analysed by distinguishing periods with different traffic conditions. During congested days, the dataset is divided in several parts indicating three conditions (see appendix 7 for specified rules used to divided these conditions):

- *Free flow:* These are the periods of a congested day when the travel time is not increased, for example between two peak periods or during night time.
- *Increasing congestion:* This category contains the first part of the peaks. Starting at the free flow level and ending a the maximum value encountered delay. Comparing the datasets during this condition indicates how fast and accurate the travel times present the occurring delay.
- *Decreasing congestion:* To prevent an overestimation of travel times, the information should be accurately adapted when congestion disappears. This last category contains the period from the top of a peak back to the free flow level.

4 Operation of the real-time travel time services

Travel time information is created by measurements and calculations. Raw traffic data should be converted to an useful travel time, to serve the road users with high quality of information. In order to assess the quality of this information, the operation of the travel time services of RWS and TomTom will be elaborated. This chapter describes how the traffic data is collected and which mathematical calculations are performed.

4.1 TRAVEL TIME OF RIJKSWATERSTAAT

Rijkswaterstaat is the road owner and traffic management authority of the Dutch freeways. The traffic information system of RWS is based on a nationwide loop detector system on the freeways and present real-time travel time information on VMS/DRIPs, like described in section 2.1.1. Initially, loop detectors are a part of the Motorway Traffic Management (MTM) system which is developed for traffic safety purposes. Speeds and intensities are monitored to encounter incidents and automatically warn the road users upstream by dynamic speed limits and lane closures on Matrix Signal Installation (MSI). The comprehensive database of speed and intensity collected by this system is converted to travel time information. Figure 13 shows the chain of traffic monitoring to traffic information. The included systems will be described in the following sections.

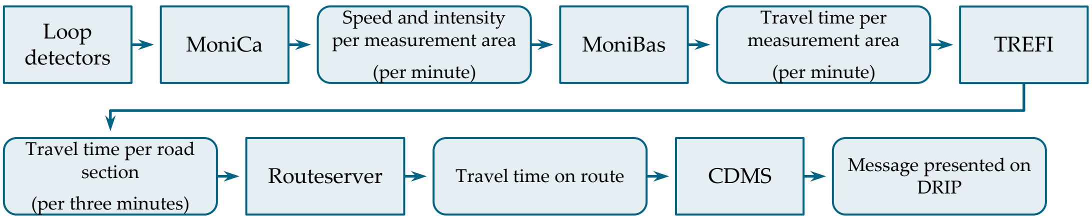


Figure 13 Chain from data to travel time information in the RWS system

4.1.1 TRAFFIC DATA SOURCES: MONICA AND ALTERNATIVE DATA

The Dutch loop detector system is called MoniCa, MONItoring Casco. Most of the freeways are equipped with dual loop detectors. These detectors are able to measure intensities and speeds, but do not measure travel times directly. The distance between two sets of loop detectors is called measurement area (in Dutch ‘meetvak’) and has an average length around 500-1.000 meters. The location of a set loop detectors is called a ‘raai’. The data of several measurement areas is aggregated within road section (in Dutch ‘wegvak’), located between two interchanges/VILD codes (in Dutch ‘VerkeersInformatie Locatie Database’).

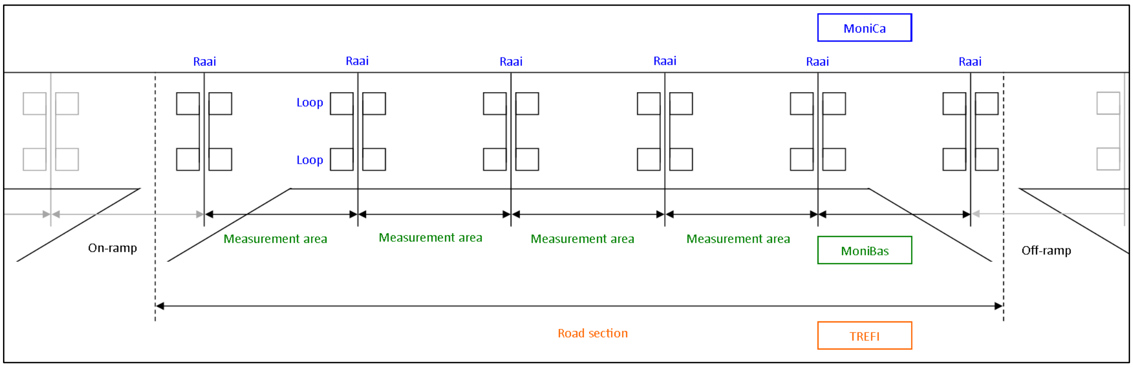


Figure 14 The RWS loop detector system

An inductive loop is a wire embedded in the surface of the road. A signal is created by a vehicle passing the inductive loop; the metal object causes an electrical current by change of magnetic field. A dual loop enable the possibility to measure not only intensities, but also speeds. The known distance between the two loops can be divided by the difference in time (moment of activation of both loops). Loop detectors are widely used for traffic monitoring and relatively cheap to produce and install. However since the loops are integrated into the road, deterioration of the road can impair the loops, for example caused by heavy vehicles or high traffic loads. Maintenance cost are therefore an important disadvantage, especially because those roadworks often require road closures (TU Delft , 2006).

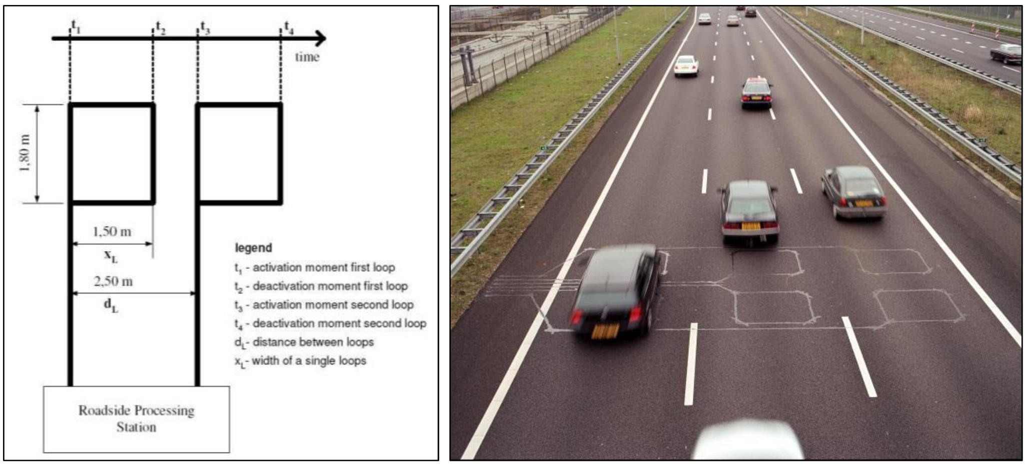


Figure 15 Dual loop detectors (TU Delft , 2006; Rijkswaterstaat, 2000)

Besides the regular data collection with loop detectors, RWS uses alternative traffic monitoring methods An example is the radar detectors installed on the A28. These systems are located above the road, each system measures the intensity and speed of the vehicles on one lane. Because radar detectors are not integrated in the road surface, they are less sensitive for roadworks and do not require road closure for installation or maintenance (Hillen, 2006).

Next to the data of own measurement systems, RWS has also access to data sources of regional roads or alternative monitoring systems of freeways collected by the National Data Warehouse (NDW) for traffic data of the Netherlands. An example of these alternative sources is the data collection by Bluetooth detectors of the VerkeersInformatie Dienst (VID). This company monitors traffic on specific roads, for example for contractors during roadworks.

4.1.2 TRAVEL TIME CALCULATION: MONIBAS

Since the loops do not measure travel times, the MoniCa data is converted to travel times. These calculations are done within MONItoring BASic applications (MoniBas). This system starts with the PrePoc application which loads MoniCa data and assess the quality of the data by reading the error codes and checking whether the values are realistic. If data is missing or unreliable, intensity data of the past two minutes and speed data of the past three minutes is used to complement the dataset. After that the measurement data of each loop are converted to MoniBas raai data by summing the intensities of the present loops and calculating the harmonic mean speed of the passing vehicles.

$$q_{raai} = \sum_{l=1}^{l_{max}} q_l \tag{3}$$

$$\frac{1}{V_{raai}} = \frac{1}{q_{raai}} \sum_{i=1}^{q_{raai}} \frac{1}{v_i} \tag{4}$$

l_{max}	number of loops at raai
V_{raai}	harmonic mean speed at raai
v_i	speed of vehicle i
q_l	intensity of loop l
q_{raai}	total intensity at raai

MoniBas continues the calculations within four calculation modules where raai data is used to create data of MoniBas measurement areas. Firstly, the RFS module (Reistijd en Filelengte Schatting) calculates travel times and queue lengths per measurement area. Secondly, the AVU module (Aantal VoertuigverliesUren) calculates the total amount of lost car hours. Thirdly, the RDC module (Reistijd Dag Curve) shows the development of travel time during the day in a graph. Fourthly, the ACS module (Actuele Capaciteiten Schatting) estimates the actual road capacity.

The RFS module is the most important one for generating travel time information. The travel time is estimated according the ASTRIVAL algorithm (Van Toorenburg, 1998). This algorithm uses two methods for travel time calculation; one speed based and one intensity based method. The speed based travel time method calculates an average travel time of a measurement area based on two measurement points. This method assumes a linear speed distribution between the two raaien.

$$T_V = \frac{1}{2}\frac{L}{V_{in}} + \frac{1}{2}\frac{L}{V_{out}} \tag{5}$$

L	length of the measurement area
T_V	travel time of a measurement area (speed method)
V_{in}	speed of the vehicles entering the measurement
V_{out}	speed of the vehicles leaving the measurement

The intensity based calculation is used when congestion occurs in the measurement area. Due to stop and go movements the speed based calculation becomes less accurate and the number of vehicles within a measurement area increases, which could create a queue. The number of vehicles in this area is estimated (4) and subsequently, the related travel time is calculated (5). This travel time represents the time needed for all vehicles to leave the measurement area.

$$N(t+1) = N(t) + q_{in} - q_{out} \tag{6}$$

$$T_N = \frac{N(t)}{q_{out}} \tag{7}$$

N(t)	number of vehicles in the measurement area at time *t*
T_N	travel time of measurement area (intensity method)

Depending on the traffic conditions, the final value of the MoniBas travel time (T_{MB}) is generated by one of the two methods or by combining the two values of T_V and T_N. At free flow conditions, T_V is leading. If congestion occurs, T_N is leading (De Ruiter, Schouten, & Frijdal, 2002). The intensity method is however not leading if the measurement area is shorter than 1 kilometre or the speed drops below 30 km/h (Kock, 2004). The precise operation of this last step is however missing in the documentation.

4.1.3 TRAVEL TIME CALCULATION: TREFI

The calculated MoniBas travel times, generated every minute, are used in the next step which creates TREFI (in Dutch 'Traffic Information Centre (Tic) Reistijden en File informatie') travel times, every three minutes. This is the travel time of a road section (between two VILD points) and is calculated by simply summing the travel times of underlying measurement areas. Since some measurement areas are only partly included in the road section, the travel time is multiplied by a percentage which represents the coverage of the measurement area within the road section.

$$T_{TREFI} = \sum_{m=1}^{m_{max}} (T_{MB} * p_m) \tag{8}$$

m_{max}	number of measurement areas (MoniBas)
p_m	percentage of coverage measurement area *m* by road section
T_{MB}	travel time of measurement area
T_{TREFI}	travel time of road section

4.1.4 TRAVEL TIME CONFIGURATION: ROUTESERVER

The last calculation step of the RWS chain is done by the Route Server. This system configures a route from the position of the DRIP to the destination of the presented route, mostly an intersection or a city. Since the start and end point of a route are not automatically equal to the locations of TREFI road sections, again a factor p_n is included to configure the coverage. Especially when a route uses several roads, the transition at the intersection requires accurate configuration. The calculation is equal to the TREFI formula, but now performed on a higher aggregation: TREFI travel times are summed for the underlying (parts of) road sections. After this aggregation the total travel time is compared to a pre-defined free flow and maximum value. So measurement below these fixed free flow value are not used to prevent fluctuations of travel time during free flow conditions. The maximum value of 3600 seconds is used during heavy delays. Measurements above this value will be replaced by the text 'travel time above 60 minutes'.

$$T_{route} = \sum_{n=1}^{n_{max}} (T_{TREFI,n} * p_n) \tag{9}$$

n_{max}	number of road sections (TREFI)
p_m	percentage of coverage road section by route
T_{route}	travel time of route

4.1.5 TRAVEL TIME PRESENTATION: CENTRAL DRIP MANAGEMENT SYSTEM

The VMS/DRIPs are controlled by regional traffic management control centres of Rijkswaterstaat. The Central DRIP Management System (CDMS) (Tenuki, 2011) determines the message presented on the DRIP and switches between travel time information and other content (like mottos or announcements of roadworks). Some DRIPs/VMS always present travel time information, others only in case of congestion or during peak hour periods.

4.2 TRAVEL TIME OF TOMTOM

TomTom is the leading navigation service provider in the Netherlands. The company produces handheld and in-car navigation devices, develops navigation software for mobile phones and offers traffic information on the internet. Since 2007 TomTom cooperates with Vodafone, one of the mayor mobile phone providers in the Netherlands, to calculate travel times based on mobile phone data (TomTom, 2006). This new technology is claimed to offer clear advantages regarding the road coverage, update frequency and travel time accuracy, compared to traditional travel time services (TomTom, 2010; TomTom, n.d.).
The newest devices, TomTom HD Traffic, are equipped with a SIM card and GPS receiver. TomTom argues this service offers travel time savings up to 15%, will inform the driver with an accurate time of arrival and contributes to overall reduction of congestion. Due to the internet connection the device receives an update of real-time traffic information every two minutes and sends his GPS-locations back to the database. Since this navigation device is an in-car system, the driver has always access to up-to-date traffic information. The following sections will explain the data sources and the calculation processes of TomTom HD Traffic.

Figure 16 TomTom HD Traffic, available for navigation systems, smartphones, etc.

4.2.1 TRAFFIC DATA SOURCES: VODAFONE AND GPS DATA

The use of Vodafone data creates a high network coverage of both freeways and rural roads. Traditional data gathering systems, like loop detectors, are embedded in or along the road and needs high investments in hardware, installation and maintenance. The mobile phone network already exist and covers the whole country. HD Traffic covers circa 23.000 kilometres of the Dutch network, while the loop detector system measures 2.300 kilometres (JouwTomTom, 2007). TomTom claims to cover 99,9% of all roads in the Netherlands (TomTom, 2010) and is still expanding the coverage.
For telecommunication purposes it is important to know the location of a cell phone to ensure this device is connected with the nearest base station. TomTom benefits from this location data, which is fully anonymous. The main challenge however is filtering the cell phone data; only car users should be included, so all Vodafone users which are not located on a road should be removed (TomTom, n.d.). Map matching could be quite challenging, since the accuracy of the GSM location data is low (from 100 meters in urban areas up to 500 meters in rural areas). The method used by Vodafone and TomTom uses different signals emitted by the base station. Each signal has its own distance and angle, which creates segments

around the base station. A moving GSM will be detected by different signals, like shown in Figure 17. Combined with the layout of the present roads, the driven route, speed and travel time of the vehicle could be derived. However not all moving GSMs are car users; an active cell phone located in a train driving parallel to a freeway barely differ from the data of the Vodafone users on this freeway.

Figure 17 Location measurement of active GSM

To improve the traffic data, each navigation device (produced by TomTom) is equipped with a GPS receiver. Due to this data source more accurate data is available. GPS data is used to monitor speeds and travel times of TomTom users and covers the total trip (including freeways, rural and local roads). Connected devices (with mobile internet connection) send this information real-time to the database, non-connected devices could upload the data afterwards when connected to a computer (Krootjes, 2011).

The used floating car data methods (based on GSM and GPS) are quite good for traffic monitoring, since individual vehicles could be followed. However this method could only benefit from this strength if a significant number of vehicles on the road are equipped with an active Vodafone cell phone or TomTom device. At roads or in time periods with low intensities, this penetration rate will become a problem. This could result in insignificant data with high variation or cause delay in discovering accidents/congestion. To monitor a change of traffic conditions at least one equipped vehicle, and preferably more, should be present on that specific route at that moment. At the other hand, the most important locations for accurate real-time travel time information are congested areas. Just in these cases the density will increase and thereby also the number of equipped vehicles within this area will increase, whereby the penetration rate probably become sufficient.

4.2.2 TRAVEL TIME CALCULATION: DATA FUSION

TomTom uses five data sources in their data fusion engine (see Figure 18). Besides the already mentioned GSM (from Vodafone users) and GPS data (from TomTom users), also incident/TMC (from Verkeerscentrale Nederland, VCNL) and historical data (from TomTom users) is used. Each data source has its own a-priori reliability indicator. The data fusion engine uses these reliability indicators and a number of other parameters, like age of the measurement and number of probe measurements, to determine the contribution of each data source to the calculation of the speed (TomTom, n.d.). The historical data of TomTom users is stored and used as input for navigation products. This service, called IQ Routes, contains speed profiles aggregated for every five minutes of the day for each day of the week.

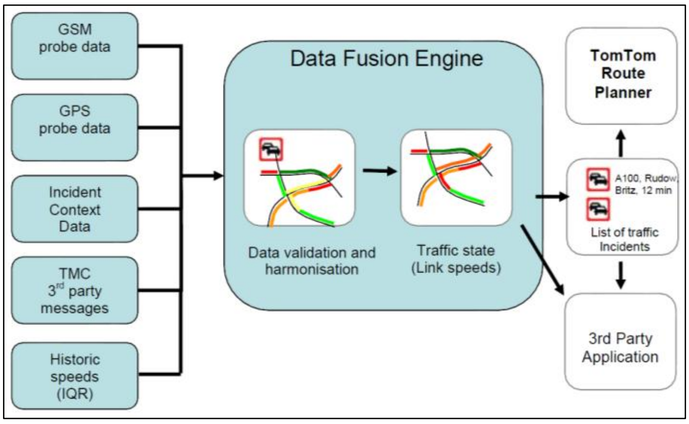


Figure 18 Data fusion engine (TomTom, n.d.)

In the data fusion, the historical data receive the highest priority if the real-time measurement does not exceed the historical values. So only in case of delays, the travel time of TomTom HD Traffic is calculated based on real-time data of GSM and GPS. The travel times which will be studied in the data analysis are TomTom HD route times; a total travel time calculated by aggregating the TomTom HD Traffic times for all underlying sections of the defined route. The congested sections will be fed by real-time data, the other remain historic. Historic data is used since the bandwidth of the current navigation systems is limited.

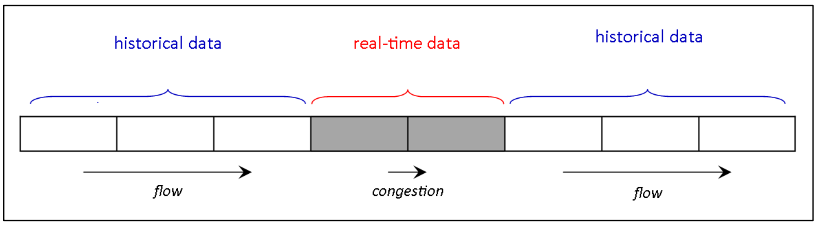


Figure 19 Data usage of TomTom HD Traffic during delays

4.3 BLUETOOTH TRAVEL TIMES

Bluetooth travel times are an innovative source of traffic data. Currently this type of information is not available for the whole Dutch freeway network, but only present at some routes. Since the detectors could be easily installed along the road, this system is applied on roads where the current traffic monitoring systems are badly performing or temporally malfunctioning.

The Verkeersinformatie Dienst (VID) is the operator of Bluetooth detectors in the Netherlands. This company uses the real-time travel time data in their own travel time services (which are not included in this research) and offers the data to other service providers, like RWS (which is included in this research). This section therefore describes theoretical characteristics of the Bluetooth detectors. Notice the operation of the VID travel time system is not further included, since the VID is not participating in this research.

Since 2010 the VerkeersInformatie Dienst (VID) installs VID Bluetooth Measurement instruments (VBM) to monitor traffic flows on the Dutch road network (VID, n.d. b). Furthermore the Dutch National Data Warehouse for Traffic Information (NDW) has tendered an important project to the consortium Data4Traffic, including VID as member. This project includes the installation of 1.000 SWARCO iTravel traffic data acquisition systems, which combines Bluetooth and passive infrared traffic detectors (Swarco, 2011). This investment indicate Bluetooth travel times will become more important in the future.

4.3.1 TRAFFIC DATA SOURCE: BLUETOOTH DATA

Bluetooth detectors monitor the traffic flow by logging passing active Bluetooth devices, like mobile phones, GPS units, computers, in-vehicle navigation systems, etc.. These electronic devices use Bluetooth technology for short-range communication. For example, Bluetooth is used to connect a mobile phone to a car kit system for hands-free dialling during a car trip. Since each Bluetooth device has his own Media Access Control (MAC) address, this technology can be used to measure travel time and speeds (Puckett & Vickich, 2010). When an active Bluetooth device passes a reader, installed along the road, this reader logs the MAC address, location and time. When the same device will be detected by another reader the travel time between those two point can be calculated. If the distance between those two points is known, also the average speed can be derived. The individual travel time of one vehicle is not enough to produce accurate travel time information, therefore the penetration level of active Bluetooth devices is highly important. Data of multiple cars should be combined to calculate an average speed and travel time per road segment. Also more detectors (between the start and end point) could improve the data and provide insight into the speed distribution along the route. The number of equipped vehicle should be significant; a low number of vehicles could result in a low accuracy of the calculated speed and travel time.

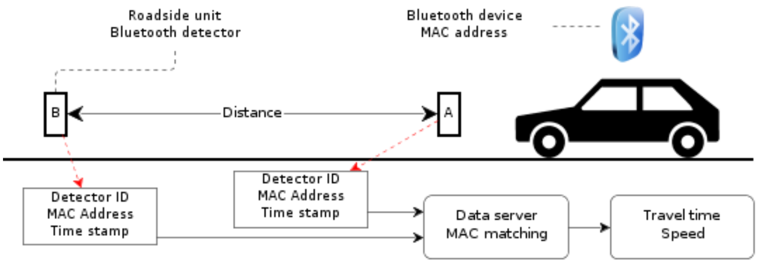


Figure 20 Bluetooth detection system

5 Qualitative analysis

The travel time systems of Rijkswaterstaat and TomTom are described in the previous chapter which contained a general overview of the operation of the services. This chapter analyses the characteristics of each system in a qualitative way in order to provide insight into the theoretical strengths and weaknesses. The table at the end of this chapter presents a complete overview of the results of the qualitative analysis.

5.1 ASSESSMENT OF RIJKSWATERSTAAT SYSTEM

The defined framework (in section 0) will be applied to the operation of the RWS system. The accuracy indicator firstly focuses on the theoretical advantages and disadvantages of the used data sources and secondly on the implementation in practice. Subsequently, the variety of the used data sources, the relevancy of the presented travel times to the road users and the accessibility of the information is analysed to assess the quality of the systems more complete.

5.1.1 ACCURACY

The traffic monitoring system of Rijkswaterstaat consist of dual loop detectors. Since the MoniCa loop detector system is employed every 500-1.000 meters, the strength of this system is the high density of measurement points on the freeways (Soriguera , 2010). This creates an extensive database with intensities and speed on nearly all Dutch freeways. Furthermore loops are able to monitor all vehicles located on the road and are therefore not depending on a penetration rate. Especially during time periods with low intensities this is a clear advantage. However the choice to use the speed and intensity data for travel time calculation already implies a clear level of inaccuracy.
Firstly, despite the relative high density of loop detectors on Dutch freeways, this monitoring system is fixed to a certain point and does not give insight into the flow dynamics between two measurement points. The travel time estimation contains therefore assumptions about the speed distribution between those points, since only an average speed and intensity per spot is known. Mostly travel time is assumed to be a linear function of space and time, however in reality this relationship is often non-linear, dynamic and (or) stochastic (Van Lint, 2004). Also more advanced interpolation methods, like (truncated) quadratic estimation, contain a some level of inaccuracy (Soriguera , 2010) (see Appendix 4 for a detailed description of these inaccuracies). The inability to monitor traffic between two measurement point is mainly causing errors during congested conditions. The loop detector system takes some time to detect congestion; the queue should cover the loop or a significant difference should occur between intensity of the in- and outflow. In both cases the delay caused by this congestion is highly important to calculate the travel time accurately. In congested conditions with stop and go movements or shockwaves, the loop detectors are not able to detect the precise positions of transitions from flowing to stationary traffic. Intelligent algorithms could be applied to reconstructed the spatio-temporal traffic dynamics and potentially be used for short-term traffic forecasting (Treiber & Helbing, 2002). However the travel time calculation of RWS only contains a simple assumption of linear speed between the loops.

Secondly, the loop detector system of RWS is unable to directly measure individual travel times. The loop only counts the number of passing vehicles and (if dual loops are available) measures individual speeds. Vehicles are not uniquely identified; vehicles are detected by change in magnetic field. Therefore it is not possible to recognize the same vehicle again at another detector nor to combine the data of two detector sets to estimate the travel time in between (like in Bluetooth based traffic monitoring). Some methods try to recognize vehicles by monitoring vehicle lengths or patterns in the traffic flow (i.e. platoons). Furthermore, newest developments show that every vehicle creates an unique inductive profile. This development could enable travel time measurements with loop detectors. This technology is promising for traffic monitoring in the future, but not yet implemented in the RWS system (Peek Traffic, n.d.).
Thirdly, if during congested conditions the speed drops to low values, the loop data contains speeds with high amounts of variation. A relative small change of speed has large influence on the travel time. For example a speed could easily double, changing from 5 km/h to 10 km/h. Next to that if the speed drops to zero kilometre per hour, the loop detectors are unable to measure a traffic flow (since there is no flow) and do not provide real-time data. This means the travel time is not updated and an alternative method is needed to ensure a reliable travel time is derived. In congested conditions RWS therefore sometimes switches to an intensity based method, calculated the time needed for a the vehicles to leave the measurement area.
Fourthly, since the loop detectors are integrated in the surface of a road, this monitoring system is sensitive to deterioration and requires maintenance. RWS generates error-files to monitor the performance of individual loops. These files show that specific loops and/or sections suffer frequent malfunctions.
Fifthly, accurate travel time calculation during roadworks is quite difficult. The layout of the lanes is often changed. For example the lanes are shifted to the side through what vehicles cross the loop detector partly or with a changed direction. Also lane closures (i.e. two lane road narrowed to one lane) could cause inconsistent or corrupt data.
Sixthly, in free flow conditions slow and fast vehicles are passing the loop detector and the individual speeds are combined to one average value. This reduces the variance in speed and therefore does not represent the travel time variance in a correct way. Furthermore the average speed calculated on loop detector data is a time mean speed, aggregating the speeds measured on a fixed location, instead of calculating the space mean speed. Fast vehicles are therefore overrepresented in this average speed which could result in a slightly underestimated travel time (Soriguera , 2010). By using a harmonic mean RWS has solved this problem.
Finally, the provided information contains an instantaneous travel time. Many drivers interpret the presented information as prediction; the travel time is applied to the route they are starting to drive. However only if traffic conditions remain unchanged, this travel time could accurately match the real travel time.

Besides the theoretical weaknesses of loop detector data, also the processes of RWS to convert traffic data into travel time information is important in the assessment of the accuracy. Like described in section 5.1 and shown in Figure 13 the RWS system exists of a chain of procedures. The raw data, containing the speed for every passing vehicle, is not directly used to derive travel times. The level of detail in the data is reduced in every step of the chain. The speeds are converted to an average speed (per measurement area, per minute) and an intensity, subsequently to a travel time (per measurement area, per minute). The travel times of several measurement areas are combined to a travel time per road section (per three minutes) and finally converted to the travel time on a route (including the position of the DRIP, the origin and destination of the presented route). Since the location of the DRIP and the origin and destination point of the route are not automatically matching with the end of a road section, the final travel time is adjusted to match this profile. Logically, this will reduce the accuracy.

- High density of measurement points; a high amount of speed and intensity data
- Loop detectors monitor all vehicles on the road
- Harmonic mean speeds solves the potential problem of overrepresented fast vehicles
- Loop detectors do not measure individual travel times
- Accuracy of the travel time calculation depends on the assumed speed distribution between the measurement points
- Loop detectors require maintenance
- Loop detectors preform badly at low speeds, standstill or changed lane layout.
- Travel times on VMS are not directly calculated based on raw data, but are a result of averaging and aggregation processes
- An instantaneous travel time only matches the experienced travel time if conditions do not change

5.1.2 VARIETY OF DATA SOURCES

RWS mainly uses one data source; MoniCa loop detector data. This data is not enriched with data from other sources. Only in case of scheduled failure of these loops (during roadworks) or when a high density loops are missing, RWS considers to use alternative sources. Despite the clear weaknesses regarding accurate travel time monitoring, RWS retains to the traditional system and barely invests in alternative or innovative traffic monitoring systems. Notice the alternative travel time data source of Bluetooth detectors is assessed in section 5.3, since this data is only used by RWS and not a part of their travel time system.

- MoniCa covers nearly all Dutch highways, so less variety required
- No investments in new or alternative traffic data sources

5.1.3 RELEVANCY

The road-users need information which is applicable to their situation. DRIPs are located along the route, so mostly the information will be specified for the current road (or connecting routes). In this way the information will be relevant for the road users. Since DRIPs are often installed at decision points (for example before an interchange), the information about an alternative or connecting road to a certain destination could be irrelevant to road users with another destination. They will ignore the information and continue travelling on the current road.

The relevancy of the information is also related to the clarity of the message regarding the destination point of the presented route. To assess the relevancy of the information, the car driver should know where the route ends to determine to what extent this information will affect his route. Especially when the driver uses the presented route partly, it is difficult to interpret the traffic information and estimate the travel time. Furthermore the presented travel time contains only the freeway-part of the route and will not provide a total travel time from door to door or an arrival time.

Since the information contains an estimation of a future travel time, the relevancy of the information is also related to the timeliness. The presented information should represent the traffic situation which the drivers will experience in the future, in order to be really relevant.

- Road specified information directly presented to drivers on that route
- Information about alternative or connecting routes is not relevant to all road users
- Driver should know the exact location of destination point of the presented route to derive travel time information relevant to his route

5.1.4 TIMELINESS

Time is a key element of providing real-time travel time information. The message not only contains information about travel time, it is also highly important to present this information as soon as possible. The information should be based on real-time data to support accurate travel time information and prevent mismatch with the real experienced travel time. This timeliness indicator therefore assess whether the system is able to directly present a change of travel time. The update rate of the presented information, and underlying data processes, is therefore an important indicator. The loop detectors continuously monitor the traffic flow and provides real time data. This data is aggregated within the following procedures. MoniCa updates every minute, MoniBas calculates a travel time every minute and the TREFI travel times on a road section are updated every three minutes (Ruiter, Schouten, & Frijdal, 2002). The update frequency of the Route Server is currently unknown. Surprisingly, CMDS updates the travel time information every minute, despite the three minute update of TREFI. Besides the frequency of the updates, the timeliness strongly depends on the synchronization of the processes. It is unclear if the process are synchronized, so it could be possible that the processes are updating one after another. In that case the total delay of this chain of calculations could increase to seven minutes or more. Such an delayed presentation will reduce the relevancy of the information and is a major drawback for real-time information.
Finally, since the VMS is located along the route, the driver has no access to the information after passing the VMS. Since the travel time on most routes are longer than the total computation time of the RWS process, the driver on the route will not receive the most up-to-date information.

- Presented information on a DRIP could be more than 7 minutes old, if the processes are not synchronized
- After passing the VMS the driver does not receive any updates

5.1.5 ACCESSIBILITY

The information is accessible for all road users which pass the VMS. The information is collectively distributed without any interaction with the users. This one-way communication sometimes means the information is irrelevant, since the driver has an different destination (see section 5.1.3 Relevancy). If the VMS is well installed and the design is correctly chosen (these categories certainly are important, but are not further elaborated due to the limitation of this research), the driver could easily read the information and does not need any special instruments. However this type of information distribution has also weaknesses regarding the accessibility. First of all, the information is only available en-route. This means the driver could only receive the information by driving along the VMS. Secondly, since this information sign is located along a freeway, the driver will mostly pass this location at high speeds. The short time period of receiving the information is therefore another important weakness regarding the accessibility. In general a driver has only a few seconds to read the information (4 seconds according Lerner, Singer, Robinson, Huey, & Janness (2009)). Furthermore the driver should quickly process the information to understand the meaning and react accordingly.

- Information is accessible for all road users without any special instruments
- The information is only accessible en-route, by traveling along the VMS
- At high speeds the time of receiving and interpreting the information is very short

5.2 ASSESSMENT OF TOMTOM SYSTEM

In this section the qualitative analysis is performed on the system of TomTom. Just like in the prevision section, the strengths and weaknesses regarding accuracy, data sources, relevancy and accessibility are performed.

5.2.1 ACCURACY

GSM and GPS data used by TomTom is floating car data; the position of an individual vehicle is frequently monitored to derive a speed profile and measure the travel time. Potentially, TomTom produces travel time information based on direct measurements of travel time. However for an accurate travel time calculation, this method needs a precise localization to ensure the travelled distance is precisely known and the traffic parameters are not biased. Unfortunately, both GSM and GPS contain certain inaccuracies regarding the localization method. Firstly, for telecommunication purposes, a location method with an accuracy of 100 meters in urban areas up to 500 meters in rural areas is sufficient (Wunnava, Yen, Babij, Zavaleta, Romero, & Archilla, 2007). However for traffic monitoring, this accuracy is insufficient. Secondly, standard GPS receivers have an accuracy around 15 meters; enough for measuring the travelled distance, too low for an exact lane position. Furthermore the signal could be impaired by large buildings (urban environment), trees, tunnels and extreme weather conditions. The locations of a vehicle based on those two databases could be determined and the route can be tracked by matching the data to a map of the existing roads.

Next to the inaccuracies of the localization, both data sources require a penetration rate to ensure a reliable dataset. If the datasets are small and/or contain high variation, i.e. during the night or on less used routes, reliable travel time calculations become difficult. GSM data meets this requirement positively, since the number of cell phone users is high (TomTom, n.d.). However a possible drawback of this source is the filtering process; only the road users should be selected out of the database (TomTom, n.d.). This emphasizes the importance of the filtering process. A strong filter will unfairly remove valuable data and makes it difficult to remain enough data in all circumstances. A weak filter will result in a biased database which may contain non-car users or vehicles on other roads. It is unclear how well the filtering procedures of TomTom preform, however it clearly indicates a possible inaccuracy.

GPS data is also dependent on the penetration rate (TomTom, n.d.). This data is collected by GPS receivers in navigation systems, so the database is created by the driven routes of TomTom users. Whether the penetration rate will be achieved depends on the number of connected devices and the travel behaviour of TomTom users. As advantage, certainly compared to GSM data, no extensive filtering is needed; all collected data is sent by road users. When an accurate location and a significant penetration rate is ensured, the TomTom system could produce accurate travel times.

Just like the RWS travel time, the information of TomTom contains an instantaneous travel time. However the characteristics of the TomTom navigation system enables continuously updating and re-calculating the time of arrival. Because the system is located in the vehicle, the driver will always have access to the travel time information. Therefore a TomTom user will not directly encounter a difference between the provided travel time and the real arrival time, but could notice a changing estimated time of arrival during the trip. When a driver reaches his destination the navigation system will present an accurate travel time (since the destination is nearly reached, the accuracy will be high), however if the driver could remember the estimated time of arrival history (at the start or during the trip) the difference could be bigger.

- Floating car data contain measurements of individual speed and travel time
- Changing time of arrival during the trip
- Inaccuracy of location method of GSM data
- Significant penetration rate of active cell phone users and TomTom users in traffic flow required

5.2.2 VARIETY OF DATA SOURCES

TomTom uses data fusion to combine different data sources. In this way deviations or changes of traffic conditions in one data source could be checked and will only be included when confirmed by other sources (TomTom, n.d.). In general historic data has the highest priority indicator and is mainly used. Only in case on delays measured by (one of the) floating car data sources, the data fusion switches to this real-time data. By using data fusion the weaknesses of one data source could be strengthen by the other sources. So when correctly executed this method is a strength of the TomTom system. Unfortunately, both GPS and GSM data sources depend on a penetration level and measure only a selection of the vehicles on the road. During free flow conditions (with low intensities) the collected data could contain high travel time variations whereby it becomes difficult to present an accurate travel time. Furthermore if during periods with low penetration rates of a low number of equipped vehicles the traffic flow get disturbed (i.e. due to an incident), it could be difficult to directly monitor the current travel time (see also timelines, section 5.2.4). However notice that if the density increase, the data collection will be more reliable.

The limited public documentation only tells which information/data is used as input. Besides the real-time floating car data sources, historic speeds of IQ routes are included. This historic TomTom database contain average speeds for specified for routes and time periods. The historic values are used to display an expected travel time based on the day, time of the day and route. Although the promotion of TomTom HD Traffic suggests the most up-to-date travel time information is presented, this historical data appear to have a major impact on the final travel time. Only if the real-time data exceed the historical values, so during significant delays, the real-time data is used to present a travel time.

Next to that data of the national traffic management centre (VCNL) is used in the validation of the measurements and as contextual information during delays. The cause of a queue, like an accident or road work, could be communicated to the driver.

Sadly, the actual strengths/weakness of the data fusion of TomTom could not be elaborated since the data fusion engine is considered as commercial secret and TomTom does provide very limited information about the operation. The influence of the different sources and the reliability indicator on the presented real-time travel time information is therefore unknown.

- Data fusion of floating car data (GSM and GPS data) and historical data
- Contextual information could explain the cause of delay
- Historical data is mostly used to present a travel time, and real-time data is only included during actual delays

5.2.3 RELEVANCY

Due to the interaction between the car driver and the navigation system, the relevancy of the information is a strength of TomTom. Since the location of the individual driver (GPS receiver), his desired destination and preferences (drivers' input) are known, the system is able to deliver user specified information which is highly relevant. Only delay information on the used route is shown, alternative routes are automatically introduced and the time of arrival is continuously updated. The driver does not need to assess the relevancy of presented information while driving, like in case of passing a VMS, but will listen to the information provided or look at the display of the navigation system.

Next to that provided traffic information covers the whole route from origin to defined destination. So the shown travel time in case of a TomTom navigation system is the time needed to travel from door to door. This is a great advantage compared to the system of Rijkswaterstaat who only provide travel times for the freeway-part of a route.

Furthermore the TomTom navigation system search for a personal optimum, mostly minimizing travel time, instead of trying to reach a system optimum. This could be negative for the total network performances, but could be beneficial for the car driver.
Besides a travel time specified for the selected route, an overview of the traffic conditions on the total network is provided. This could be useful to determine if major problems are present on other routes. Furthermore if problems will influence the used route the system will automatically present this information.

- Information specified to personal preferences and desired destination
- The travel time covers the whole trip from door to door
- Overview of traffic conditions on total network is available

5.2.4 TIMELINESS

The navigation systems are equipped with a mobile internet connection and receive an update every two minutes. This means the route and travel time information will be frequently updated. Since TomTom is an in-car system, the timeliness is not affected by the location of the driver. Regarding the 'age' of the data, since an update is receive every two minutes, this information is averagely one minute old. However the previously processes of collecting and processing also require time. The processing part of converting the traffic data to a travel time claims around 30 seconds. The collection process however could require much more time. In optimal conditions, the penetration level of TomTom devices is high and a change of traffic conditions is immediately monitored. In this case the collection part depends only on the speed of sending the data to the server. However when an accident happens during a time period with a low number of equipped cars, the collection time could highly increase. Imagine a traffic situation during the night when only a few TomTom vehicles are on the road, the presence of a incident could easily be missed. At the other hand, if due to an incident a queue is creating, the density becomes high and also the number of TomTom users at that location will increase. Furthermore during time periods with low intensities (i.e. at night) the need for information will also be lower since less traffic is on the road.

- Update of information every two minutes
- In optimal conditions the total chain from monitoring to presentation requires around 2 minutes
- Time of detecting an accident during periods with a low number of equipped vehicles on the road could highly increase

5.2.5 ACCESSIBILITY

Since TomTom HD Traffic is a commercial product, the travel time information is accessible for clients who purchased the HD Traffic service. This service can be integrated on a TomTom navigation device, an in-car navigation system or a smartphone. Next to that the information is freely available at internet or other service providers (which are using TomTom data).
In case of a handheld device the traffic information is accessible both pre- and on-trip. Furthermore, due to the internet connection the LIVE systems receive an update of traffic information every three minutes. So the driver frequently receives the real-time traffic information which is easily accessible by the visual and auditory presentation of the navigation system. This makes this information services time and location independent.

- Information continuously accessible, both pre-trip and on-trip
- Information automatically updated and visual and auditory presented
- Subscription to HD Traffic required to access the traffic information on-route

5.3 ASSESSMENT OF BLUETOOTH TRAVEL TIMES

In addition to the travel time system of RWS, this section assess the quality of real-time Bluetooth travel times. It is described separate from the RWS system, since Bluetooth travel times are only used by this information provider and not a part of its system. Furthermore only the quality indicators 'accuracy' and 'timeliness' are applied, because the Bluetooth travel times are studied as alternative data source for real-time information providers. The other quality indicators are related to the service of the provider which uses this data source (like RWS in this case).

5.3.1 ACCURACY

Bluetooth detectors are able to identify individual vehicles based on unique MAC-addresses emitted by active Bluetooth devices. Matching MAC-addresses on two different locations leads directly to a travel time by calculating the time difference. So this system is able to directly measure travel times.
Besides this clear strength of the system, there are two important disadvantages regarding the accuracy of the monitored travel times. Firstly, since the Bluetooth detectors have a circular- or oval-shaped scope (i.e. a reach of 100 meter (Puckett & Vickich, 2010)), the location of a detected vehicle is not precisely known. Furthermore the travelled distance is a predefined distance; the distance between the two detectors. This could lead to a deviation between the length of the measurement area and the real travelled distance. This deviation reduces the accuracy of the monitored travel time and is mainly a problem if the measurement area is relatively small. If the travelled route is long, the deviation of the travelled distance is negligible.
Secondly, just like floating car data, the Bluetooth monitoring system requires a significant penetration rate to produce accurate travel times. If only a few vehicles are equipped with an active Bluetooth device, an insignificant amount of traffic data is generated. Furthermore the monitored vehicles should be a good representation of the total traffic flow, so no overrepresentation of fast or slow vehicles.

- Bluetooth detectors directly measure travel times of individual vehicles
- Deviation caused by the scope of the detector has a strong influence at systems with relatively small distance between the detectors
- Significant penetration rate of active Bluetooth devices required

5.3.2 TIMELINESS

Since the Bluetooth detection system only provides a travel time when a vehicle leaves the measurement area, the travel time information is always somewhat delayed. A vehicle need to finish the whole route before the route travel time is updated. Mostly several detectors are installed along the route, to receive updates earlier, but still the measured travel time is perceived in past traffic conditions. This is a strong weakness of Bluetooth travel time, especially for real-time applications which aim to present up-to-date information.
Furthermore if the travel time increases, i.e. due to congestion in the measurement area, it takes longer to leave the measurement area. Therefore up-dating the Bluetooth travel times gets also delayed since it takes longer to measure higher travel times. This is an important drawback for real-time travel time information during congestion and is inherent to the operation of the Bluetooth detection method.

- Bluetooth detectors only measures a travel time if a vehicle leaves the measurement area
- The delay of detection increases if the travel time of a measurement area increases

Table 5 Overview of strengths and weaknesses of RWS and TomTom on qualitative indicators

	RWS system	TomTom HD Traffic
Accuracy	• High density of measurement points; a high amount of speed and intensity data • Loop detectors monitor all vehicles on the road • Harmonic mean speeds solves the potential problem of overrepresented fast vehicles • Loop detectors do not measure individual travel times • Accuracy of the travel time calculation depends on the assumed speed distribution between the measurement points • Loop detectors require maintenance • Loop detectors preform badly at low speeds, standstill or changed lane layout. • Travel times on VMS are not directly calculated based on raw data, but are a result of averaging and aggregation processes • An instantaneous travel time only matches the experienced travel time if conditions do not change	• Floating car data contain measurements of individual speed and travel time • Changing time of arrival during the trip • Inaccuracy of location method of GSM data • Significant penetration rate of active cell phone users and TomTom users in traffic flow required
Variety of data sources	• MoniCa covers nearly all Dutch highways, so less variety required • No investments in new or alternative traffic data sources	• Data fusion of floating car and historical data • Contextual information could explain the cause of delay • Historical data is mostly used to present a travel time, and real-time data is only included during actual delays • Data fusion engine is black box
Relevancy	• Road specified information directly presented to drivers on that route • Information about alternative or connecting routes is not relevant to all road users • Driver should know the exact location of destination point of the presented route to derive information relevant to his route	• Information specified to personal preferences and desired destination • The travel time covers the whole trip from door to door • Overview of traffic conditions on total network is available
Timeliness	• Presented information on a DRIP could be more than 7 minutes old, if the processes are not synchronized • After passing the VMS the driver does not receive any updates	• Update of information every two minutes • In optimal conditions the total chain from monitoring to presentation requires around 2 minutes • Time of detecting a queue or accident during periods with a low number of equipped vehicles on the road could highly increase
Accessibility	• Information accessible for all road users without any special instruments • The information is only accessible en-route, by traveling along the VMS • At high speeds the time of receiving and processing the information is very short	• Information continuously accessible, both pre-trip and on-trip • Information automatically updated and visual and auditory presented • Subscription to HD Traffic required to access the traffic information on-route

6 Quantitative analysis

This chapter presents all results of the data analysis. Since the scenarios contain many different characteristics (see section 3.4.1), the result will be described for each scenario. In this way, the relationships between accuracy of travel time and the monitoring systems, traffic conditions, presence of roadworks and road type are studied.
The sections contain a small introduction of the scenario, including the expectations regarding the performances of the travel time systems. Subsequently, the results are presented. Firstly, describing the trends and specific differences based on some illustrative plots. Secondly, the results of the statistical test are presented. Each scenario ends with a small conclusion with the most important results. Scenario 0 and 1 contains also the comparison the experienced travel time data to verify whether the provided information matches experiences of drivers (see section 3.4 for comprehensive explanation of the performed analyses).

> This chapter contains many figures to show the differences between the travel time services. For every scenario a few plots are selected to present the general trends and to illustrate the made observations. The electronic appendix (see Appendix 9) contain all the plots of the studied days, sorted by type of day. These can be used to confirm the results or to study the differences in detail.

6.1 SCENARIO 0: NIJKERK - NUNSPEET (VIA A28 BOTH DIRECTIONS)

This preliminary scenario is a special case, since it does not study travel time information presented on a DRIP. However this scenario elaborates the differences between low density loop detectors and innovative Bluetooth detectors. This creates an interesting introduction to traffic data sources. To assess the quality of this new source of Bluetooth data and existing source of loop detectors, both travel times will be compared to experienced travel time data of TomTom.

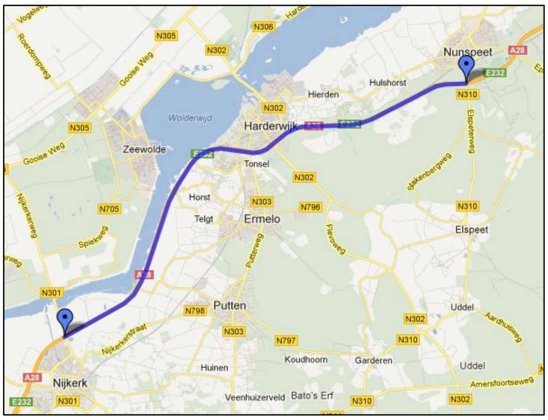


Figure 21 Route from Nijkerk to Nunspeet and vice versa (via A28)

6.1.1 EXPECTATIONS

The A28 is a rare part of Dutch freeway where the distance between the loops is quite large. To improve the traffic monitoring on this 'blind spot' the NDW has contracted the consortium Data4Traffic to install and operate Bluetooth detectors. This data source is available since 27 January 2012 and so this scenario studies the months February and April 2012 to check whether the Bluetooth data differs from the loop data.

Based on the theoretical characteristics of loop detectors, data of the present loops at the A28 is expected to be of low quality. Since the average distance between the loop is around 4 kilometres (normally 500-1.000 metres) the detection of congestion could take longer. Next to that the low amount of measurements will result in less accurate travel time calculations, because the speed is only known for some points on the route and the assumptions of speed distribution will have a stronger effect on the final travel time. Furthermore low quality of data is also suggested by the performance indicator of 75%, which means the loops on this road are not able to produce data during 25% of the studied period (see Appendix 6).

The distance between the Bluetooth detectors is comparable to the distance of the loops. Furthermore, based on the theoretical characteristics (see section 3.2), it is known Bluetooth detectors could only measure a travel time after a vehicle has passed the whole section. So this source will always be somewhat delayed in detecting changes of travel time. However, in contrast to loop detectors, this method directly measures travel times, which will probably result in more accurate travel time data.

6.1.2 RESULTS OF NUNSPEET TO NIJKERK (A28 LEFT)

The results of both the RWS and D4T data show (somewhat) instable travel time data. Especially during February when the Bluetooth detectors just started operating, this monitoring system is not yet able to produce a reliable travel time. The figures below present the travel time data during three days of the studied period.

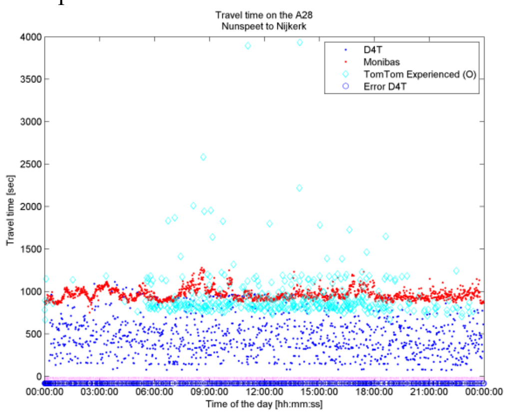


Figure 22 Thursday 2 February 2012

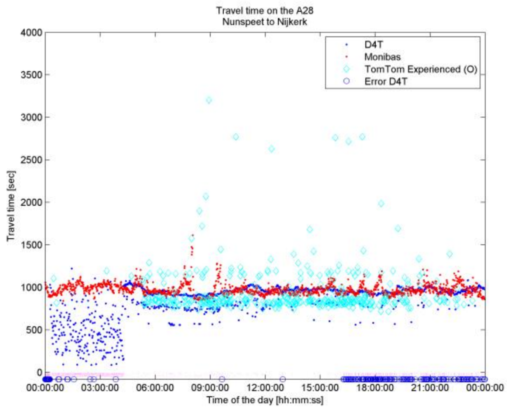


Figure 23 Tuesday 21 February 2012

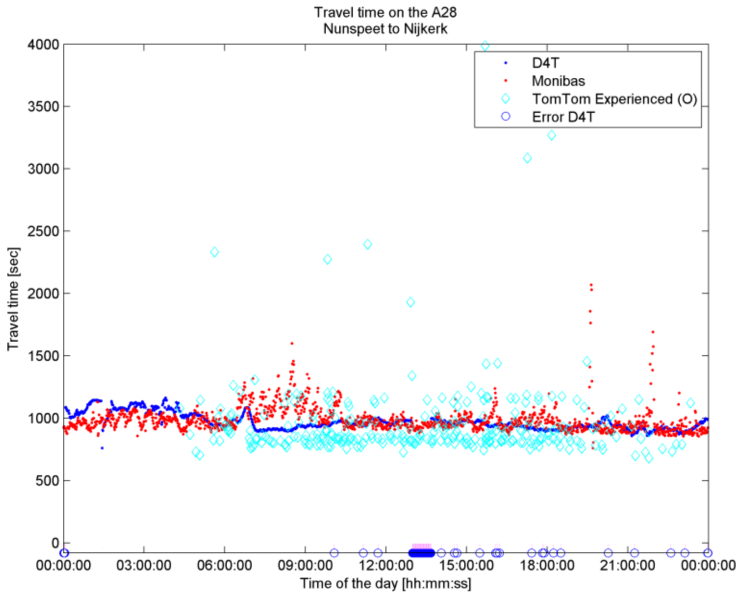


Figure 24 Tuesday 3 April 2012

Based on the plots above the following observations can be made regarding the performances of D4T Bluetooth detectors and RWS loop detectors (also confirmed by the other plots of this scenario, see Appendix 9):

- The results of the Bluetooth detectors of D4T show a very instable travel time for the month February 2012. Like visible in Figure 22, the data contain many errors (like missing data or low values). After several weeks, the travel time data by D4T is improved (see Figure 23). During daytime the travel time data is more stable and less errors are occurring. Notice however, the travel time during the night (of 21 February, Figure 23) is not really improved. Low intensities during nightly hours and the required penetration rate of active Bluetooth devices could be a good explanation for these less accurate travel times.
- The travel time produced by the Bluetooth method at Tuesday 3 April (Figure 24) is slightly higher during the night than during the day. This is not really realistic, but could be a result of less accurate traffic monitoring during periods with low intensities (penetration rate not high enough) and/or an increased amount of slow traffic (like trucks). This weakness is also confirmed by comparing the travel time of D4T to the somewhat lower values of the RWS data during the night.
- The results of the loop data are more stable, but produce deviating values during congested periods. For example Tuesday 3 April (Figure 24), during the morning peak hours, the travel time is rapidly changing (like a sequence of several peaks) and during the evening some strong peaks are visible. These values might represented the real traffic situation, however such a steep curve of increase and decrease seem to be not very likely.
- Comparing both travel time sources with each other shows that the free flow travel times during daytime are almost equal. This indicates that if a free flow speed can be driven, both sources are able to measure a reliable travel time. So the indirect travel time calculation method of RWS with a low numbers of loops is able to produce a value comparable to the direct monitoring of travel time by D4T. However when congestion occurs the weaknesses of the inaccurate calculation method of RWS becomes clear. The assumption of a linear speed distribution between two sets of loop does not hold and produce an overestimation of travel time. So during peak hours the travel time of RWS is higher than the data of D4T, especially visible for the morning peak hour of 3 April (Figure 24). In the next section the travel time sources will be further analysed in case of real delay and compared to experienced travel time data.

6.1.2.1 COMPARING TO EXPERIENCED TRAVEL TIMES

To verify whether the data of RWS and D4T produce reliable travel times, the data will be compared to ground truth travel times of TomTom users. These experienced travel times are measured by GPS receivers in the TomTom devices. The plots show two series of data. Both data series contain the same travel time data, however the timestamp is varied. The first dataset presents the travel time at the moment of a TomTom user enters the route ($t = t_O$, TomTom Experienced Origin), the second presents the same travel time at the moment of arriving at the destination ($t = t_D$, TomTom Experienced Destination) (see timeline and explanation at section 3.4.2). By doing this, the first curve represents the travel time which the real-time information services should had presented to be exactly accurate and the second one represents what the systems should have monitored.

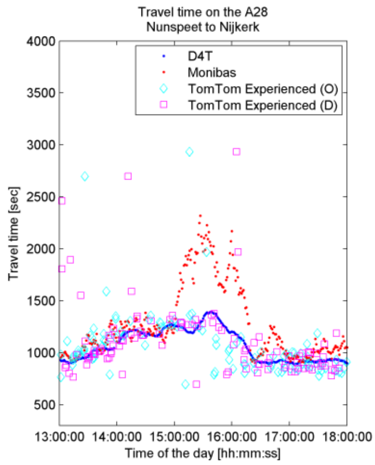


Figure 25 Monday 9 April 2012

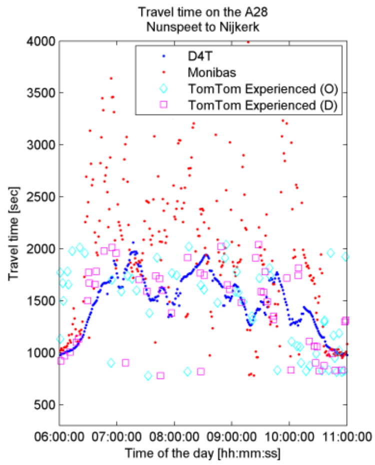


Figure 26 Tuesday 10 April 2012

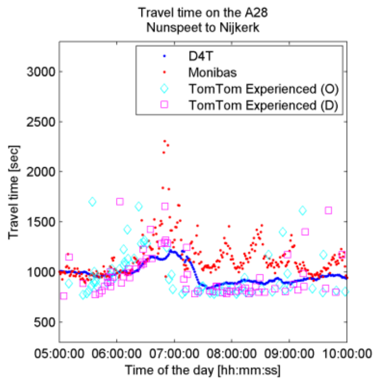


Figure 27 Monday 2 April 2012

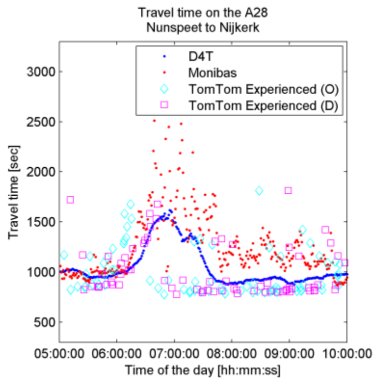


Figure 28 Monday 23 April 2012

In general, the results of the peaks on the A28 show the RWS loops produce longer travel times than D4T. So when congestion occurs the travel time calculated based on the low number of loops are an overestimation (visible in the plots above). Compared the experienced data these high values of travel time appear to be unrealistic (Figure 26, Figure 27 and Figure 28), although in some cases (like Figure 25) TomTom drivers have experienced such long travel time. Most of the TomTom measurement are however clearly below the maximum values of RWS, which could indicate these high values are overestimations of travel time. During congestion, especially with much stop and go movements, the small amount of speed measurements is insufficient for accurate travel time calculation. The measured low speeds are interpolated for the large measurement area which results in a high travel time based on this loop data.

Regarding the Bluetooth data, increase and decrease of travel time is somewhat delayed, confirming the described expectations based on the theoretical characteristics. Both the experienced and loop detector data show delays earlier than D4T. This is well visible at the start of the peaks (Figure 26 and Figure 28).

6.1.3 RESULTS OF NIJKERK TO NUNSPEET (A28 RIGHT)

The results for the A28 from Nijkerk to Nunspeet are comparable to the earlier described outcomes of the opposite direction. Two examples are shown in the figures below.

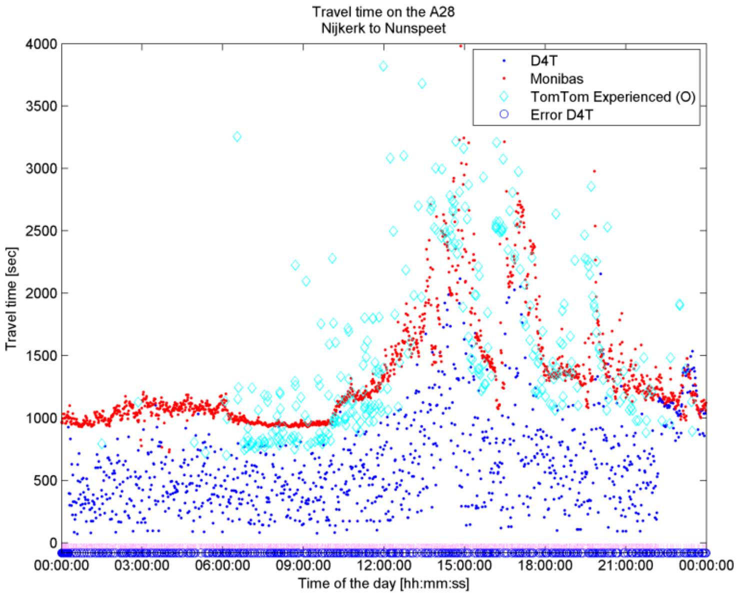


Figure 29 Friday 3 February 2012

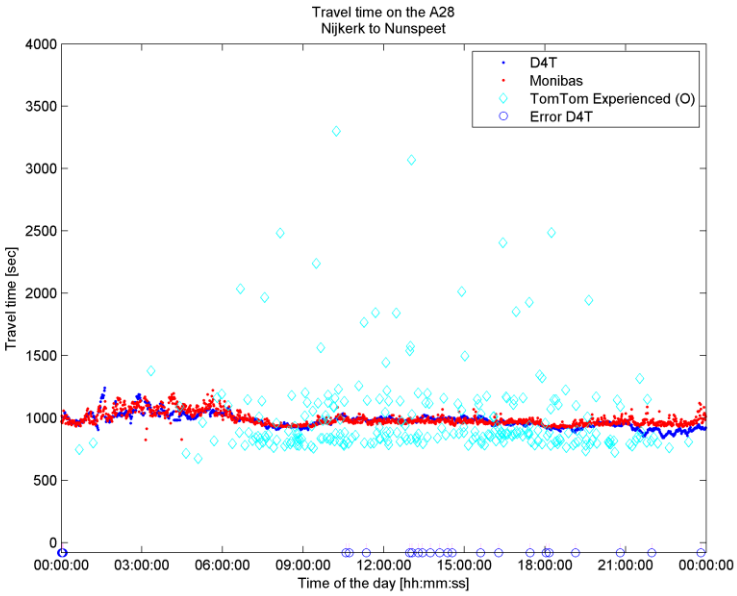


Figure 30 Wednesday 4 April 2012

The following results can be derived from the plots above (see also the other days, Appendix 9):

- The data of D4T is instable in the first month of operation, like visible at Friday 3 February (Figure 29). Even in this case of a heavy congested day, the Bluetooth detectors are not yet able to reliable monitor a travel time. Two months later, in the first week of April, the start-up problems, like missing data or incorrect detection, are solved and a stable travel time curve is presented by both RWS and D4T .
- Remarkable is the similarity of those sources during a free flow day, like Wednesday 4 April (Figure 30). Bluetooth detectors and low density of loop detectors produce the same quality of data for this type of day. This is however not the case during non-free flow days, which are studied in the next section.

6.1.3.1 COMPARING TO EXPERIENCED TRAVEL TIMES

During the studied months, February and April 2012, only a few days with serious delay appear on the A28 from Nijkerk to Nunspeet. Despite the limited amount of congested days, the figures below show a clear trend and the results are in line with the described hypothesis.

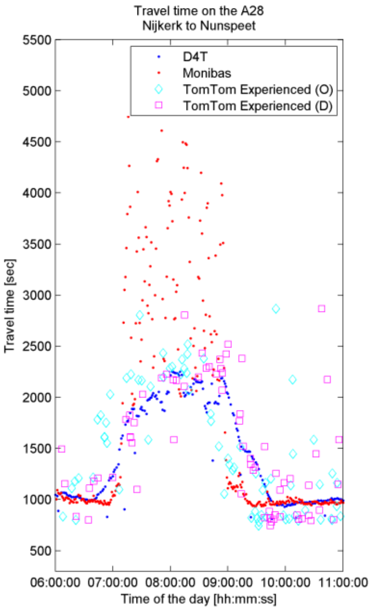


Figure 31 Thursday 23 February 2012

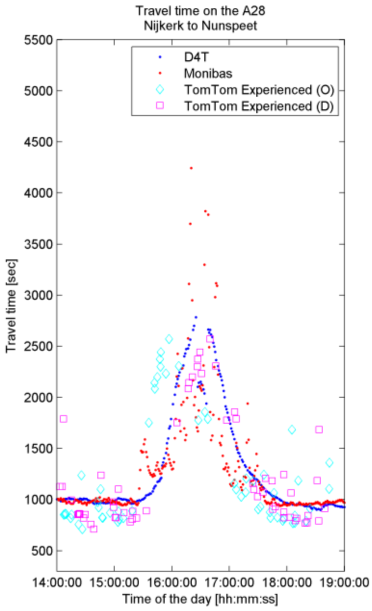


Figure 32 Wednesday 18 April 2012

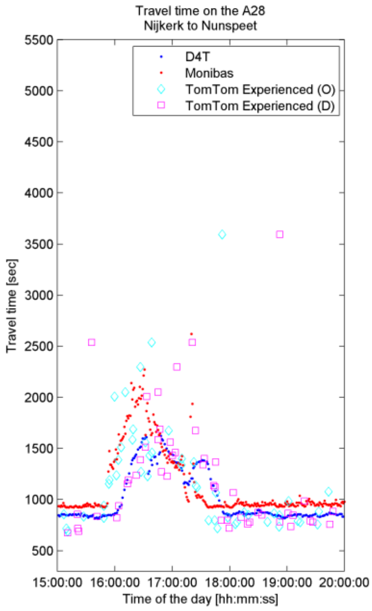


Figure 33 Sunday 8 April 2012

Just like the previously studied route, the MoniBas travel time for the opposite direction Nijkerk to Nunspeet still produces high values of travel time during congestion. Also the free flow travel time of RWS and D4T are equal. Notice, the difference in travel times during 8 April (Figure 33) is caused by failing Bluetooth detectors whereby the data of some measurement areas is missing.
During the congested days, the delayed monitoring of changes in Bluetooth travel times become clear. This confirms the theoretical described weaknesses and the results of the opposite direction. Both a delayed growth and decrease of travel time are visible for the travel time measured by D4T (see figures above). The difference between growing travel time of the loops and the historic GPS values is smaller.

6.1.4 SUBCONCLUSION

This preliminary scenario nicely shows the different characteristics of both loop detector data and Bluetooth data. Firstly due to the large distances between the loops at the A28, the travel times of RWS are

quite inaccurate during congestion. The values are instable and substantially higher than the historic data of TomTom, indicating no TomTom user has encountered such a high travel time.
Secondly, the travel time data produced by Data4Traffic contain a high amount of missing data or unrealistic values for the first two to three weeks of operation. After this start-up period the travel time becomes comparable to the data of the existing RWS system, except the high values during delays. Due to the more realistic travel times during peak hours this new data source is value-adding, however also the theoretical weaknesses of low accuracy during periods with low intensities and the delayed monitoring of changes in traffic conditions are present.
Thirdly, the free flow travel times of both system are comparable. The low number of loops do not measure travel times directly and the used calculation method was expected to produce less accurate travel time information, but the assumption of constant speed holds in free flow conditions.
Finally, the theoretical disadvantage of delayed detection based on Bluetooth is observable in the traffic data. The Bluetooth travel time start increasing later than the loop data. So, timeliness of recognizing changes of traffic conditions is also in practice a weakness.

6.2 SCENARIO 1: HOEVELAKEN TO UTRECHT (VIA A28 AND A1/A27)

This scenario contains two possible routes from the A1 near Hoevelaken to Utrecht. The travel time information on the DRIP therefore suggest taking the shortest route. During free flow conditions the travel time via the A28 is lower than via the A1/A27, however when congestion occurs the route become more equivalent.

Figure 34 Route from Hoevelaken to Utrecht (via A28 and A1/A27)

6.2.1 EXPECTATIONS

Due to roadworks on the A28, the traffic monitoring systems are frequently malfunctioning, which is shown by the performance indicator (see Appendix 6). During the studied period 25% of the data is missing. This is expected to reduce the accuracy of the travel time information for this route. Furthermore the intersections Hoevelaken and Rijnsweerd, at the start and end of the route, are busy traffic nodes which require precise configuration of measurement areas to prevent blind spots. Another reason for studying this scenario is the argumentation for using alternative data sources by RWS. At the A12, studied in scenario 4, RWS do use an alternative traffic data source during roadworks. At the A28 RWS remains traffic monitoring based on the existing data source. Probably the floating car data of TomTom will be more accurate, particularly on the A28, and might be a good alternative source.
The performance of the RWS system on the A27 are better. The performance indicator of 95% shows good availability, whereby the travel time information is expected to be more accurate.

6.2.2 RESULTS OF A28

The results for the A28 are illustrated in the plots of two days: a typical free flow day (Sunday 4 December 2011, Figure 35) and a congested day (Wednesday 14 December 2011, Figure 36). A short remark at Figure 35, the aggregated TREFI measurements of RWS are lower than the presented DRIP travel time caused by missing data of three road sections.

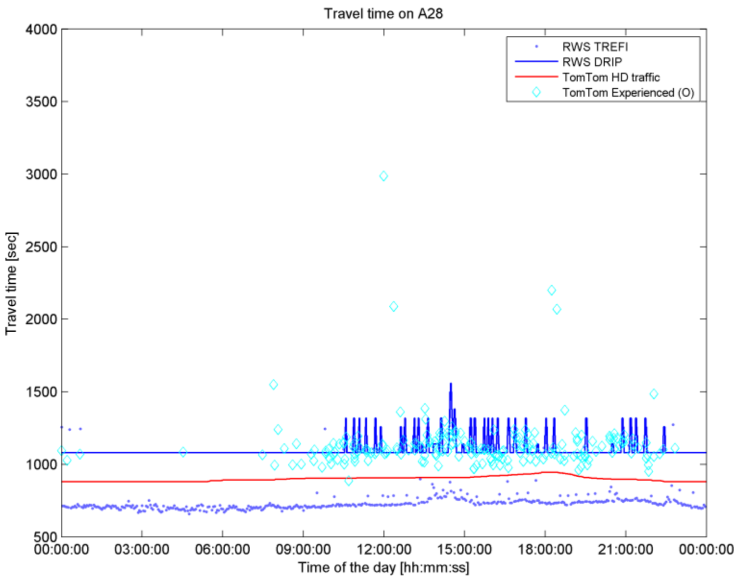


Figure 35 Travel times of TomTom and RWS on Sunday 4 December 2011

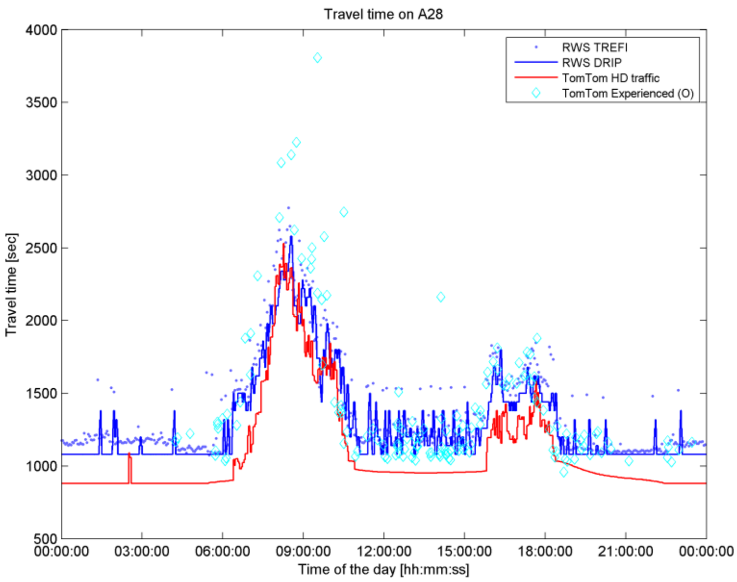


Figure 36 Travel times of TomTom and RWS on Wednesday 14 December 2011

The general results are summed up below and divided in performances during free flow conditions, start of congestion, and development of peak. The described trends could be confirmed by checking the figures above or the plots of the other free flow and congested days (see Appendix 9).

- The free flow travel times of TomTom HD Traffic and Rijkswaterstaat DRIP differ on the A28. During nonpeak hour periods, the travel time of RWS is structurally higher than the travel time presented by TomTom. On the route via the A28 this difference of free flow travel time is around 200 seconds (above 3 minutes). Furthermore during a typical free flow day, like in the weekends, the travel times of TomTom remain unchanged, while the travel times of RWS on the A28 vary (see Figure 35).
- Comparing to the available experienced travel times, the free flow value presented by TomTom seems to be too low. All present TomTom users have experienced a longer travel time than presented at the navigation device. Furthermore the experienced travel time data suggest the higher values of RWS do match the reality, although the instability is not very plausible.
- A morning and evening peak hour are present on the A28 during regular workdays, like Wednesday 14 December (Figure 36). Congestion causes an increasing and decreasing travel time. The time between the change of traffic conditions and the increase of travel time represents how well the system is able to recognize a change of travel time. The data fusion engine of TomTom does not directly change the presented travel time when (one of) the data sources indicate an increasing travel time to prevent instable travel times. This behaviour is visible in the data by a 'jump' in the curve at the start of a peak (like visible at the evening peak of Figure 36). The travel time increases somewhat later than the travel time of RWS which results in an increasing difference at the start of the peak. When the delay increases, the difference becomes smaller caused by the bigger growth of TomTom's travel time.
- Besides the difference at the start of the peak, the bigger growth and higher peak values of TomTom, also the decreasing travel time and end of the peak differ. Despite the growth of TomTom's travel times starts somewhat later, the end of the peak is reached earlier than the RWS's peak. Just like during the growth of the peak, the travel times of TomTom decrease faster than RWS. This results in a smaller peak; the peak hour period is shorter. Furthermore when the delay is small, the peak of TomTom lays under the peak of RWS; TomTom's travel time remains the lowest. When the delay increases the travel times become more comparable or, during major distributions, TomTom's travel time become higher. These latter results are displayed in the next section and analysed based on historic data.

To verify whether the performances of TomTom and RWS represent accurate travel times during congestion, the figures below present the data of three congested days with increasing amount of delay.

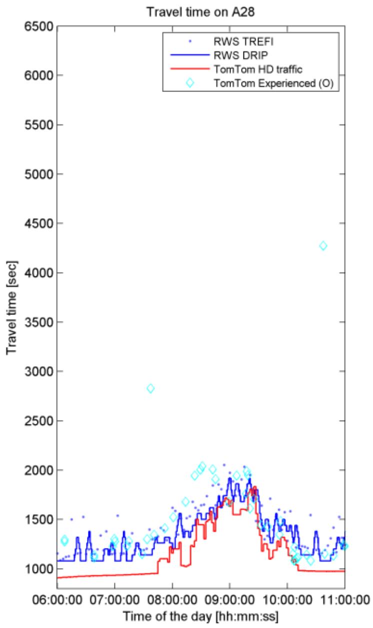


Figure 37 Friday 20 January 2012

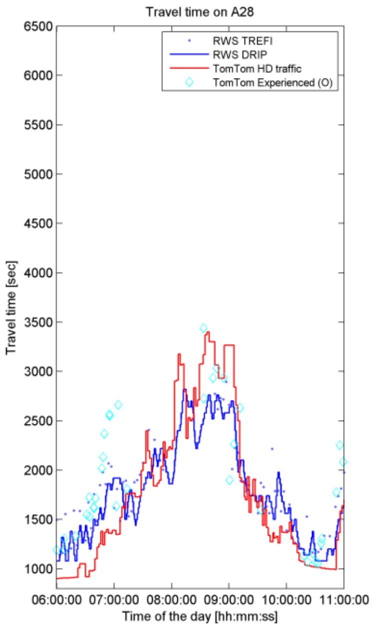


Figure 38 Monday 23 January 2012

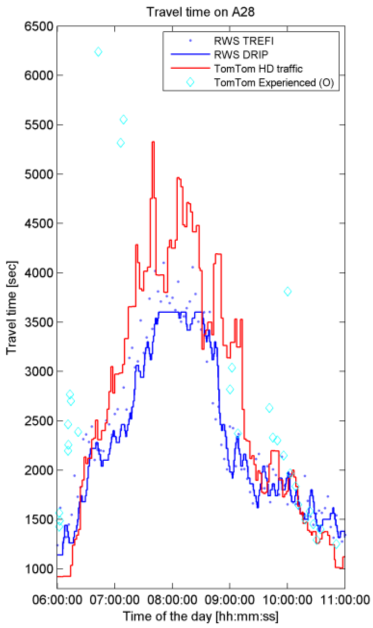


Figure 39 Monday 30 January 2012

The plots of 20, 23 and 30 January 2012 (Figure 37, Figure 38 and Figure 39) contain three morning peaks and show the trend of the difference between RWS and TomTom. If a high amount of delay occur, the travel time of TomTom exceeds the travel time of RWS. This could also be confirmed by the other congested days, despite a precise boundary of exceeding is difficult to determine. However, certainly during heavy congestion the maximum values of TomTom are bigger than those of RWS. This trend is strengthened by the rounding behaviour of RWS, which do not present travel times higher than 3600 seconds (60 minutes). Notice however, the TREFI measurements of RWS which are rounded to a fixed maximum present a smaller difference compared to TomTom's peak values (see 30 January, Figure 39).

6.2.3 RESULTS OF A27

The results of the comparison on the A27 do confirm the findings described in the previous section. The figures below show the general trends of the performances of both information providers.

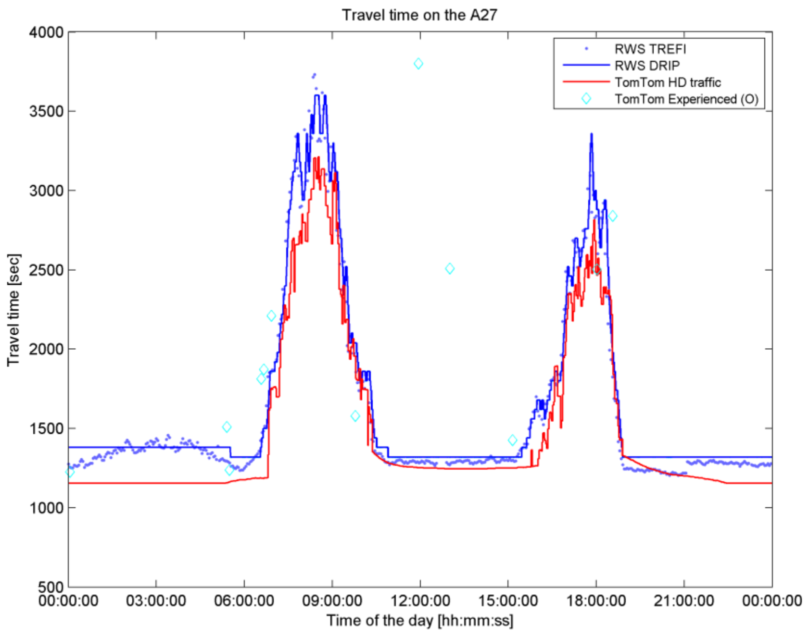


Figure 40 Tuesday 6 December 2011

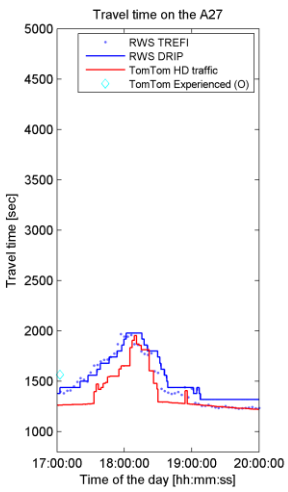


Figure 41 Monday 19 December 2011

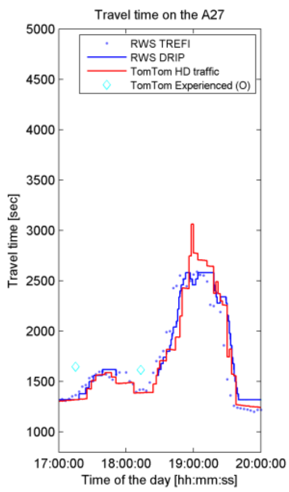


Figure 42 Thursday 12 Jan 2012

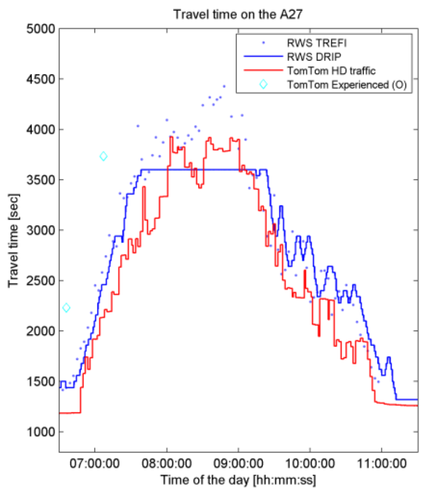


Figure 43 Tuesday 13 December 2011

The following observation can be made based on the plots (see also the other congested days, Appendix 9):

- Just like the route via the A28, a clear difference appear between the free flow travel times, especially during the night (Figure 40). The differences between the free flow times during daytime are smaller, strengthened by the more constant free flow travel time of RWS on the A27.
- Again the increasing and decreasing speed of TomTom is bigger which ends up in a smaller peak. In contrast to the A28, the peak values of TomTom do exceed the travel time of RWS less often. In case of travel times above 3600 seconds, when the RWS DRIP travel time is rounded, the peak of TomTom is higher than the RWS peak (see Tuesday 13 December 2011, Figure 43).

- Furthermore at several days during decreasing congestion, the travel times seem to become more comparable, like during the evening peak at 6 December 2011. So the difference in travel time are smaller during decreasing congestion than during increasing congestion.

Besides these general results, there are some remarkable differences between the travel times of TomTom and RWS. Two cases are displayed in the figures below; the influence of historical data on the TomTom HD travel time (Figure 44 and Figure 45) and missing delay of RWS/TomTom (Figure 46 and Figure 47).

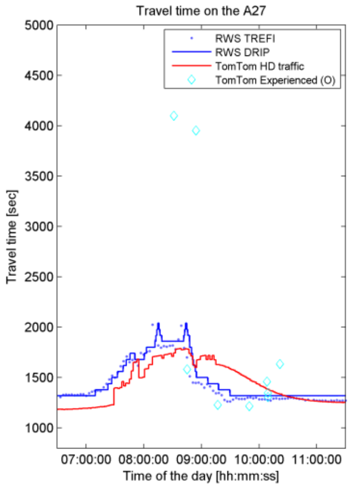


Figure 44 Wednesday 21 December 2011

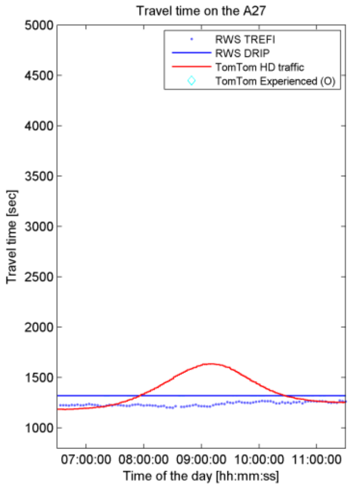
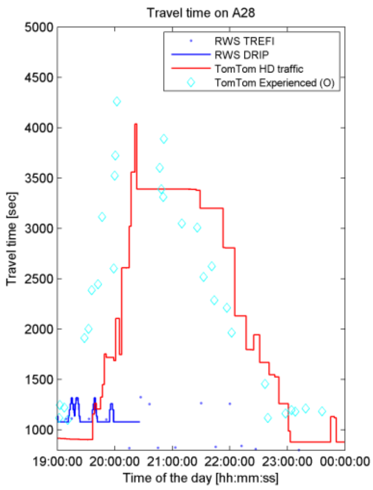


Figure 45 Wednesday 28 December 2011

Firstly, during the Christmas holidays the free flow travel time of TomTom vary during peak hours (see all medium congested days of this period at Appendix 9). This behaviour is caused by the input of historical data in the data fusion. If the real-time data sources of GSM and GPS do not measure delay during a weekday, the historical data is not overruled in the data fusion. This causes a small peak, since on a normal weekday a peak hour could be expected. However due to the holiday there is less traffic and the travel time of RWS indicate free flow conditions. Besides the differences this already creates at a non-congested day, also in case of small congestion is present this will lead to differences. At Wednesday 21 December 2011 the RWS system monitors some delay during the morning peak hours. This delay is also encountered by the measurements of TomTom. However when the delay decreases, RWS returns to the constant value of the free flow travel time, while TomTom's system switches back to the historical data.



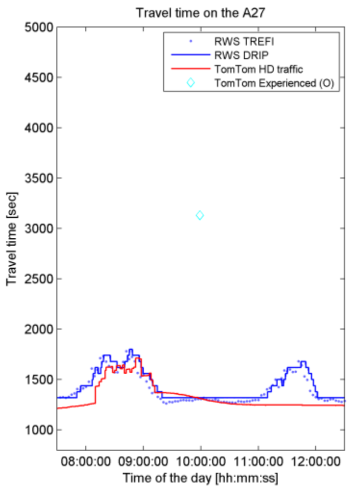


Figure 46 Saturday 10 December 2011

Figure 47 Friday 2 December 2011

Secondly, during an accident at Saturday 10 December (Figure 46) the DRIP at the A1 does not display an increasing travel time, but do show the texts 'A28 big delay' (at 20:25h) and later 'A28 closed' (at 21:06h). Notice however the big difference between the TomTom travel time, which start growing at 19:37h, and the RWS travel time. Till 20:25h the RWS DRIP displayed a free flow travel time and the difference with TomTom grows to more than 2000 seconds (30 minutes). Next to that, during Friday 2 December (Figure 47) TomTom sometimes remains free flow, while RWS encounters delay. The small peak indicates some congestion is missed by TomTom or incorrectly displayed by RWS.

6.2.4 STATISTICAL TESTS

The description of the results in the previous section will be complemented with more general results of all the used data. The differences between the travel time data is tested with a MAPE and t-test, like described in the research method (see section 3.4.3).

The MAPE describes the relative difference between the two data sets and is applied on the whole day (24 hours), distinguishing three categories of days, and on the three specified traffic conditions within the congested days, namely increasing/decreasing congestion and the period without delay between two peaks (free flow).

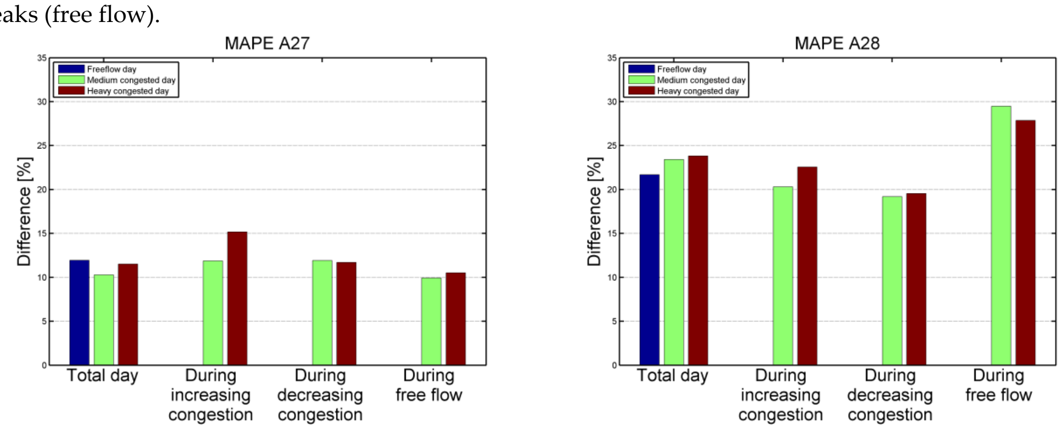


Figure 48 Relative difference between travel time of TomTom and RWS

The results presented in the figures above, show that the performances of the travel time systems are depending on the route. Logically, this is the case for the RWS system which is based on the performances of road related monitoring systems. In general, the values of the MAPE test tell that there is a difference between the two travel times, since the MAPE values are not zero. Next to that the results do not indicate structural differences between the two categories of congested days, over all 24 hours and for the specific traffic conditions. Small changes of results could indicate the free flow period on congested days on the A28 creates deviations, and on both routes the difference between the travel times during heavy congestion is bigger than the medium congested days. This latter is also recognized in the plots, where during heavy congestion TomTom's peak values exceed those of RWS.

The previous sections already made clear that there are differences between the travel times of TomTom and RWS comparing the trends. More precisely a t-test calculates the significant differences between the two datasets. Overall, the null-hypothesis of the two tailed paired test is rejected, which means the travel times of TomTom and RWS are not equal. The hypothesis of the one tailed t-test is also rejected which means the travel times of RWS are bigger than those of TomTom. Only in a few situations the hypothesis are not rejected. This deviations are summed up below.

For the A27

- 21 December 2011: During decreasing congestion TomTom and RWS are equal. Higher peak values of RWS and longer peak period of TomTom, influenced by historical values, neutralize the differences.
- 25 January 2012: TomTom not smaller than RWS during increasing congestion, caused by disturbances in the DRIP texts. The RWS travel time is not updated during half time of the peak.
- 30 January 2012: Due to rounding the RWS times do not exceed the 3600 seconds, while the delay of TomTom grows to more than 5000 seconds. Therefore during decreasing congestion TomTom not smaller than RWS.

For the A28

- 6 December 2011: During free flow conditions, RWS and TomTom are equal. Deviating values of TomTom during the night neutralize the deviations during daytime.
- 19 December 2011: TomTom's travel times start decreasing somewhat later than those of RWS, through what the null-hypothesis of the one tailed t-test is not rejected.
- 9 and 30 January 2012: Again the values of TomTom are bigger during a heavy morning peak, so the travel time of TomTom is not smaller than RWS.

The t-test checks whether the difference between the two travel times is equal to zero and returns with a confidence interval, representing the average value and standard deviation of the differences. The results are plotted in the figures below and also divided the days into the categories.

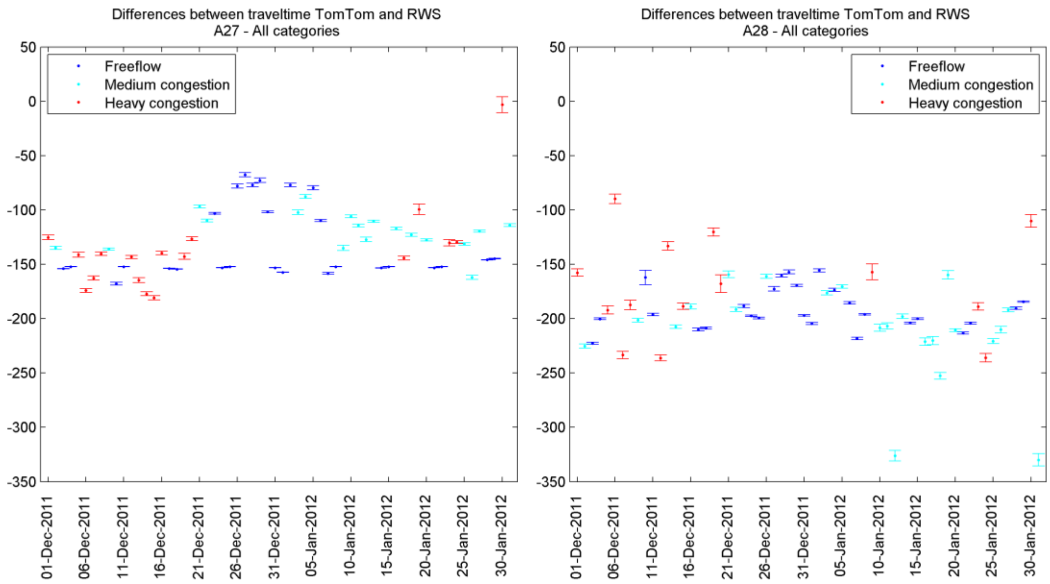


Figure 49 Confidence interval paired t-test, A27 and A28

6.2.5 SUBCONCLUSION

The first scenario studying the travel times on a DRIP shows clearly that the accuracy of the travel time information of RWS is related to the performances of the loops.
The RWS data on the A28 is in stable, even for free flow periods. The frequently adapting travel time could represent the real traffic situation, however certainly during weekend days these fluctuation appear to be caused by inaccurate traffic data. This suggestion is confirmed by the more stable travel time information on the A27, resulting in a smaller difference between the two information providers.
Comparing the free flow travel times of TomTom and RWS, clearly shows TomTom presents a lower travel time. However this low value is not confirmed by the experienced travel times, available at the A28. On the other hand, the free flow value of RWS is quite well matching the travel time experienced by TomTom users. This suggest the free flow travel times of RWS are more accurate than the times of TomTom.
Next to the differences during free flow conditions, the comparisons of the peaks of TomTom and RWS present the following observations. Firstly, the travel time of RWS start to increase earlier followed by a slightly later reaction of TomTom, explained by the required level of certainty in the data fusion to switch to real-time data. Secondly, during growing congestion the travel time of TomTom increases faster and during decreasing congestion the decrease of travel time is bigger or comparable to the data of RWS. This results in a shorter peak hour period of TomTom, since the peak starts later and ends earlier (or comparable to RWS). Thirdly, the maximum values of the peak of TomTom are somewhat bigger than the travel time of RWS. Especially during congestion at the A28 the travel times of TomTom exceed those of RWS. At the A27 this occurs less often, only in case of travel times above 3600 seconds when RWS travel times are rounded to this maximum value.

6.3 SCENARIO 2: GOUDA TO DEN HAAG AND ROTTERDAM (VIA A12 AND A20)

The DRIP on the A12 near Gouda presents travel time information of the route via the A12 to Den Haag and via the A20 towards Rotterdam. These freeways are important connections with large traffic amounts. The scenario studies a time period of four weeks, from 16 June to 16 July 2012. Unfortunately a comparison between real-time provided travel time data and experienced travel time data is not included, since for this recent period TomTom could not yet provide this data.

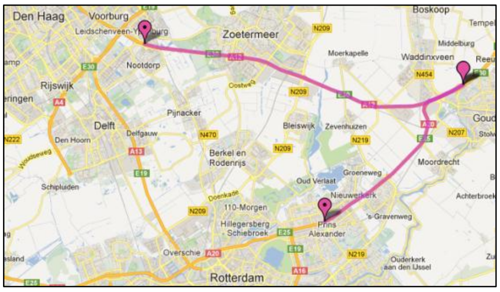


Figure 50 Route from Gouda to Den Haag (via A12) and to Rotterdam (via A20)

6.3.1 EXPECTATIONS

Since this scenario contains two sections with high density of loop detectors, the performance of the RWS monitoring system are expected to be accurate. This expectation is supported by the high performance indicators of 96% (for A12) and 99% (for A20) (see Appendix 6). This scenario could therefore indicate whether the use of loop detector data could compete with floating car data and how big the difference is between those two sources (when both preform good). Due to the high traffic intensities, also the TomTom systems should take advantage of the traffic conditions. A significant penetration rate will probably not be a problem, so accurate floating car data will be available.

6.3.2 RESULTS OF A12

The results for the A12 show high similarity of RWS DRIP and TomTom HD Traffic travel times. Both during free flow and congested conditions the travel times are almost equal.

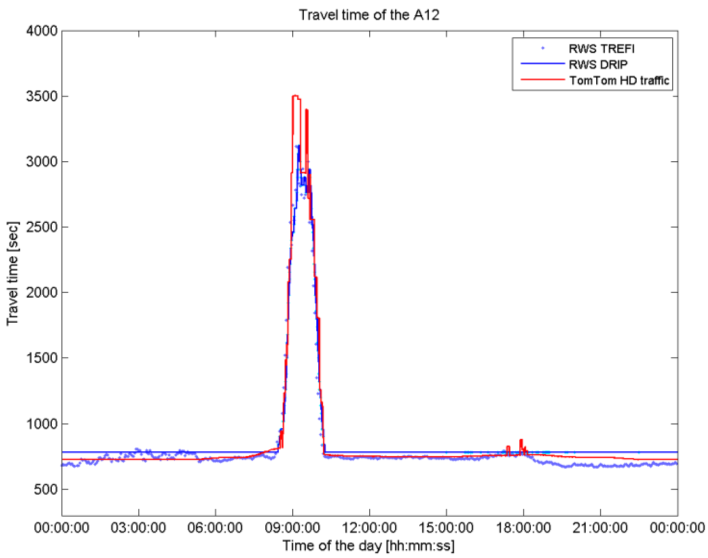


Figure 51 Wednesday 27 June 2012

The above presented day shows nicely how close the performances of the different travel time services met for the route on the A12. The following observations can be made based on the plots of the studied period (see Appendix 9 for plots of all days):

- The differences between the free flow travel times are less than 60 seconds (1 minute), so smaller than in the previous scenarios. The travel time on the DRIP is slightly higher than the TREFI measurement, since the travel time is rounded up to the first full minute. This indicates the real difference between the monitored travel times is negligible.
- The peaks of TomTom and RWS seem to match almost perfectly. Certainly at Wednesday 27 June, but also at the other congested days (see Appendix 9). Remarkably is the nearly identical growth and decrease of both travel time providers, while the growth of the peaks in the other scenarios resulted in deviations between the two peaks. The only substantial differences are occurring at the top of the peak. The maximum values of TomTom are higher than the peak of RWS.

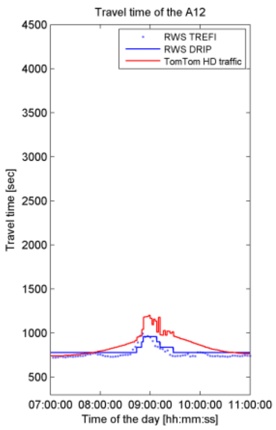


Figure 52 Thursday 21 June

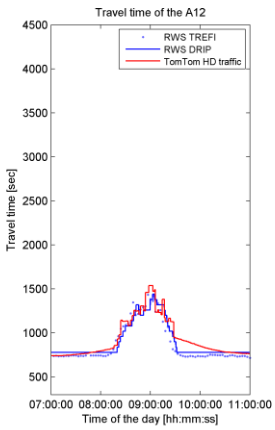


Figure 53 Thursday 5 July

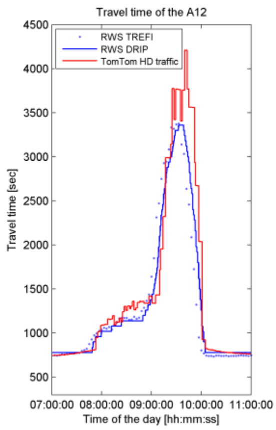


Figure 54 Monday 18 June

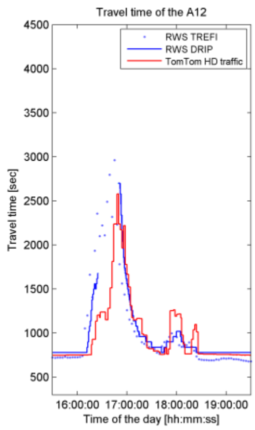


Figure 55 Wednesday 20 June

Also at other days during June and July 2012 the peaks show similarity (see also the other congested days of this scenario, Appendix 9). The figures above are some examples which confirm the previously made observations, including the somewhat higher maximum values of TomTom during heavy congestion. Next to that the following differences are visible:

- Differences are again occurring during morning and evening periods where TomTom presents a peak based on historical data. Even for this scenario, where the travel time data for both services are matching and accurate, during morning and evening peak hours without delays deviating values are presented by TomTom since the real-time travel times do not overruled the historically expected peak. Furthermore if during these time periods a small disturbance is encountered, the difference between RWS and TomTom remains. See for example Thursday 21 June 2012 (Figure 52) where TomTom HD Traffic starts increasing after 7:00h (based on historical data) whereby the small disturbance around 9:00h results in a further increase.
- At the evening peak of 20 June bigger differences are encountered. The growth of the peak of RWS is bigger and starts earlier. However the DRIP update does not follow the TREFI measurements between 16:30-17:00h, but displays a detour advice without travel time information.

Next to these regular days with free flow or congestion conditions, the studied period contains one striking day with an accident on the A12 (Figure 56). Notice the difference between the travel time of TomTom and the RWS DRIP, but also the similarity between TomTom and RWS TREFI.

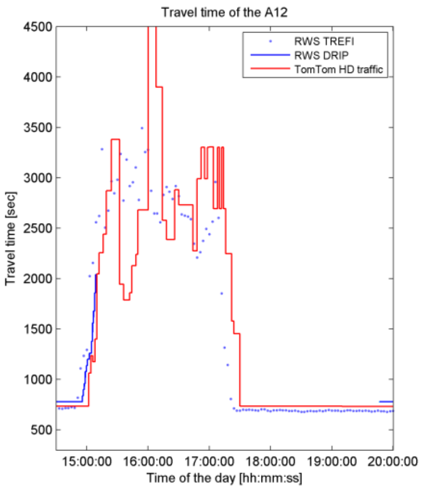


Figure 56 Accident on Saturday 23 June 2012

During Saturday 23 June 2012 (Figure 56) the accident causes a huge delay on the A12. The travel times of TomTom and RWS are comparable till 15:09h. Subsequently the RWS DRIP text is manually changed and a detour is presented. Drivers on the A12 with destination Den Haag should adapt their route and travel via the A20/A13. However, no travel time information of the A12 nor the A20 is provided at the DRIP. Comparing the TREFI measurements and TomTom HD travel time shows that even in this unexpected heavy congestion, the two systems do measure comparable delays. Although TomTom produces some fast changes between 15:45-16:15h.

6.3.3 RESULTS OF A20

As well as on the A12, the analysis of travel times on the A20 result in confirmation of the results found in the earlier routes. Again due to the good performances of both systems the travel time seem to match.

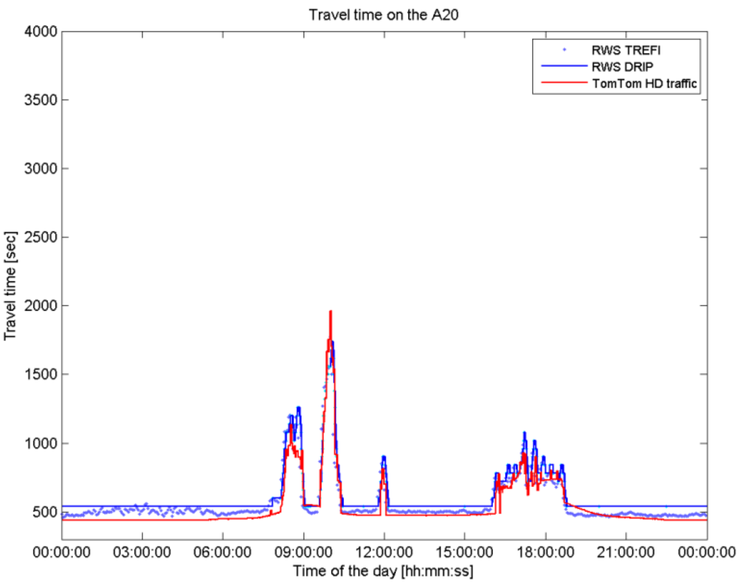


Figure 57 Tuesday 3 July 2012

This plot represent the following results (confirmed by for all days of the studied month, see Appendix 9):

- The free flow time of TomTom is somewhat lower than those of RWS, around 100 seconds (1,5 minutes) in the night and less than a minute during daytime. This confirms the result of the A12, the other route of the scenario, and indicate the travel time measured by a high number of good performing loops is equal to a direct measurement of travel time by floating car data.
- Next to that the presented day contains several peaks, all recognized by both RWS and TomTom. The curves in Figure 57 nicely show how disturbances on the A20 appearing in both the datasets.

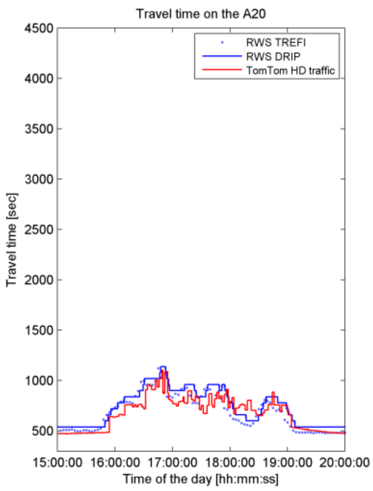


Figure 58 Monday 22 June 2012

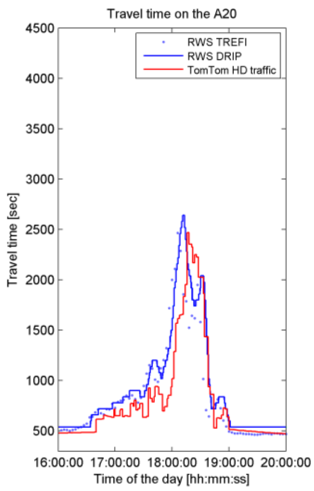


Figure 59 Friday 25 June 2012

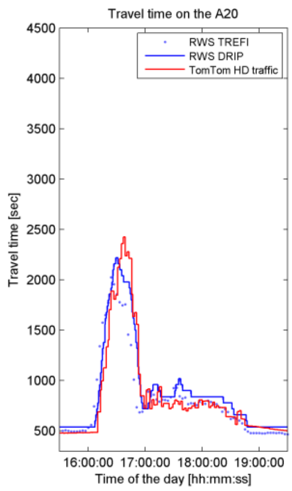


Figure 60 Monday 26 June 2012

Also the evening peak of 22, 25 and 26 June 2012 (see Appendix 9 for the plots of other congested days) are selected to show that the travel times are almost matching. Although when the growth of the peak is high, like on 25 June, the difference at a certain point of time could be big due to the somewhat later increase of TomTom. This means the same trend is visible, but the mutually differences could be substantial.

6.3.4 STATISTICAL TESTS

The MAPE outcomes show that the travel times on the A12 have big similarity. The differences over the whole day are low, mainly caused by the low deviations during free flow conditions. Next to that the decrease of the peaks seem to match better than the growth of the delay. In particular for the heavy congested days on both the A12 and A20. Further comparing the A12 and A20 shows that the performances on the A20 differ more than on the A12. Which could be linked to the greater difference in free flow travel time and the influence of historical data in the TomTom system.

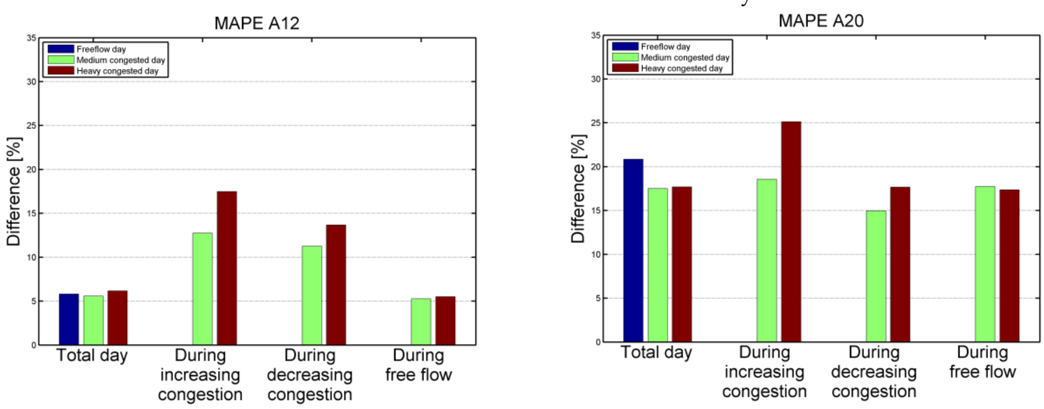


Figure 61 Relative difference between travel time of TomTom and RWS

The t-test for checking whether the travel times of TomTom and RWS are equal is not able to prove the similarity, however the confidence interval presented in the figures below, indicate the differences are not as big as in the previous scenarios. Overall TomTom's travel time remains the smallest. Furthermore when distinguishing the travel conditions TomTom's travel time appears bigger than RWS times during most of the congested days (see confidence intervals in appendix 8). This is caused by the rapid growth and decrease of the peaks, which causes statistical differences although the trends are comparable.
A closer look to the confidence intervals for the A20 show that the differences in the free flow days are slightly bigger during free flow day. Furthermore, just like the MAPE values claim, the differences on the A12 are smaller than on the A20.

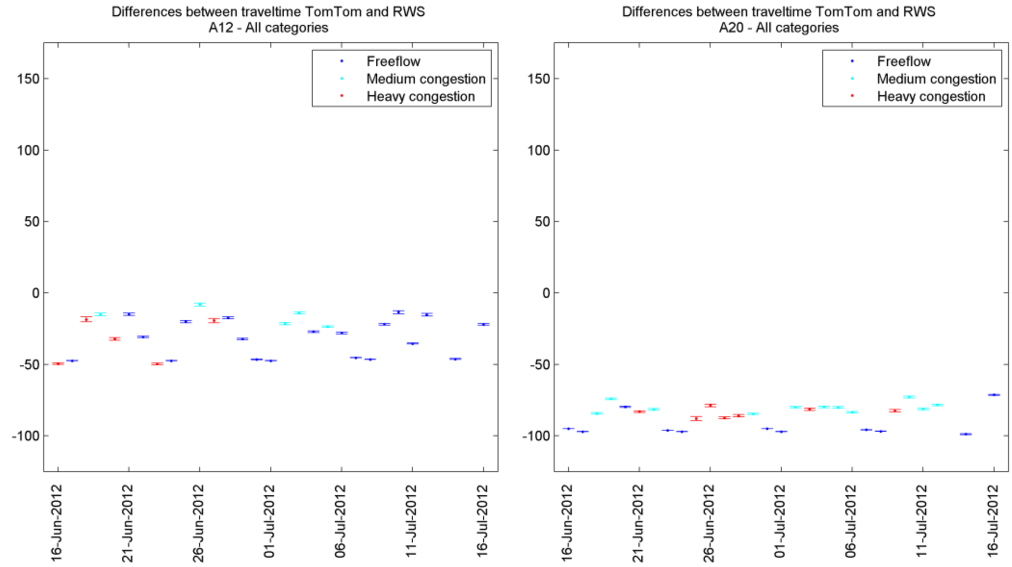


Figure 62 Confidence interval paired t-test, A12 and A20

6.3.5 SUBCONCLUSION

This scenario indicates that if the loop detector system preforms well and the conditions are right, the traffic data sources of RWS and TomTom become nearly identical. For the A12, a straight freeway section with high density of well operating loops, the differences are small. The growth and decrease of the peaks are nearly matching, except the slightly higher peak values of TomTom in case of heavy congestion. Also the free flow travel times, in other scenario causing significant differences, are comparable.
The result for the A20 shows that although the general trends of the peaks show similarity, the mutually differences could become big in fast changing traffic conditions. The slight later increase of TomTom causes deviations compared to the travel times of RWS, caused by the steepness of the peak.

6.4 SCENARIO 3: LEIDERDORP TO BODENGRAVEN (VIA A4/A12 AND N11)

This scenario contains two different type of roads. The first route is travelling via the A4 and A12 to Bodengraven, using RWS freeways with high densities of loops. The second route uses a non-RWS motorway N11 (2x2 lanes, 100km/h speed limit, see Figure 63), monitored with loop detectors of NDW. Remarkably, the first route is clearly longer regarding distance and travel time.

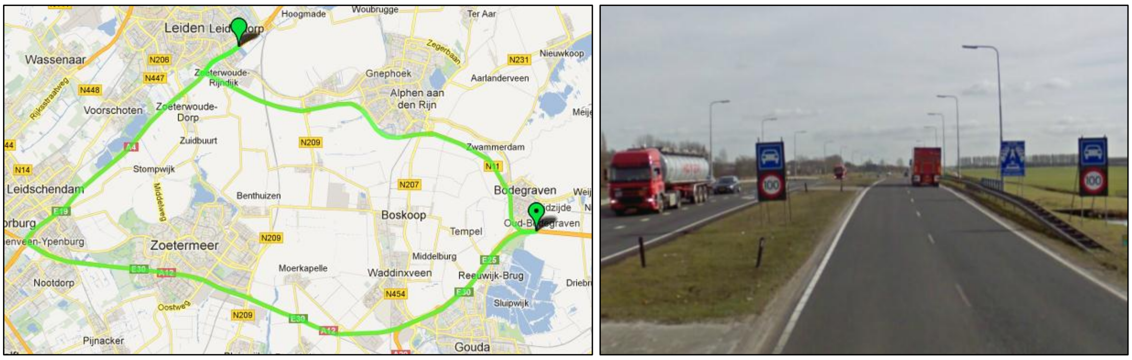


Figure 63 Route from Leiderdorp to Bodengraven (via A4/A12 and N11) (left) and layout of N11 (right)

6.4.1 EXPECTATIONS

This scenario is an indirect comparison between the NDW and RWS loop detector systems. On the N11 the loops are operated by NDW. Comparing this loop data to the travel times of TomTom will indicate whether this data source shows similarities with the results found in earlier comparisons of RWS and TomTom. Furthermore in contrast to all other scenarios the N11 is a 2x2 motorway. The performances of TomTom will therefore be interesting, since they claim coverage of non-freeways is an advantage of their system. However because the intensity on this road is lower than on a freeway, the number of TomTom users on the N11 is probably an issue for accurate travel time calculation. Therefore even with a low density of loop detectors, this system might be more accurate than TomTom floating car data during off-peak hours.

For the route via the A4/A12, the results are expected to match with earlier scenarios. Both the A4 and A12 contain high densities of loops with good performance indicators (92% and 98%, see Appendix 6), only the intersection between those two roads and rapid changes in traffic flow could impede accurate traffic monitoring by RWS.

6.4.2 RESULTS OF A4/A12

The results of the route via the A4 and A12 to Bodengraven are comparable to the trends found in the previous scenarios. However the studied days also contain interesting results indicating differences between TomTom and RWS, but also between TREFI and DRIP travel time of RWS.

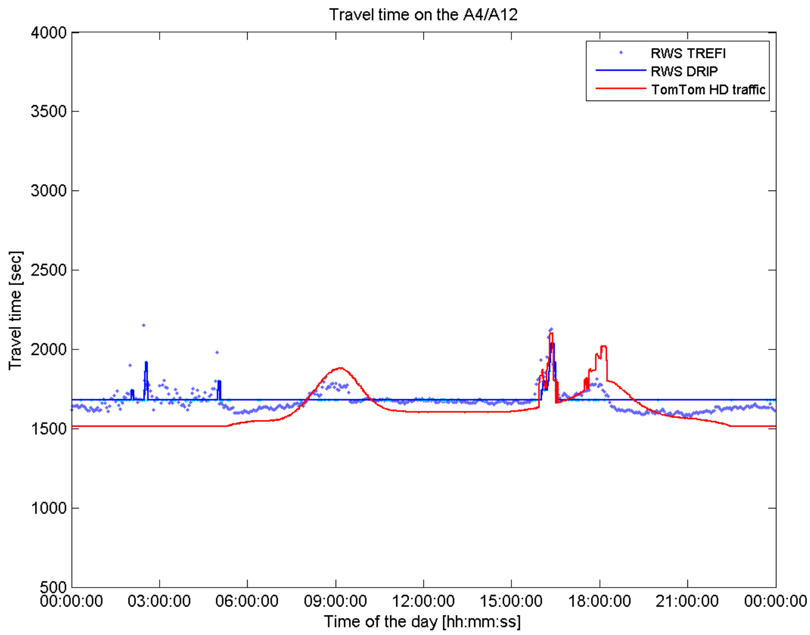
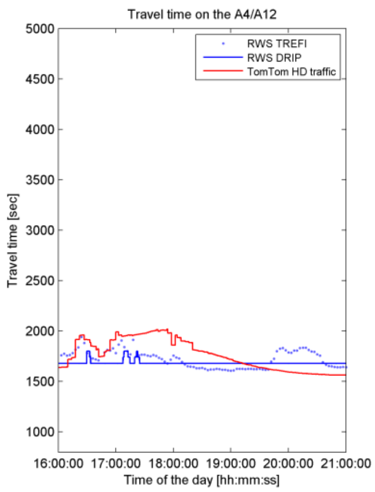


Figure 64 Tuesday 19 June 2012



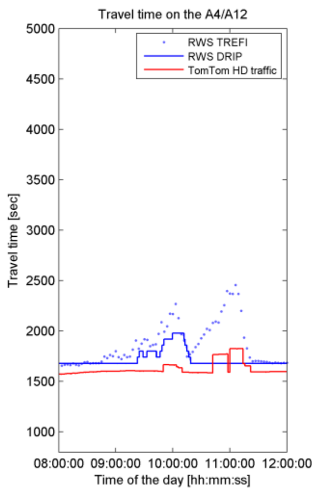


Figure 65 Thursday 21 June 2012

Figure 66 Friday 22 June 2012

The above presented plots contain good examples of the performances of both travel time providers for this relative long alternative route (see Appendix 9 for other plots). The following notes can be made:

- Just like the other routes studied in this research, the free flow time of TomTom on the route A4 via A12 to Bodengraven is lower than RWS. The maximum difference appears during the night; around 165 seconds (2,75 minutes). And again, between the morning and evening peak, the difference is reduced.

- During low amounts of congestion the travel time of TomTom become frequently bigger than RWS's travel time. This is mainly visible during peak hours without big delays, like at Tuesday 19 June (Figure 64) and Friday 21 June (Figure 65). This validates the earlier observations that TomTom presents an increased travel time based on historical values which results in deviations when small delay is encountered.
- Another more remarkable result of this scenario is the deviation between the TREFI measurements and DRIP travel time. The measured delays by TREFI are not always visible in the DRIP travel times. These misses are present during several days of the studied period. For example during the morning (around 9:00h) and the evening (around 18:00h) of Tuesday 19 June (Figure 64), at Thursday 21 June around 20:00h (Figure 65) or Friday 22 June between 10:30 and 11:30h (Figure 66). The small delays of TREFI seem to be ignored in the DRIP time. The lower values of TREFI during free flow periods are also not visible in the DRIP travel time, since the minimal free flow travel time is a pre-defined value.

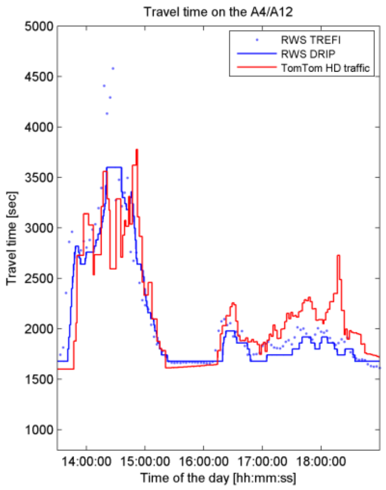


Figure 67 Thursday 5 July 2012

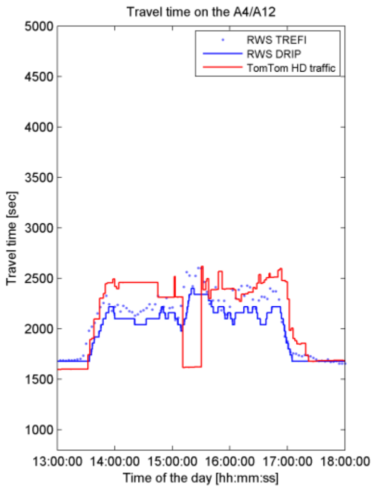


Figure 68 Friday 6 July 2012

Regarding the peaks of this scenario (see all congested days, Appendix 9), some additional observations can be made based on the plots above:

- In previous scenarios, the peak of TomTom was mostly smaller than those of RWS. Especially during medium congestion the travel times were comparable or TomTom's peak laid completely under those of RWS. The plots of the A4/A12 show however contrary results. On Thursday 28 June during the whole evening peak the travel time of TomTom is higher than the travel time of RWS. Apart from a relapse to free flow travel time, this is also the case for Friday 6 July (Figure 68). A day later, at Friday, there is nearly no congestion, however due to the historical data and some small disturbances again TomTom exceeds the RWS travel times.
- Despites these results for traffic conditions with low congestion rates, the peak during Thursday afternoon 28 June (Figure 67) shows similarities with earlier findings. Compared to RWS, this peak of TomTom starts later, has comparable maximum values, has some fast variations in the top, and decreases comparable to RWS.

Besides the described trends of differences between the two services, some days show values which are not in line with these general results.

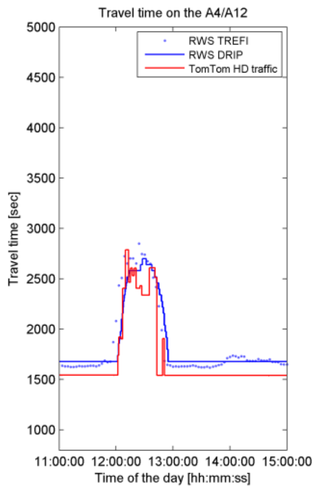


Figure 69 Sunday 8 July 2012

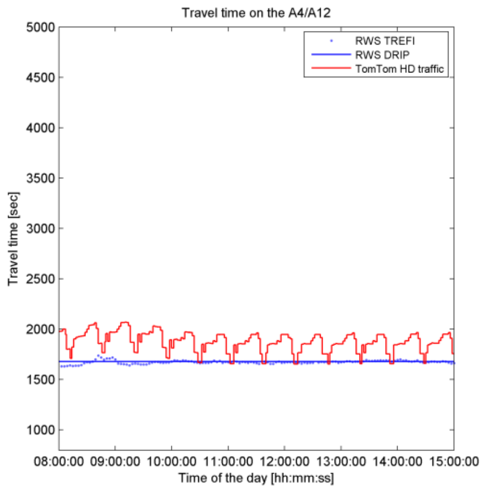


Figure 70 Wednesday 4 July 2012

- The growth of RWS and TomTom for the majority of days in this scenario are different. However during Sunday 8 July (Figure 69) a good example of nearly perfect matching growth is presented. Based on the time, this peak is probably caused by an incident or another unusual cause.
- The travel time curve of Wednesday 4 July 2012 (Figure 70) shows a strange pattern. The disturbances of the travel time service runs from 9:00h at 3 July to 11:00h at 5 July. This failure is however not occurring at other routes during this day. Therefore it seems to be a route specific problem.

6.4.3 RESULTS OF N11

The second route of this scenario is using the 2x2 motorway N11 monitored by NDW loop detectors. The results shows the performance differ from the trends encountered up to now. In contrast, the free flow time of TomTom is bigger than the loop travel time.

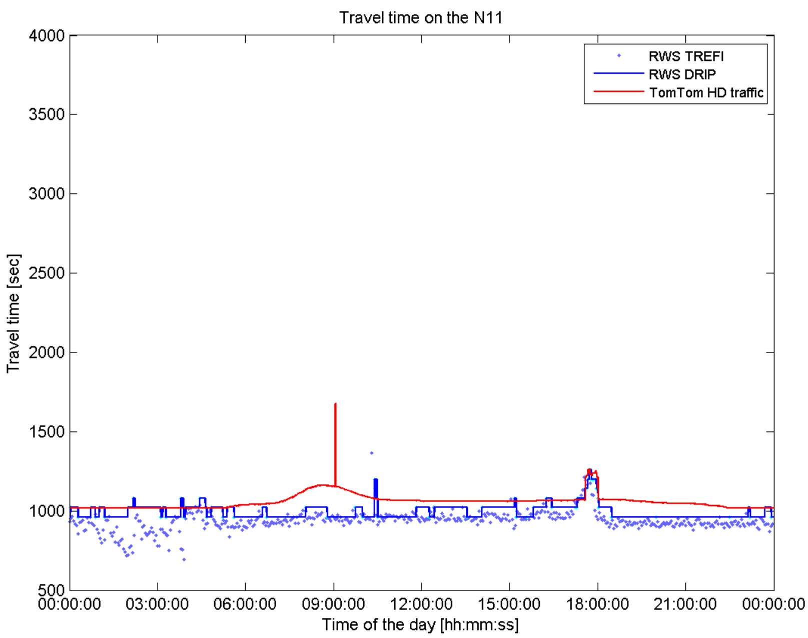


Figure 71 Monday 2 July 2012

The plot above illustrates the results for this route (confirmed by all days, see Appendix 9) , namely:

- The free flow time of TomTom is bigger than the travel time of the NDW loop system. This result is remarkable, since the opposite observation is made for all comparisons at RWS freeways. This result suggest that the travel time estimation of TomTom for non-freeway might be higher than for freeways. This difference could be caused by the travel time calculation method for the NDW loops (possibly different with the RWS method), or the accuracy of monitoring local roads by TomTom differs from monitoring traffic on freeways.
- Next to that the free flow travel time of the loops is frequently adapting during 'free flow' periods, like during the night. This small increase (+ 1 minute) leads to a smaller difference compared to TomTom or matching values.
- The analysed period (6 June - 6 July 2012) did not contain heavy congested days and only during 10 of the 30 days some amount of delay is occurring. Most days are comparable to Monday 2 July, so a fluctuating low travel time based on NDW loops and a higher travel time of TomTom displaying the influence of historic data and some strange peaks, like the one on Monday 2 July at 9:00h (Figure 71).

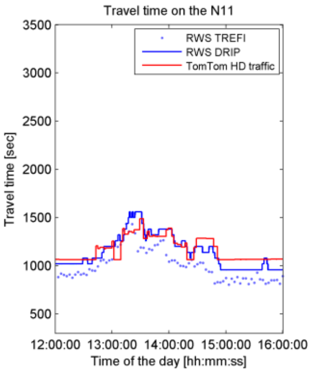


Figure 72 Tuesday 26 June 2012

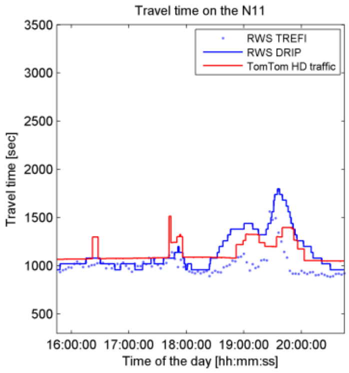


Figure 73 Thursday 28 June 2012

The majority of the ten medium congested days contain only a small steep peak. Only at 26 and 28 June a serious delay peak is present. Based on these two plots (Figure 72 and Figure 73) it is quite difficult to derive solid results. The maximum values of the DRIP appear to be higher than TomTom when the travel time exceed the 1400 seconds. However regarding the growth and decrease of the delay, the results are not consistent.

6.4.4 STATISTICAL TEST

The MAPE results for the A4 (and A12) are quite different compared to earlier results, but need more explanation to really understand the scores. Firstly, despite the clear difference between the free flow time of RWS and TomTom, the MAPE score for these conditions indicate only a small deviation. These optimistic values are caused by the characteristics of the MAPE. Since this test calculates the relative difference between the two data sets and the free flow travel times on the A4/A12 are larger than those of all other scenarios, the difference has less effect on the statistical results.

Secondly, the low scores for heavy congested days could suggest similarity of travel time. However only this category contains only two days, whereof one day is 4 July when TomTom's system is malfunctioned and produces unrealistic high values. This disturbs the final results which are therefore not representative.

Thirdly, despite the trends of the medium congested days appear to show similarity of growth and decrease of congestion, the MAPE values indicate significant deviations. A closer look shows that due to steep peaks and the different reaction times, the mutually differences are indeed quite big.

For the N11, the MAPE results do not lead to much distinction between the performances of the travel time services during different conditions. The results are stable and suggest similarity, which was also found in the analysis of the plots. Difference in free flow travel times are small and due to the limited delay the deviations are not big.

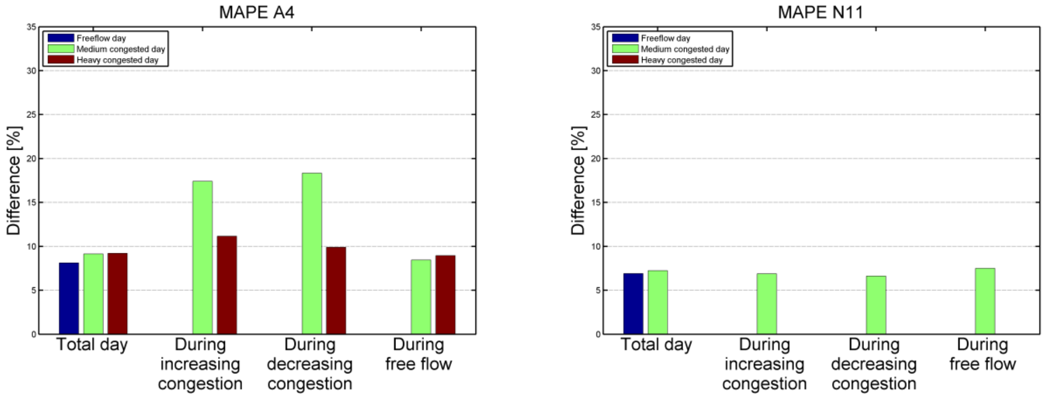


Figure 74 Relative difference between travel time of TomTom and RWS

Again the t-test confirms the travel times of TomTom and RWS are not equal during free flow, increasing or decreasing congestion. Only one exception can be made for the A4/A12, where on 26 June 2012 during increasing congestion similarity is approved.

The confidence intervals of the two routes confirm the interesting difference between the comparison based on NDW or RWS loops. The one tailed t-test also clearly confirms TomTom's travel time are bigger than the travel times of the loops on the N11, while this travel time service in all comparisons with RWS loops produces lower travel times.

Furthermore the figure below shows that the differences on the A4/A12 vary more than on the N11, explainable by the level of delay. Regrettably, the plots do not indicate a relation between the performances and the traffic conditions. The only striking results are appearing on 3 and 4 July when the travel time system of TomTom is defect.

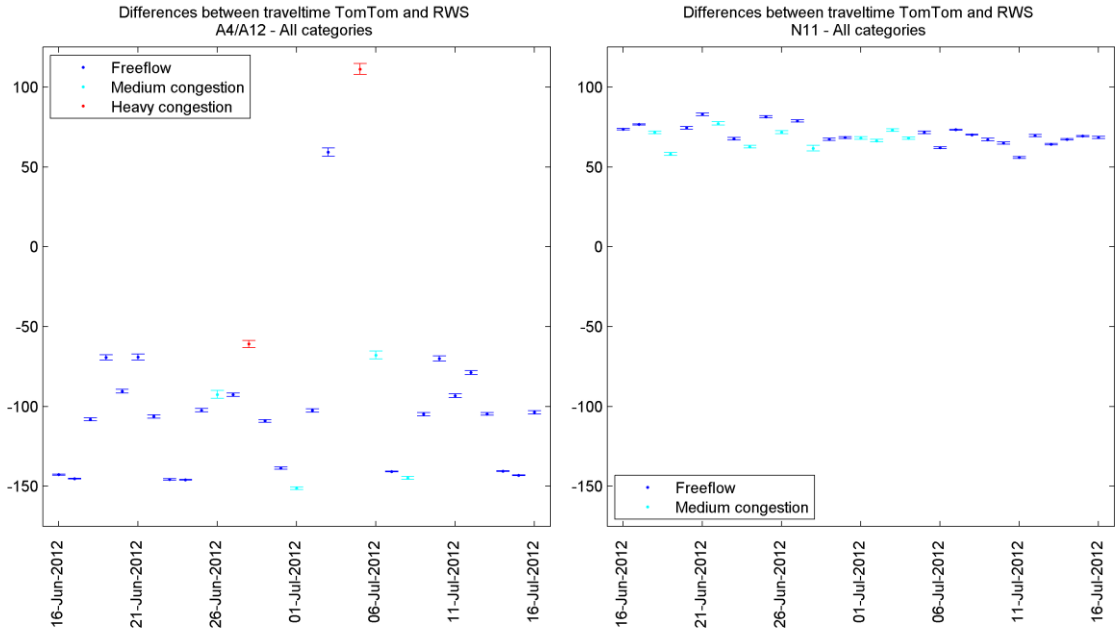


Figure 75 Confidence interval paired t-test, A4/A12 and N11

6.4.5 SUBCONCLUSION

The results of this scenario could be summarised in the following conclusions. Firstly, at the A4/A12 the values of TomTom are higher than RWS during small and medium delays. When delays become bigger, the difference between the two information providers decreases. Next to that, studying the RWS systems shows some delays encountered by TREFI are not presented in the DRIP travel times. This suggest these travel times are filtered out or missed by unknown errors in updating or aggregating the DRIP travel time. Regarding the free flow travel times of TomTom and RWS, the results for the A4/A12 confirm the made conclusions of previous scenarios.
Secondly, the results for the N11 show interesting results by comparing the free flow times of NDW and TomTom. The travel time of TomTom is higher than the travel time of NDW during free flow. This conclusion is contrary to the earlier observed results in the comparison with RWS free flow travel times. This suggest the free flow travel time of TomTom for non-freeways is higher than for freeways.
Since less congestion occurs on this route, no consistent result could be derived for the performances during congested traffic conditions.

6.5 SCENARIO 4: EDE TO LUNETTEN (VIA A12)

This final scenario studies the A12 between Ede and the interchange Lunetten. Roadworks of maintaining and expanding this freeway cause malfunctions in the loop detector system and result in delays. For accurate travel time information during this period, RWS uses an alternative traffic data source collected by Bluetooth detectors (operated by the VerkeersInformatieDienst, VID).

Figure 76 Route from Ede to Lunetten (via A12)

6.5.1 EXPECTATIONS

Firstly, since the loop data is not used for travel time information during the roadworks this source generates probably low quality of traffic data. The road surface will be removed, including loops, and need to be replaced. Next to that, the road layout is frequently changed whereby the loops could be passed in a different/opposite direction. Therefore this work is expected to affect the data collection and will result in missing data or unexpected measurement values, which is show by the relatively low availability of 75% during the studied period (see Appendix 6). Secondly, the alternative data source is created by Bluetooth detectors of the VID. This system is independent of the infrastructure and shall provide more accurate traffic data. Compared to floating car data of TomTom, VID Bluetooth data will probably be somewhat delayed, since the system measures offline travel times. Especially in case of congestion, this will result in less accurate travel time information. Thirdly, because TomTom uses floating car data, the accuracy of this system will not be influenced by roadworks. Detecting delays due to work during the night might be slight more difficult, since the dependence of a penetration level.

6.5.2 RESULTS OF A12

The plot of 24 June 2012 is perfect summary of the performances and differences of the data sources on the A12.

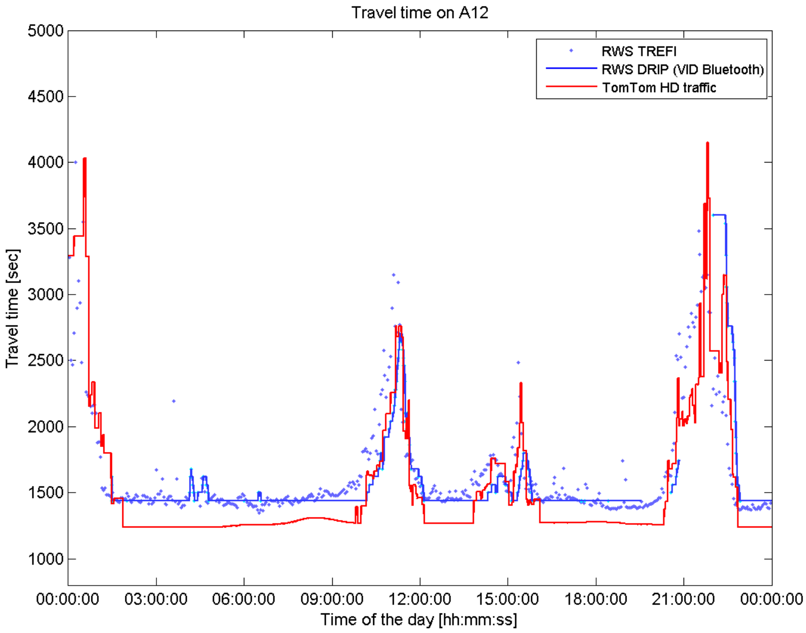


Figure 77 Sunday 24 June 2012

The following results are shown in Figure 77 and observed based on the plots of the studied period (see Appendix 9 for plots of all days):

- First of all, the measurement of the loops (aggregated by TREFI) are quite stable and notwithstanding the roadworks this source still produces a travel time. This is not in line with the expectations and might be a result of the accelerated execution of the works on the A12, whereby for the studied period the road was not almost restored.
- Secondly, the travel time of VID on the DRIP starts increasing later than both the TREFI measurements and TomTom HD Traffic travel times in case of congestion. Just like the Bluetooth detectors of D4T in scenario 0, the VID system detects an increased travel time after the first delayed vehicle (equipped with active Bluetooth device) passes the whole road section. This weakness is inherent to the operation of this detection method.
- Thirdly, the DRIP does not always present a travel time. Even in case of substantial delay, like during the night of 23 to 24 June, other information gets priority. The presented information contains detours and are used for traffic management purposes. In case of major delays due to the roadworks, RWS tries to unburden the A12 and reduce the inflow of vehicles by redirecting them via for example the A30 and A1 to Utrecht. This behaviour may seem reasonable, but could also cause a strange curve when the detour information is switched to travel time information again. An example is the peak during the evening of 24 June; when the travel time starts a road closure on the A12 is reported at the DRIP without travel time information. Subsequently at 22:00h the DRIP switches to travel time information and jumps to 3600 seconds.
- Fourthly, comparable to the other scenarios, the free flow time of TomTom is lower than the time on the DRIP. During the delays at 24 June the peak values of all sources are comparable, however this is not the case for all days of the studied period which will be elaborated in the next paragraphs.

To elaborate the delayed reaction of the Bluetooth detectors, secondly mentioned at the results above, the following figures show some more detailed plots of peaks.

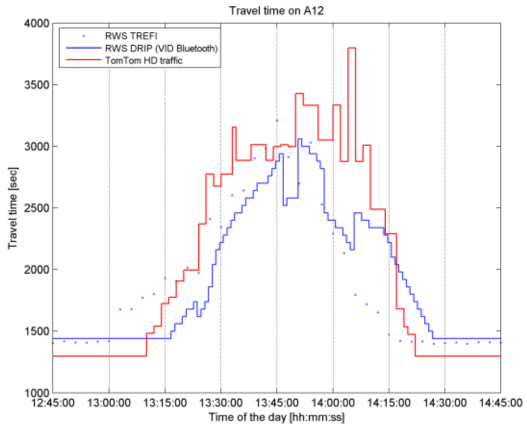


Figure 78 Monday 18 June 2012

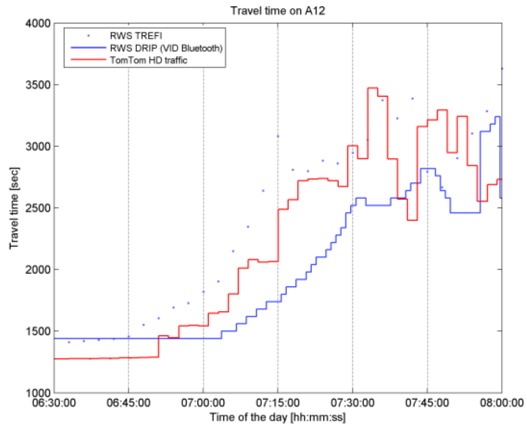


Figure 79 Tuesday 3 July 2012

Regarding the timeliness the weakness of the Bluetooth detectors is clearly shown in the plots of the A12 (see all congested days, see Appendix 9). The travel time of the DRIP based on VID Bluetooth data is clearly delayed compared to the TREFI and TomTom value.

- The results show that the Bluetooth travel time start increasing more than 15 minutes after the loops detect delay, and 5 to 10 minutes after TomTom presents delay. Remember the earlier described operation of TomTom, which uses a threshold before switching to the real-time measurements of delayed travel times.
- The end of the peak of Bluetooth data is also delayed for most of the congested days, but the differences are smaller at this point; maximum difference compared to RWS around 10 minutes, and 5 minutes to TomTom.

Because of the roadworks traffic management gets frequently priority above travel time information. The drivers receive an advice to avoid the A12 and use the alternative route. Three examples are shown below.

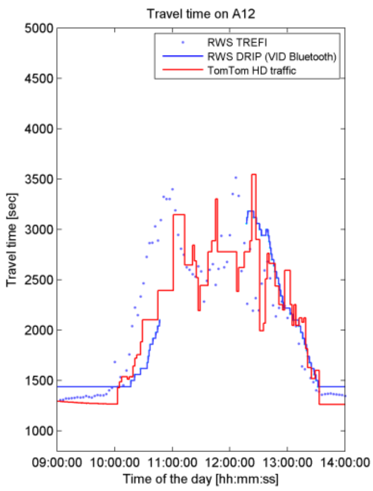


Figure 80 Sunday 1 July 2012

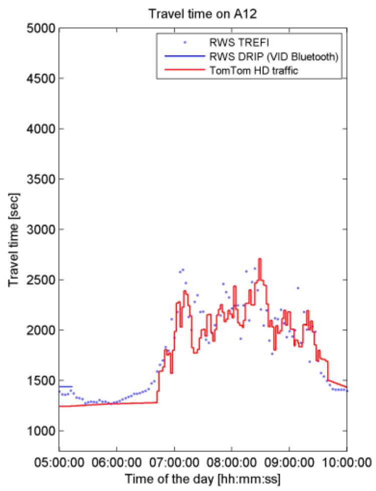


Figure 81 Thursday 5 July 2012

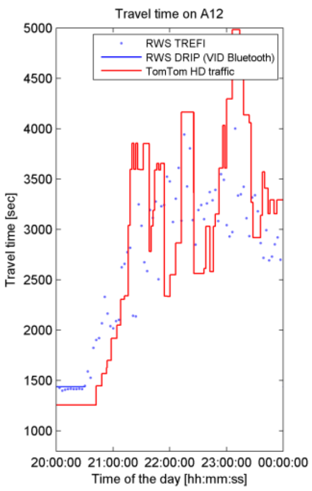
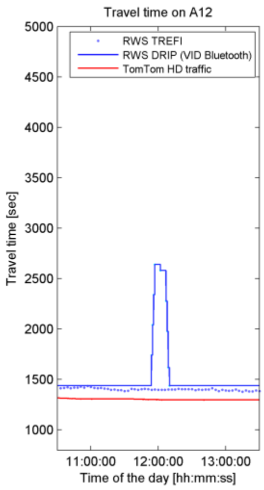
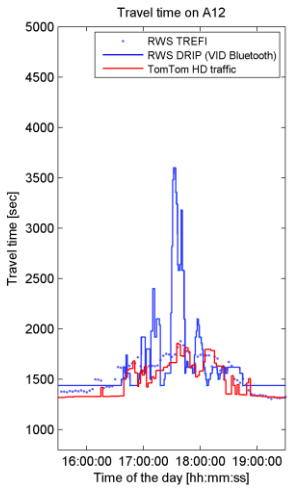


Figure 82 Monday 23 June 2012

The peak on 5 July is a special one. On this day the driver get a warning for closure of the A28 to Utrecht and receive the advice to continue travelling on the A12. However due to the increased use of this route, a delay is occurring. Nevertheless, even these travel times are not presented.

At last some examples of special cases, not yet mentioned in the general results, presented in the figures below.





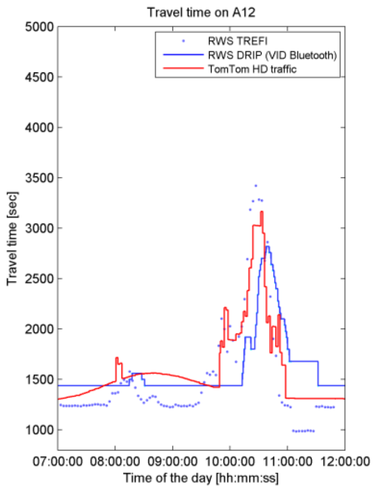


Figure 83 Wednesday 27 June 2012 Figure 84 Thursday 28 June 2012 Figure 85 Wednesday 4 July 2012

- In contrast to both the loop detector data and the TomTom information, the DRIP based on Bluetooth data presents a higher travel time in some cases. Like 27 June at 12:00h (Figure 83) or 28 June (Figure 84) during the evening peak hour, the steep peak indicate congestion which is not monitored by the other systems. Possibly, these values are outliers of the system, however a clear explanation is missing.
- Although the TREFI measurements for most days match the other source, there are a few examples like on 4 July. Failure of some measurement area will cause missing data and results in slightly unreliable travel times. However this is not frequently occurring and does not prove the alternative data source was really required in the studied period. Perhaps the disturbances were bigger during an earlier building phase of the roadworks.
- Just like observe on other routes, TomTom HD Traffic presents an increasing travel time during expected peak hour if real-time data does not measure delays. This strange behaviour does not match with the traffic situation presented by the other sources.

6.5.3 STATISTICAL TESTS

The relative differences of between the VID Bluetooth data and TomTom HD Traffic information are comparable to the results of MAPE found in other scenarios. So the deviations of those two data sources are not much bigger or smaller than comparing the RWS loop data compared to TomTom data. The mean reasons for the deviations between the VID and TomTom data are the differences in free flow time and somewhat later reaction of the Bluetooth method in case of congestion.

The two tailed t-test clearly proves the travel times of VID and TomTom are not equal. Also the plotted confidence intervals show that the values are not near zero. The negative values show TomTom's travel time is again smaller, just like in the previous cases. Only for increasing congestion the one-tailed tested is able to prove the opposite. Due to the delayed increase of Bluetooth travel time, the values of TomTom's peak are significantly higher during the growth of the congestion.

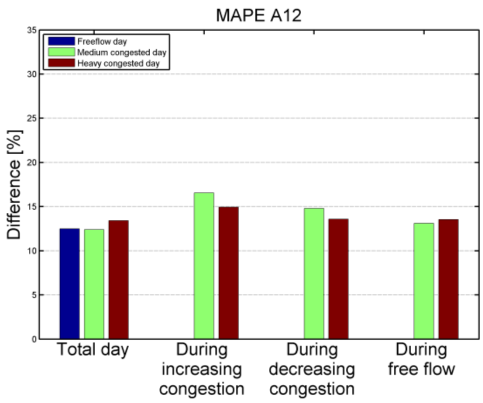


Figure 86 Relative difference between travel time of TomTom and RWS

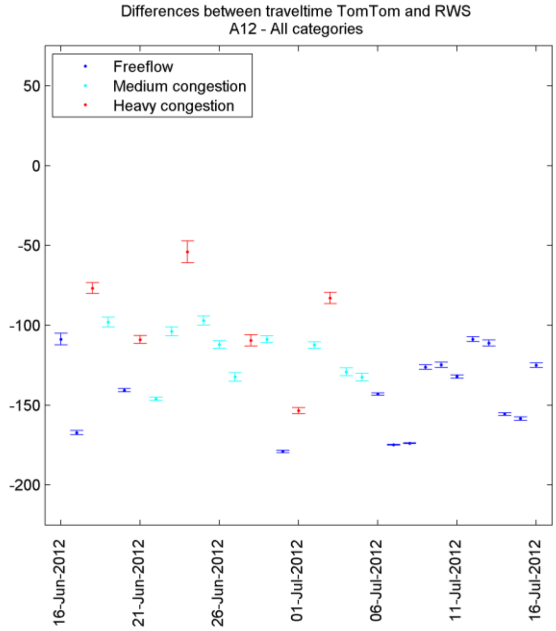


Figure 87 Confidence interval paired t-test, A12

6.5.4 SUBCONCLUSION

Firstly, the most important result of this scenario is the clearly delayed recognition of increasing travel times by Bluetooth detectors. Just mentioned in previous conclusions, the plots present clearly that the loop data firstly presents a delay, followed by TomTom which requires some more deviation before switching to real-time data. However, the Bluetooth data starts increasing substantially later than those two, resulting in significant mutually differences. Next to this difference at the start of the peak, also during decreasing congestion, Bluetooth is somewhat delayed, however this difference is smaller and sometimes comparable to TomTom.

Secondly, the free flow travel times of TomTom are again smaller than TREFI measurement (loop data), but also smaller than Bluetooth data (DRIP logging).

Subsequently, the TREFI data of the loop detectors contain enough data to calculate a reliable travel time during most of the days in the month June and July 2012. In contrast to the expectation and the motivation of RWS, the data does not appear to be strongly inaccurate. This good performances of loop are probably a result of the accelerated roadworks, whereby during the studied period most of the loops were already replaced.

Finally, during high delays at the A12 the DRIP is used for traffic management purposes. This means no travel times are presented, and the drivers are redirected to an alternative route to reduce the traffic intensities at the work sections.

7 Explaining the results

To determine the quality of the provided traffic information by both TomTom and RWS, the results presented in the previous chapter will be further interpreted by adding the characteristics of the systems, described in chapter 4 and 5. Subsequently, the consequences of the differences between the two travel time services are described based on the users' perspective. The chapter starts with a short overview of quantitative differences between RWS and TomTom to compare the results of all scenarios.

7.1 AGGREGATED DIFFERENCES BETWEEN RIJKSWATERSTAAT AND TOMTOM

Overviewing the results of all scenarios shows the relationships between the accuracy of travel times and the present monitoring systems, traffic conditions, road work and road types. The figure below contains the differences (instantaneous travel time of TomTom - instantaneous travel time of RWS) aggregated to one average value for each scenario, combining all days in the category. Although this figure is able to illustrate some trends, one should realize that the mutually differences between the scenarios are large and that aggregating those values strongly reduces the level of detail.

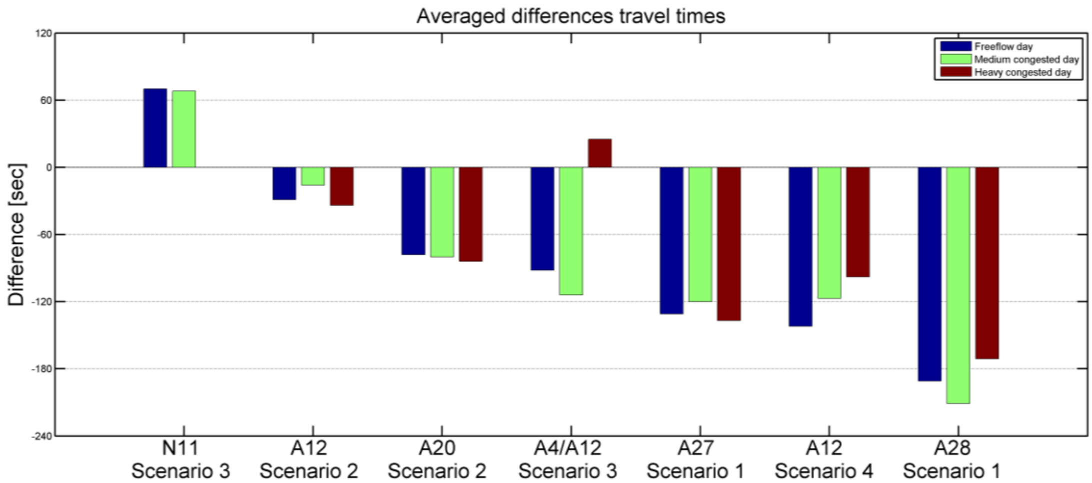


Figure 88 Averaged differences: travel time TomTom – travel time RWS

The differences between TomTom and RWS were already show in higher detail by the confidence interval in the previous chapter, however sorting the average values clearly presents the following results. If a high density loop detectors is present, like at the A12 (scenario 2), the performances of TomTom and RWS are showing high similarity. Next to that the presence of roadworks leads to significant differences and less accurate travel times of RWS, as indicated by the relatively high deviations shown at the A28 (scenario 1). Also the Bluetooth travel times at the A12 (scenario 4) used by RWS result in substantial bigger values compared to TomTom. The results for the N11 show that TomTom's travel time is higher at this non-freeway in contrast to all other results.

7.2 COMBINGING QUALITATIVE AND QUANTITATIVE RESULTS

Based on the known operation of the travel time services, the results could be explained to gain more insight in the quality of the information and the reasons why differences occur. Notice however that the qualitative analysis is limited by the available documentation which leaves black boxes of both RWS and TomTom. The following explanations of the results are therefore only possibilities based on this information.

1. Free flow travel time of RWS is larger than TomTom

   The difference in travel times during free flow conditions is the first clear result. In all scenarios which compare TomTom HD Traffic and RWS DRIP data, TomTom's travel time is smaller than those of RWS. Furthermore the free flow travel times of TomTom do not match the experienced travel times of TomTom users, studied at A28 in scenario 1.

   A first explanation for this difference, varying from 1 to 3 minutes, is a difference in exact start and end location of the route. A wrong configuration of the route could easily lead to deviations in travel time. In this research the GPS coordinates of the DRIP location (as start point) and destination (as end point) are used to indicate the route. However, the destination provided by the RWS system is not always completely clear. The exact location of for example an interchange is arbitrary. Although the RWS route configuration files are used to determine this destination, it might be a possible cause of the difference in free flow travel time.

   Secondly, another explanation can be given by indicating a difference in performance. Comparing the quality of the data at the different roads, the results show that if the quality of the loop data improves the difference between the free flow travel times becomes smaller. Compare for example the performances of the A28 (scenario 1) and the A12 (scenario 2). This could suggest the deviations between TomTom and RWS are caused by inaccurate data of the loops.

   Thirdly, since RWS loops measure all types of traffic the calculated travel time information is a general travel time for all road users. So the travel times for slow traffic (trucks) are combined with normal traffic (cars). Possibly, the travel times of TomTom are more specifically calculated for car drivers.

2. Travel time of RWS starts increasing earlier than TomTom

   A second result of the data analysis are the differences of travel time during congestion. Despite of the comparable trends of the two datasets, the timeliness appear to be crucial. Especially in case of fast increasing delays, the mutually differences become big because TomTom starts showing an increasing travel time somewhat later (maximum around 5 minutes). The operation of the data fusion engine is a well explanation of this later reaction. Changes in traffic conditions indicated by one data source will not directly influence the output of TomTom. More certainty is required, i.e. by a high delay or confirmation by another data source. The negative effect of this threshold is mainly visible at high peaks. Notice however also the positive side of preventing unnecessary small fluctuations of travel time.

3. Maximum values of RWS peak smaller or comparable to values of TomTom

   The comparisons of the peaks divides the performances of the services in two types. For the A27 (scenario 1) and A20 (scenario 2) the travel times of TomTom remains smaller than the travel times of RWS for the whole peak period. So the maximum values of TomTom are smaller than the values of RWS, and TomTom's peak lays completely under the peak of RWS. However the level of delay seem to be comparable considering the already encountered difference in free flow time. So this result suggests the difference in free flow, analysed above at point 1, still leads to lower value of TomTom during congested conditions.

In contrast, on the A28 (scenario 1) and A12 (both scenario 2 and 4) the travel time of TomTom exceeds RWS during heavy congestion. This difference is strengthen by the rounding behaviour of the RWS system. DRIP travel times above 60 minutes are displayed as 'more than 60 minutes', while TomTom HD Traffic contain a precise travel time.

Besides this rounding, inaccuracy of loop detectors during low speeds might be another reason for lower maximum values of RWS for these roads. The transition from increasing to decreasing congestion frequently causes stop and go movements. Especially in these conditions the loops are unable to precisely calculate a travel time. Fast changes of speed between two loops could not be detected. This will cause an error, however does not directly explain why the travel time is lower for all mentioned road. Possibly, this is caused by the inability of loops to measure travel times at standstill. Especially during these high delays, standstill will further increase the travel time which explains the higher values of TomTom. Floating car data is not depending on a flow and could also monitor the travel time when the vehicles are not moving.

4. The travel time of RWS is bigger or comparable to TomTom during decreasing congestion

Again the higher values of RWS could be caused by the initial difference in free flow travel time. However a closer look to the results show a steeper decrease of TomTom. This shows the monitoring system of TomTom detects a faster decrease of congestion. Based on the theoretical characteristics it is clear that floating car data could more precisely determine when and where the congestion disappears and turns to flow again. Logically, the loop based calculation method of RWS could overestimate the travel time during decreasing congestion, since the speed is interpolated over the whole measurement section. If the transition of congestion to flow is located between two loop sets, it requires some time to detect this change. Furthermore solving congestion normally causes stop and go movements which increase the difficulty for loop detectors and lead to an overestimation of travel time.

The comparable values of travel time should be explained by good performance of loops. For example if a high density of loops is present the problem described in the previous paragraph is smaller. A more detailed measurement network result in more precise data of the speed distribution over the route. This could explain the similarities during these conditions at specific roads.

5. The influence of historical data causes deviating peaks of TomTom during weekdays without delays

Variation of travel time during free flow days based on historical data seems to be not matching the reality. It is quite remarkable that even during holidays TomTom presents a smoothened peak during both morning and evening peak hour. The current travel time system of TomTom only uses real-time data to present actual delays, so during free flow conditions and peak hours without substantial delays the travel time of TomTom is calculated based on historical values. For example the historical data for a typical Monday morning contains a small peak. Aggregating the historical data of many Monday morning periods will certainly display the influence of regular congestion. The question rises why TomTom uses this aggregation method, since real-time data will be available and expected to be accurate during these daytime periods. The answer to this question is rather simple; the current systems of TomTom are not yet able to use real-time data for the whole day. During the development of TomTom HD Traffic the choice is made to only use real-time data for presenting delays due to the limited bandwidth.

Remarkably, the promotion of TomTom HD Traffic emphasis the advantages of high update rates and the use of real-time traffic data. In reality this update contains mostly historical data and only sends real-time data in case of actual delays. So receiving an (somewhat) increased travel time at your TomTom HD Traffic device during peak hours does not automatically represent the current traffic situation. Notice that the interface of TomTom do show the source of the presented data (IQ routes = historical data, HD Traffic = real time data), although this might be not directly clear for all users.

Furthermore a delay presented outside the peak hours or a high amount of delay will always be caused by an update with real-time data.

6. Bluetooth travel times react later than both RWS and TomTom at changes of traffic conditions
   The results of the data analysis clearly confirm the weaknesses of Bluetooth detection, described in the qualitative analysis. Since a travel time is measured after a vehicle has passed a second detector (so end of section or route), this travel time method is always delayed in detecting changes of travel time. This timeliness problem causes mismatch with other data sources and therefore Bluetooth data will not be able to present a highly accurate travel time during changing conditions. The encountered differences, for example 10 to 15 minutes compared to loop data at scenario 4, are a serious problem for real-time travel time information provision. Notice, if the travel time remain constant, for example free flow or a fixed amount of delay, the Bluetooth travel time does match reality. Next to that the measurements seem to contain reliable values, so could be useful for offline applications when timeliness is not required.

7. Free flow travel time of TomTom at non-freeway is higher than a loop based travel time
   This result is based on the results of the motorway N11 (scenario 3). The lower travel time at this non-freeway is interesting, since for all other route (which do use freeways) the results are contrary. The question rises why TomTom's free flow travel time is higher than the travel time of the NDW loop detector, while compared to the RWS travel time TomTom's travel time is higher during free flow conditions. Several reasons can be used to explain this result.
   A first explanation could be the presence of traffic lights at three intersections of the N11. Waiting times at these intersections will certainly have an influence at the travel time. How these amounts of delay are implemented in the travel time of this route is however unclear. Therefore it could be an obvious reason for the encountered difference.
   Another interpretation of the differences is a simple one and focuses on a difference between NDW and RWS. Both authorities uses loops to calculate travel times, however it is unclear whether the performed calculation methods are equal. Possibly, the data is differently used which could lead to a lower/higher free flow travel time.
   However it is also possible that the difference should be explained by characteristics of TomTom. For example the number of active TomTom users at the N11 might be too low to generate the required penetration level.

7.3 RESULTS IN DRIVERS' PERSPECTIVE

During the analysis of the travel time data and the description of result, the focus was at the quality of traffic monitoring and the accuracy of the used method. However the user perspective at these travel time information will tell what differences of travel time mean in reality.

To assess the quality of the real-time travel time information, it is firstly important to know the need of the drivers. Like described in the introduction chapter of this report, drivers need insight in the traffic situation to choice the shortest route or estimate the arrival time. Furthermore, although not included in this research, human behaviour is an important factor in interpreting the quality of the provided information. Most drivers will not precisely monitor their departure and arrival time and therefore are not able whether the experienced travel time confirms the presented travel time. Next to that, congestion could result in a higher perception of trip duration.

However despite these above mentioned restrictions to travel time quality in drivers' perspective, the results certainly contain important outcomes to the quality based on users' perspective.

Firstly, the differences in timeliness are highly important to drivers. The time required to detect changes of travel time, both increasing and decreasing, and process the data is determinative for the difference between the provided information and the time the driver will experience. For example, Bluetooth travel times which need relative much time for detection, will could lead to big differences during rapidly changing conditions, like during the development of a queue. Another example, since the loop travel time presents delay as first, this could be interpreted as strength regarding the quality of the information. Overall, regarding timeliness at the increasing congestion RWS delivers the highest quality of information, closely followed by TomTom. Bluetooth data scores low at this requirement.

Secondly, the value of the provided travel time should match the experienced travel time. Because of travel time variation this requirement is difficult to assess. The results indicate that the lower (free flow) travel time might be suitable for car drivers but do not match the experience of other traffic. The travel time of RWS, an average of all drivers, matches the experiences of TomTom users (at the A28 , scenario 1). However the question rises whether a general travel time is really useful or that the travel time should be personally specified. Despites this interesting question in developer's perspective, for most drivers this difference of free travel time is not a major problem. During free flow conditions the need for travel time is the lowest. The information is only used to select the shortest route and only when precisely monitored the driver could encounter this difference.

During congested conditions the need of travel time information however increases. However the travel time for delay also presents differences between the two information service. This could lead to a dilemma for the user, which source to trust. The transition of free flow to congestion requires accuracy and speed. Accuracy is needed to rightly determining whether delay is present. Speed is required to rapidly ensure the most up-to-date travel time information is presented to the road users, especially since the development of congestion causes fast changes of travel time. The somewhat delayed reaction of TomTom, compared to RWS travel time information is a good example of reduced speed of information provision. The delayed monitoring of Bluetooth detectors results in an even stronger deviation (for the whole peak) and lower quality of information. Since all travel time services offer a instantaneous travel time, drivers could certainly encounter differences between their experienced travel time and the presented information. This difference is illustrated in the first two scenarios and shows that accurately presenting a travel time is fast changing traffic conditions is a difficult task.

Thirdly, travel time information of RWS is hided in some cases to present detour information for traffic management reasons. A detour is expected to have a bigger effect than presenting the travel time of both routes, which might suggest a choice is still possible. In driver's perspective, just in those major disturbances the need of accurate traffic information is high. Removing the travel time information reduces the overview of traffic situation and requires complete trust in the given detour advice. Alternatively, advising to travel via an alternative route and also presented a travel time plus delay may increase the response since this travel time information could confirm the suggested route is shorter. However, in some cases, the traffic manager (RWS) tries to minimize the traffic amount on a road or aims at a system optimum, in which not all drivers could take the shortest route to improve the network performances.

> The quality of the provided travel time of RWS is also influenced by the way of presenting. Although the information is reaching all road users, the accessibility of this communication channel is limited. Once a driver has passed the DRIP no updates will reach him. This results in an underestimation of travel time during increasing congestion and an overestimation of travel time during decreasing congestion, like is shown by presenting historical data. This weakness is less applicable for TomTom. Since this company provides in-car information, the driver has always access to updated information. This way of information distribution leads to an increased level of quality, whereby the differences between the presented information and the experience travel time is reduced. Notice however that fast changes of travel time leads to frequently adaptations of travel time.

8 Conclusions and recommendations

The results of the qualitative and quantitative analysis will be summarized to give concisely answers to the research questions. This chapter concludes which travel time information provider is preferable, regarding the qualitative indicators and the accuracy of the presented travel times. Subsequently, recommendations to RWS, TomTom and other researchers are defined based on the results. The chapter ends with a discussion about the reliability of the results and limitations of this research.

8.1 CONCLUSIONS OF THE QUALITATIVE ANALYSIS

The first part of this research focused on the operation of the travel time system of RWS and TomTom and analysed the accuracy, variety of data sources, relevancy, timeliness and accessibility in a qualitative way. An answer is given to the first sub-question: *How do the travel time services operate, including data sources, parameters and assumptions?*
Overall, the precise operations were difficult to explore, since most calculation methods are not documented or consciously secret. Nevertheless, the difference of the two information services is further elaborated and based on the available documentation the strengths and weaknesses are described. The highlights of the two systems are described below.
Firstly, Rijkswaterstaat uses speed and intensity data of loop detectors to calculate instantaneous travel times for important freeway routes. The most important assumption in this calculation is the linear speed distribution between two sets of loops. This shows directly an important weakness of this system; no travel times are measured and changes of traffic flow between two loops are difficult to monitor (blind spots). Especially in congested conditions (for example with stop and go movements) this will result in inaccuracy. The calculated travel time is presented on a DRIP which is accessible for all drivers on the route, however updates of real-time travel time will not reach the road users who have passed this DRIP already. Next to that drivers should evaluate whether the information is relevant to their personal route and receive only a travel time for the freeway part of the route.
Secondly, TomTom collects floating car data with both GPS receivers in their navigation devices and cell phones of Vodafone. This latter data source of GSM location data requires extensive filtering and contains inaccuracy in the location method. Furthermore both the GPS and GSM method only measure a selected amount of traffic and are therefore depending on a significant number of equipped vehicles (penetration rate). This research discovered TomTom uses this data only to present real-time delay information, but in periods without delay, historical data is used to present a travel time. The data sources are combined via data fusion, where real-time data only gets priority when it exceeds the historical values. The travel time information contains the whole route from origin to destination (including all type of roads) and updates are received at the in-car navigation device.
Overall, the assessing the accuracy, variety of data sources, relevancy, timeliness and accessibility shows the two service provider are clearly different due to the used data, calculation method and communication

channel. The analysis shows clearly advantages of TomTom, since the travel time product is expected to be more accurate. Furthermore TomTom's system is based on traffic data sources which directly measure travel times, presents a travel time for the whole user defined route and provides continue access to up-to-date travel time information. The assessment of the RWS systems presents less strengths, since the travel time is expected to be inaccurate due to the indirect travel time calculation method. Next to that the RWS travel time is only based on loop data, only applicable to the freeway part of a route and has limited accessibility whereby updates will not receive the drivers who have passed the VMS.

8.2 CONCLUSIONS OF THE QUANTITATIVE ANALYSIS

The second part of this research analysed the travel time data of RWS and TomTom in five scenarios. The results of this quantitative analysis give answer to the sub-question: *How do the travel time information services perform during free flow and congested conditions?*

In general, the information of RWS and TomTom does not present the exactly same travel time. However despite these differences the general trends of the presented travel times contain similarities. Furthermore, at sections with high quality of loop data (like A12/A20 at scenario 2) the travel time information becomes almost equal. The conclusions are described below; firstly for the different information providers, secondly by comparing RWS and TomTom. Notice that the exact performances are depending on the specific road and selected days.

8.2.1 INDIVIDUAL PERFORMANCES OF TRAVEL TIME INFORMATION SERVICES

Travel times of Rijkswaterstaat

The quality of the travel times presented by RWS is strongly depending on the performances and characteristics of the present loop detectors. At road sections where Matrix Signal Installations (MSI) are present for throughput and traffic safety purposes, the detector system contains high densities of loops and is able to produce high quality of data with less malfunctions. Due to these good performances the accuracy of the calculated travel times is high. The loop based travel time becomes comparable to floating car data of TomTom. However at sections without MSI, the data produced by the monitoring systems with low densities will generate less accurate travel times. Also at road sections where roadworks are executed, the travel time information becomes inaccurate. During these conditions the data might contain many malfunctions and/or missing data notwithstanding a high density of loops.

At some routes the travel time information is consciously hidden when serious disturbances occur. Although the measurements of RWS indicate accurate travel time information is possible, the DRIP messages present only detour advices in those cases. Just during these conditions when the need for accurate information is high, drivers do not receive insight into the travel times.

Travel times of TomTom

The travel time information of TomTom is based on historical data and only during delays updated with real-time data. The low free flow times might be valid for car drivers, but are not confirmed by experienced travel time data (although only checked at A28, scenario 1). Regarding accurate travel time information two weaknesses are observed. Firstly, during possible peak hours without real delays the travel time information is disturbed by a peak of historical data. The real-time data is only used in case the actual values exceed those historically created curve. Compared to historical and RWS data, these peaks do not match the real traffic situation. A second weakness of the travel time system of TomTom is the timeliness at the start of a peak. Some level of certainty is required to use the real-time data, therefore the travel time of TomTom sometimes start somewhat delayed.

Bluetooth travel times

The Bluetooth method to monitor traffic flow is an innovative source to monitor travel times. However for real-time travel time information provision, the timeliness is a major problem. This theoretical weakness is also observed in this research and clearly shown in the delayed recognition of changes in travel times (especially at the start of congestion).

8.2.2 COMPARISON OF RWS AND TOMTOM DURING FREE FLOW AND CONGESTION

Free flow conditions

The free flow travel time of RWS is higher than TomTom in all scenarios. The differences vary for each route. When the loop system performs better (high density and high quality of data), the difference decrease. This trend suggest the difference is caused by inaccurate travel times of the loop system. However the RWS free flow travel time match the historical data, containing individual measured travel times (only checked at the A28, scenario 1). In contrast to the difference at the RWS freeways, the free travel time of TomTom is higher than the travel time of NDW, based on loop detectors. This could suggest travel times of TomTom differ comparing freeways and non-freeways.

Congested conditions

Overall, by comparing the performances of RWS and TomTom for congested conditions, the differences during increasing congestion are bigger than during decreasing congestion. This is caused by deviations during the start of a peak and similarities during decreasing delay. The following trends explain this conclusion. Firstly, the travel time of RWS starts showing delay slightly earlier than TomTom, because a threshold is use to switch between historical and real-time traffic data in the data fusion of TomTom. Secondly, the increase of RWS' travel time is smaller than TomTom whereby at high delays TomTom's travel time become comparable or even exceeds the values of RWS. Thirdly, during solving congestion two cases are observed; the travel times of TomTom and RWS decrease comparable or the travel time of TomTom decreases faster and present free flow conditions somewhat earlier.

Next to that, if the difference of the free flow times are ignored in comparing the delays, it appears the level of disturbance shows high similarities. This suggest that when the free flow travel times become more comparable, this will also lead to more equal travel times during congestion.

8.3 ANSWER TO THE RESEARCH QUESTION

Combining all the results of this research together create an answer to third sub-question. Furthermore it formulates a final answer to the leading question of this research: *What is the quality of real-time travel times of RWS, TomTom and Bluetooth based services in the Netherlands, measured in mutually differences and differences to experienced travel times?*

The quality of the travel time presented by RWS is comparable to the travel times of TomTom, at routes with a high density of loops which produce high quality of data. Furthermore under free flow conditions the travel time of RWS appears to be more realistic, especially compared to travel times of TomTom during peak hours without delay. Overall, despite the described weaknesses of the loop data and indirect travel time calculation method of RWS, the travel times studied in the data-analysis appear to be reliable.

However if the qualitative indicators are also taken into account, TomTom becomes more preferable. This company combines good quality travel time information with in-car communication. Hereby the travel time information of TomTom is more relevant and better accessible than the public information provided by RWS at DRIPs.

Bluetooth travel times are less accurate due to delayed detection of increasing travel times. This weakness is inherent to the operation of this detection method; travel times are measured at the end of a route. This data source appears to be less applicable for accurate real-time travel time information.

8.4 RECOMMENDATIONS

Based on the results of this report a number of recommendations can be provided, to the involved traffic information services and to researchers in general. These recommendations are meant to translate the collected knowledge to practice.

8.4.1 RECOMMENDATIONS FOR RIJKSWATERSTAAT

Since the research goal was evaluating the current strategy and quality of the travel time information of RWS, the following recommendations can be given.

Firstly, despite the theoretical weakness of travel time calculations based on loop detector data, the performances of the RWS system are certainly not completely insufficient. At roads with high densities of loops due to the presence of MSI, the travel time information can compete with other travel time data sources, and RWS should continue their strategies for these routes.

Secondly, at roads without MSI or at roads with disturbances in traffic monitoring (for example during roadworks), RWS should change their strategy. The quality of the available loop data for these sections is not accurate enough for high quality of travel time information.

- A first possibility to improve the travel time data on this type of roads is using different data sources. For example at the A28 (Nijkerk – Nunspeet); RWS could benefit from the strengths of the current loop system and improve the accuracy by adding Bluetooth data. This means the loop data is used to detect a increasing travel time and after this start, RWS switches to Bluetooth data. In this way, both the delayed detection of increased travel time by Bluetooth detectors and the inaccurate travel time during congestion of low density loops are removed.
- A second possibility is investing in new data sources on roads without MSI and high density of loops. Since the purpose of the data is providing travel time information, it is strange to invest in loop detectors which do not directly monitor travel times. For this reason RWS should deviate from their current strategy and choose for example floating car data. Furthermore, since the general business strategy of RWS and traffic data market are changed, RWS could consider outsourcing the data collection task and buy licenses or data from other companies, like TomTom.

Thirdly, to improve their travel time information system RWS should create insight in their own processes. Currently, multiple processes are linked together and create a cluttered system whereof the functions are obscure. Hereby it is quite difficult to precisely evaluate the current methods and make improvements. RWS should improve their system by reducing the number of processes. A suggestion is directly calculating a route travel time based on MoniBas data. This removes the unnecessary aggregation process of TREFI which only generates a reduction of detail. An even bigger step forwards is not retaining to the current methods and building a new system. A new algorithm should combine the strengths of loop data and innovative sources by data fusion and apply the state-of-art knowledge. The current system is not created for the purpose of high quality travel time information provision, but is created by connecting processes which were originally not meant for this purpose.

Fourthly, the DRIPs of RWS are not only used for traffic information purposes but also traffic management messages could be presented. However it is questionable, also based on currently available literature, whether the response of drivers is bigger when only a detour advice is provided. Since this research shows the available measurements during incidents are comparable to travel time information on TomTom, one could argue that in case of an incident both a detour advice and the travel times on the routes should be presented. In this way the driver himself could verify whether the given advice is right and select the shortest route. In the current situation, at serious delays (when the need of travel time information is high) travel time information is hidden which leaves the drivers without insight in the traffic situation and requires complete trust in the given advice.

Finally, the current communication channel of VMS is a weakness of the travel time information system. The usefulness of the VMS is expected to reduce in the future, since the number of navigation and other in-car information system is increasing. RWS could improve the traffic information provision by shifting to in-car information provision. The future of their traffic information will probably be roadside-to-vehicle communication; sending the traffic information to drivers by wireless communication. Car manufactures could subsequently build in-car data receivers and present the public traffic information at a display in the vehicle.

8.4.2 RECOMMENDATIONS FOR TOMTOM

This research clearly shows the free flow travel times of TomTom deviate from those of RWS and historical data. TomTom should therefore further investigate how these values are calculated and improve the free flow values. Since the navigation system provided personalized information the free flow travel time could be adapted to individual characteristics, like specified for car or truck driver. Next to that, the system could be self-learning; monitoring the driving style of the user and providing a fitting travel time.
Subsequently the deviating values regarding the influence of historical data should be removed and travel time information could be improve by the following three methods:

- The current data fusion engine only switches to real-time data when the real-time monitored travel time exceed the historical values. However the historical peaks are not suitable for periods without delay. The current algorithm could be adapted to not only take in account the current point of time and type of day, but also the season or special days (like holidays).
- Another way to prevent the deviating peaks, is not only checking whether the real-time data exceed the historical data, but also set a lower boundary. This means if during periods with reliable measurements (like during daytime) the monitored travel time is significantly lower than the historical data, TomTom should also use real-time data. This will result in presenting travel times lower than the historically expected values during peak hour periods without delays.
- A last way of improving the travel time information is increasing the use of real-time data even more. If enough bandwidth is generated, one could continuously use real-time data. Only in periods without accurate measurements, for example due to a low penetration rate, TomTom should use historical data.

8.4.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Besides the described practical recommendations to RWS and TomTom, this research also leaves several topics for further discussion or research.

- The processes of the RWS system to generate travel time information based on loop data should be further studied to analyse the possibilities to improve the presented information, like already described as task for RWS. However this recommendation is not only a task for the company, but also interesting for independent scientific research. Exploring the possibilities to use loop detector data in a different way could indicate whether theoretically known weaknesses of this type of data indeed always result in less accurate data, like some researchers claim, or that intelligent algorithms can be used to provide useful travel time information.
- Developing improved travel time algorithms will be an essential step toward high quality travel time information. Independent researchers could play an important role in bringing different data sources together. Each traffic information provider has its own data source and claims to have the most accurate data, however a critical and fresh look on all those data could be really useful to determine how the strengths of the sources could be combined in one algorithm.

- The current travel time information providers are highly focused on data and do not use traffic theory. Simple relations between the performance of a road (i.e. capacity), the monitored flow (i.e. intensity) and the restricting speed limits could provide more insight in the performance of the network and travel times of the routes. For example the known behaviour of a shockwave will be useful to calculate or predict a travel time more accurately.
- This research studied the quality of the travel time information based on the technological characteristic of the systems and measured the accuracy of the presented information. However the relation between the human behaviour and the quality of the information was not included. This leaves an important question whether these information is really used by the driver and to what extent this information improves the traffic flow. This is a challenging subject for further research.
- At last, this research has started to compare real-time travel time information to historically monitored travel times, experienced by TomTom users. A more extensive research could be executed if more historical data was available. In this way the performance of the information providers can be measured more precisely. Furthermore, it could feed the discussion about the quality of different traffic data sources and might give an answer to the complex question of which travel time is the ground truth.

8.5 DISCUSSION

The results of this research a carefully generated and precisely described, however despite this effort there could be place some remarks at the final results. This section therefore describes the known weaknesses of the executed research.

8.5.1 POSSIBLE SOURCES OF INACCURACY

This research validates the quality of travel time information services by accuracy of the travel times. The following sources of inaccuracy could indicate the weaknesses of these comparisons.

- The configuration-files of RWS describes which measurement/road sections are included in a certain route. However because not all sections are completely included a complex system is created to aggregate the right amounts of travel time. Furthermore the system contains a chain of processes, each with his own configuration-files and output. It appeared to be difficult to get the right configurations, therefore this is a possible source of error.
- Errors in the used data could suggest malfunctions of the monitoring system, however could also be caused by downloading/extracting the data from the RWS databases. Especially errors in non-RWS data, like D4T/NDW data, could not directly be addressed to misses of the measurements but are possibly be caused by the RWS database.
- Limited documentation about RWS leaves black boxes to the precise operation of the calculation method. Only the MoniBas calculations, containing the conversion of speed data to travel times, is well documented. The used method of TREFI and CDMS are however not exactly known.
- The data fusion used by TomTom remains the company's secret. Although due to the cooperation with the company and the data analysis, it became clear that historical data has a strong influence at the final presented travel time.

8.5.2 LIMITATIONS OF THIS RESEARCH

Since this graduation research has a limited scope, the following limitations should be known.

- A data analysis is restricted by the selection of a time period and a number of routes. Since real-time data is collected, the number of congested days or incidents is unknown in advance. This leads for example to only a few congested days at scenario 3. If more time were available, the data collection process could be executed earlier to ensure a significant number of days for all categories.
- Since TomTom HD Traffic is a real-time product which is not standardly collected, the data collection tasks require a lot of time. Furthermore, because the data analysis started direct after the data collection only the TomTom HD Traffic was available. Historical data is collected in the months afterwards, especially since not all TomTom navigation systems are connected devices. Therefore reference data is not available in all scenarios. However the trend of the first two scenarios is expected to be illustrative for the overall performances of the systems.
- Travel time information could be very accurate, i.e. correctly calculated to seconds. However the interpretation of humans could strongly differ from the presented information. Especially waiting could be experienced longer than the real time. Next to that most drivers do not consciously monitor their travel time. This is certainly the case for roadside information, since the passing time is very short. A driver should notice the travel time on the DRIP, look at the current time, and check at the destination point whether the presented time was correct. Furthermore this destination point, mostly an interchange, is not a clear location.
- The reasons of precise peaks of travel time are not known. This research focuses on the travel time information provided to the driver and does not completely explore the quality of the pure data measured by TomTom and RWS. Therefore the reasons for deviations are not precisely directed to individual deviations. However the qualitative analyses do provided clear suggestions for explaining those differences.

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Appendix 1 Literature review on Variable Message Signs

EFFECTS OF TRAFFIC INFORMATION ON VMS

Like described in the Introduction, chapter 1, the effects of traffic information of VMS depend on the content of the messages and the response of drivers. The latter will be elaborated in Appendix 1, since this is more a human behavioural subject. The first subject is strongly related to travel time information, because this is part of general traffic information. Earlier outcomes of researches will be described to create an overview of key factor, subsequently the effects of traffic information provision on VMS are presented.

CONTENT OF THE MESSAGES

"Message content is an important control variable for improving system performance", conclude Peeta, Ramos & Pasupathy (2000) after their stated preferences study to the relation between VMS messages and driver route diversion rates. In order to understand or improve the VMS system, this section describes the current knowledge regarding content of VMS messages.
One of the first researches to the content of messages is performed by Bonsall & Palmer (1995) who designed a route choice simulator experiment in Scotland and Denmark to measure the effectiveness of messages on VMS. They found the following key factors; clarity of the message, size of the implied diversion, distance between the VMS sign and the incident, inclusion of information about the extent of the delay and familiarity with the network. Wardman, Bonsall & Shires (1997) studied the impacts of different messages and mention that additionally delays are preferred instead of normally expected travel times with ratios depending on the delay. Next to that the cause of the delay is important; delay related to accidents has the biggest impact on the route choice, while delay without any cause mentioned has relatively low effect. The authors suggest that motorists might be sceptical about travel information and may think that traffic authorities use delays in order to influence the traffic flow, which not necessary means an optimal trip for an individual driver, however that the message can be trusted if the cause is known. Also visible confirmation of the message by queues ahead lead to an increase of the impact, especially for experienced drivers and those who are critical about the reliability of the VMS information. Emmerink, Nijkamp, Rietveld & Van Ommeren (1996) studied the effects of a VMS in the Netherlands and state more drivers will divert if the alternative route is still on the freeway and has a distance comparable to the original route. Peeta, Ramos & Pasupathy (2000) showed that if the level of detail in the provided information increases, also the willingness to divert increase. For example, when messages combines location of accident, expected delay and best detour, the diversion rate is higher than when the message only contains one of those elements. Xu, Sun, & Hao (2011) studied traffic data of Shanghai, China and their results indicate that "drivers are more sensitive to travel time information than traffic congestion information". Other factors that significantly influence the diversion behaviour are off-ramp conditions and visibility of downstream congestion.

EFFECTS ON ROUTE CHOICE AND TRAVEL TIME

Road networks offer users a multiplicity of possible routes connecting each origin-destination pair. However even for drivers who are familiar to the network, selecting an optimal route is difficult, caused by i.e. changing traffic conditions, roadworks and weather conditions (Mammar, Messmer, Jensen, Papageorgiou, Haj-Salem, & Jensen, 1996). Therefore actual on-route travel information on VMS can potentially influence route choices (Wardman, Bonsall, & Shires, 1997). The shift of drivers to an

alternative route could lead to improved performance of the network (Erke, Sagberg, & Hagman, 2007). The traffic is distributed among all possible routes and congestion is reduced. In this way route information is useful for traffic management. The traffic manager could use route information to control the traffic flows and improve the traffic conditions towards a system optimum.
However the effects of VMS on route choice depends strongly on the response of drivers. The travellers' behaviour result in moderate effects of route diversion. Chatterjee & McDonald (2004) studied VMS in nine European countries and found an average divert rate of 8%. Horowitz, Weisser, & Notbohm (2003) analyzed the diversion to an alternative route during roadworks and measured that 7-10% of the traffic changed their route. Foo & Abdulhai (2006) studied the introduction of 17 VMS in Toronto, Canada and found a diversion rate around 5%. Higher diversion rates are found by Ramsay & Luk (1997). In their research the messages contained road closure which lead to 33% more traffic on the alternative route. Erke, Sagberg & Hagman (2007) studied also the effects when a road closure occurs, their results show that 20% of the drivers followed the suggested route. Chatterjee, Hounsell, Firmin & Bonsall (2002) found out that drivers assess the information provision as useful, but that only a few driver actually divert.
No researches were found which measure the effects of VMS information in changes of travel times. Probably, the calculation of effects on travel time are difficult due to complex traffic processes, especially in congested conditions. (Van Lint, Hoogendoorn, & Van Zuylen, 2005). Logically, diverting to a route with a smaller travel time will reduce the individual travel time and an improved distribution of traffic in the network will improve the total network travel time.

RESPONSE OF DRIVERS

The impact of advanced traveller information systems (ATIS) on travellers' decision-making behaviour can be distinguished in four factors: (1) drivers' socioeconomic characteristics (such as age, gender, driver familiarity with the network), (2) drivers' attitudes and perceptions (such as drivers' risk preferences, perceived usefulness of VMS), (3) information characteristics, (4) trip characteristics (such as trip purpose and departure time) (Tsirimpa, Polydoropoulou , & Antoniou, 2007; Kattan, Nurul Habib, Tazul, & Shahid, 2011). For the response on VMS, the third category contains characteristics of VMS, i.e. content of the messages and location. Additionally to those factors also the network characteristics, congestion levels and road weather conditions influence the response (Kattan, Nurul Habib, Tazul, & Shahid, 2011). Due to the interaction between all those variables, the effects of VMS measures are difficult to explain.
The factors that influence travelers' decision making are included in many researches. In the following sections an overview of the results will be given for each factor. Regarding characteristics of VMS (third category), the content of the messages is already described in the section 2.2.1. Therefore the third category is skipped in the elaboration.
Next to that two different information strategies can be used: Prescriptive information suggests one alternative route as a strict advice. Descriptive information provides choice options and the driver should decide which route is the best option. Furthermore the presented information could contain congestion kilometers, travel times, alternative routes, weather conditions, roadworks, closed roads, etc.

DRIVERS' SOCIOECONOMIC CHARACTERISTICS

Emmerink, Nijkamp, Rietveld & Van Ommeren (1996) argue that women are reluctant to be influenced by traffic information than men and that the information has less effect on commuters than on drivers with other purposes. Peeta, Ramos & Pasupathy (2000) confirm the differences between male and female drivers based on a stated preference study and logit models and also show significant differences related to age, education, income, technology and mode use. Drivers younger than 40 years are more likely to divert compared with older drivers. Drivers with a high education level, and consequently which a high income and high level of comfort with technology, show greater compliance to VMS than low educated ones. Non-truck drivers divert more easily than truck driver, because routes which are accessible for non-truck drivers may not be feasible for truck drivers.

DRIVERS' ATTITUDES AND PERCEPTIONS

Bonsall & Parry (1990) conducted interviews and group discussions about the usefulness of a route guidance system based on traffic data. The respondents react reticent; they find it hard to believe that the system could select a better route than they themselves. The authors mention this as strong implication for traffic control. Trust of the driver could decrease even further, since the advice is built on a system optimum instead of a user optimum. Next to that the research shows that the drivers are mainly interested in minimization of travel time. Emmerink, Nijkamp, Rietveld & Van Ommeren (1996) state if person is influenced by radio traffic information, he is more likely to be influenced by VMS traffic information. Kattan, Nurul Habib, Tazul, & Shahid (2011) also recognize the correlation between responding to information displayed at the VMS and seeking information between other sources, i.e. TV or traffic radio. Chatterjee, Hounsell, Firmin & Bonsall (2002) studied the effects of the introduction of traffic information on VMS in London. The respondents assess the traffic information as useful, but only a small amount of them changed their route. Furthermore the number of diversions in real traffic situation is lower than the expectation based on the survey data; drivers are exaggerating their responsiveness. Zhenlong & Chonglun (2011) conclude that the driver can constantly learn and accumulate his experience with VMS information and analyze the payoffs from the recommendation after every decision making. If the driver follow the recommendation, but it seems to be wrong, this will result in a decreasing payoff. The VMS systems should make a positive first impression and the payoff to accept the recommendation should be positive and as large as possible.

TRIP CHARACTERISTICS

Emmerink, Nijkamp, Rietveld & Van Ommeren (1996) mention flexible arrival time as a factor in willingness to divert. A person who has the ability to arrive later is less likely to change his route. Mahmassani & Lui (1999) studied advanced traveler information systems in general and conclude commuters will tolerate greater scheduled delays if they recently encountered an increased travel time as result of a small change in departure time. Commuters switch their routes when high difference occur between preferred and predicted travel times and prefer an earlier arrival time instead of a delayed arrival. Drivers are more willing to switch routes based on under-estimated travel times than on over-estimated travel times. Xu, Sun, & Hao (2011) show that period of the day also influences the diversion rate. During morning peak hours the willingness of drivers to change their routes is high. Most of the drivers are commuters who are familiar with the network and would prevent delayed arrival at work. In other time periods the number of home-work trips is lower which results in a reduced response.

Appendix 2 Traffic Data sources

Different technologies are available for traffic monitoring. Traditionally, loop detectors are used to measure traffic flows and provide real-time traffic information. Newer technologies uses Floating Car Data (FCD) based on Bluetooth detection, cell phone or GPS data. These systems will be described in this chapter. Other technologies, number plate recognition and passive infrared detection, are shortly elaborated in the end.

LOOP DETECTOR DATA

An inductive loop is a wire embedded in the surface of the road. A signal is created by a vehicle passing the inductive loop; the metal object causes an electrical current by change of magnetic field. A dual loop enable the possibility to measure not only intensities, but also speeds. The known distance between the two loops can be divided by the difference in time (moment of activation of both loops). Loop detectors are widely used for traffic monitoring and relatively cheap to produce and install. Since the loops are integrated into the road, deterioration of the road can impair the loops, for example caused by heavy vehicles or high traffic loads. Maintenance cost are an important disadvantage, especially because those roadworks often require road closures (TU Delft , 2006).

BLUETOOTH DATA

Mobile phones, GPS units, computers, in-vehicle navigation systems and comparable electronic devices uses Bluetooth technology for short-range communication. For example, Bluetooth is used to connect a mobile phone to a car kit system for hands-free dialling during a car trip. Since each Bluetooth device has his own Media Access Control (MAC) address, this technology can be used to measure travel time and speeds. Readers are installed along the roads for data gathering. When an active Bluetooth device passes a reader, this reader logs the MAC addresses, location and time. When the same device will be detected by another reader the travel time between those two point can be calculated. If the distance between those two points is known, also the average speed can be derived. This data of an individual car is however not enough for traffic information. Data of multiple cars should be combined, and also multiple roadside units should be installed to be able to calculate an average speed and travel time per road segment. Next to that the penetration rate of Bluetooth devices is highly important. The number of equipped vehicle should be significant; a low number of vehicles could result in a low accuracy of the calculated speed and travel time.

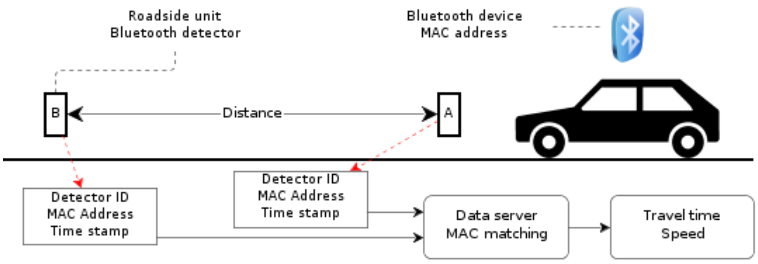

Figure 89 Bluetooth detection system

MOBILE PHONE DATA

The cell phone networks contain multiple base stations which all serve a network cell. In rural area these cells may have a radius of a few hundred meters in cities and a few kilometres in rural areas. In order to select the nearest base station, the location of the phone is frequently checked. If the distance to the phone exceeds a threshold, the active base station hands off the connection to another base station to ensure a good connection to the mobile phone network. The data of this handover, including location data, is logged (Wilson, 2005). However the handover procedure requires a quite low accuracy of 500 meters in a large cell and 100 meters in a small cell. Another limitation of the cell phone location method is the strength of the signal. Buildings, trees and other objects could disturb the signal which causes an attenuation, unknown and different for each phone, and result in large errors. Two methods could be applied to improve the accuracy of this data source (Wunnava, Yen, Babij, Zavaleta, Romero, & Archilla, 2007). Firstly, the Time of Arrival (TOA) method use the travel time of the signal from phone to base station. The distance can be calculated based on the known velocity of the signal through the medium. Furthermore, triangulation method combines the signals of three base stations and improves the accuracy of the location. The accuracy of this method is about 50-200m. Secondly, the Angle of Arrival (AOA) method requires directional antennas or antenna arrays. Two base stations are needed to determine the position of the cell phone. The accuracy of this method is about 50-300m.

GPS DATA

A currently well-known localization method is Global Positioning System (GPS). A GPS receiver, embedded in a navigation system, smart phone of specifically installed in the vehicle, uses signals from at least four satellites to determine the vehicle’s position. To improve the accuracy the differential GPS (DGPS) uses a differential correction station; a fixed signal from a tower on the ground. To use the GPS data for traffic monitoring, the data should be matched to a map with the road network. Depending on the source of GPS data, the data should be filtered to ensure only car users are included.

NUMBER PLATE RECOGNITION AND PASSIVE INFRARED DETECTION

Other technologies to monitor traffic are automatic number plate recognition (ANPR) and passive infrared (PIR) detection. The first method uses cameras, located above the road, which are able to recognize number plates based on mathematical algorithms and pattern recognition. Intensities could be measured by simply counting the passing number plates, however more comprehensive systems could also calculate travel times by combining data from different cameras on a route. The second method, PIR detection, uses a comparable technology. Infrared radiation is invisible for the human eye. Passively means the detector does not emit an infrared beam but receives the radiation of the passing vehicles. Detectors located above the lanes will count the amounts of traffic and more complex systems can also derive travel times from this data.

Appendix 3 Evaluation criteria

Wang & Strong (1996) designed, based on two surveys among data experts, an indicator framework to assess data quality. In the table below the indicators are summed up and shortly elaborated. Some of them will be used in a qualitative description of the travel time services.

	Data quality indicators of Wang & Strong (1996)	*Considerations regarding the selection*
Intrinsic data quality	**Believability** Believable **Accuracy** Error free, Correct, Reliable, Precise **Objectivity** Unbiased, Objective **Reputation** Reputation of the data source, Reputation of the data **Variety of data sources** Data and data sources	The main focus of this research is on accuracy. Therefore these intrinsic data quality indicators are important. However there seems to be overlap between the defined parameters, for example error free versus unbiased. Therefore most of the characteristics are included in the indicator accuracy. Since data sources are quite important to estimate the differences between the travel time systems, the variety of data sources (part of the initial frame work of Wang & Strong (1996)) will be added.
Contextual data quality	**Value-adding** Data add value to your operation **Relevancy** Applicable, Relevant, Interesting, Usable **Timeliness** Age of data **Completeness** Breath, Depth and scope of information **Appropriate amount of data** Amount of data	Quality of travel time information in a driver point of view will mainly be on the usefulness. The car driver needs information which support his decision making process. Therefore the information should be relevant to his situation and on time, since fast decisions are needed in a dynamic situation. Relevancy seems to cover these situation the most. Supplement by timeliness, since time is a major aspect in the provision of actual or predicted travel times.
Representational data quality	**Interpretability** Interpretable **Ease of understanding** Easily understood, Clear, Readable **Representational consistency** Same format, Consistently formatted, Compatible with previous data **Concise representation** Well presented, Compactly presented, Form of presentation, Format of data	These indicators focus on the human behavioural side of information provision. A good presentation is essential to transfer the information and remain the meaning of the content. Since people are different, the information could be misunderstood or wrongly interpreted. However this research is limited to the technology related characteristics and excluded this side of quality of travel time information.
Accessibility data quality	**Accessibility** Accessible, Retrievable, Speed of access, Available, Up-to-date **Access security** Not access by competitors, Data are of a proprietary nature, Access to data can be restricted	A driver mainly needs actual information about the traffic situation on-route. Therefore the accessibility of the travel time information is important. Access to the data is the basis requirement for using the information. Security might be important for the services provider itself, but not for the car driver.

Papageaorgiou et al (2007) have defined eight factors to characterize Route guidance and information systems (RGIS):

- Basis of guidance: This divides nonpredictive and predictive systems.
- Local/area wide focus: A local focus provide information about a small network element, for example a road segment or junction. An area wide focus provides guidance throughout the whole network.
- Transmission range: This characteristic determines the location(s) where the information can be receive, for example line-of sight or wide area.
- Collective/Individual dissemination: This characteristic also focusses on the scope of the system. Collective dissemination delivers information to all drivers, for example VMS along the route shows information for all road users. Individual dissemination requires special equipment to receive the information, for example in-car navigation system to receive traffic information via TMC or cell phone connection.
- One way/two way communication: This explains whether the user is interacting with the system or not. One way communication is simple system which sends information without any input or feedback of the drivers. Two way communication is used to estimate user preferences or trips specifications, before providing specified information, and/or afterwards receiving data of the user to estimate travel times and improve traffic predictions.
- Pre-trip/ en-route access to guidance: This characteristic determines the accessibility of the information based on time. En-route information may influence route choices, pre-trip information potentially influence also mode choice, time of departure, destination.
- Message dissemination and guidance update intervals: Message dissemination interval is the period of time in which the content of the information remains unchanged. The length of this period depends on technological and human factors. Guidance update interval is the period between two computation runs to formulate the content of the messages.
- Messages design: This characteristics divides the systems based on the syntax and semantics of the messages, for example prescriptive/descriptive, or visual/audio information.

Appendix 4 Inaccuracy of trajectory-based travel time methods

A commonly used travel time estimation is the indirect calculation of the speed trajectory method. This method can use online or offline loop detector data and derives a travel time by interpolating the measured speed. Despite of the high density of loop detectors, the accuracy of this method is criticized. Soriguera (2010) expresses his criticism about speed interpolation methods, like piecewise constant, linear or quadratic interpolation. "None of the advance methods face the key issue of the problem: where the transition (from flow to congestion) occurs within the link. The proposed mathematical interpolations are blind to traffic dynamics, and hence still prone to errors, as they locate the traffic state transitions according the whims of the mathematical functions. The improvements in travel times obtained by considering detailed trajectory of the vehicle within the transition are negligible when compared to the benefits of accurate estimation of the location of the transition at each time period" (Soriguera , 2010, p. 116). He underpins his statements with empirical evidence from an experiment on a close toll freeway. The ground truth derived from automatic vehicle identification (AVI) of control points of the tolling system is compared to different trajectory methods. The results, shown in Figure 90, indicate good performances during free flow conditions, however significant errors occur during congestion. "All method are not accurate enough when congestion spans for the whole stretch" (Soriguera , 2010, p. 127).

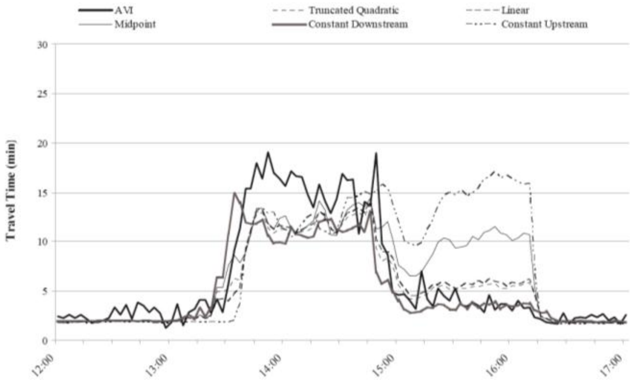

Figure 90 Comparison of measured travel time (AVI) and results of interpolation methods of spot speed (Soriguera , 2010, p. 125)

Sun, Yang, & Mahmassani (2008) also tested different trajectory-based travel time methods and found that the results are "similar during free flow condition but significantly different during transition flow and congestion conditions". Furthermore they performed an experiment to observe travel times based on three cameras and probing vehicles. The observations used as ground truth indicate significant relative errors of the tested trajectory methods, like shown in Figure 91.

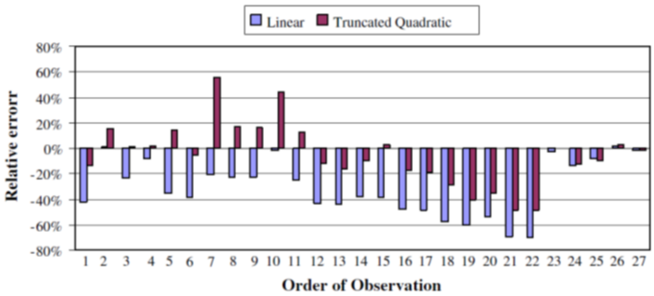

Figure 91 Relative error between observed travel time and linear and truncated quadratic speed trajectories (Sun, Yang, & Mahmassani, 2008)

Appendix 5 Travel time measurements of VerkeersInformatieDienst

The VerkeerinformatieDienst (VID) provides traffic information via multiple media. Traditional presentations of congestion information are given via radio and television bulletins. Next to that the VID has a website, offers raw data services to other websites, operates a cell phone service (information number) and emits information via the Traffic Message Channel (TMC) (VID, n.d. c). This latter contains two products VIDBASIS (congestion information on freeways) and VIDEXTRA (including rural roads, roadworks and speed monitoring). Due to the cooperation with Garmin and Mio, the VIDEXTRA information is used as input for their navigation systems. Via these media the VID reports disturbances of the traffic conditions, including congestion lengths and delay time. Notice, if the traffic is undisturbed and in free flow condition, no information is provided about this link.

Besides these multiple costumer services the VID focuses on dynamic traffic management services for the business sector. Travel time measurements on specific routes are delivered to companies, i.e. to a contractor in case of roadworks. The contractor can use this data to measure the delay in order to improve his operations and/or offer extra information to road users about the actual travel time (like the VMS in Figure 92). For this purpose the VID has developed innovative traffic monitoring based on video cameras, automatic number plate recognition (ANPR) and Bluetooth detectors. This latter will be elaborated in the following section.

Figure 92 Travel time information on VMS on rural road (left) and freeway (right) operated by VID (VID, n.d. d)

BLUETOOTH DATA

Since 2010 the VID installs VID Bluetooth Measurement instruments (VBM) to monitor traffic flows on the Dutch road network (VID, n.d. b). The Dutch National Data Warehouse for Traffic Information (NDW) has tendered an important project to the consortium Data4Traffic, including VID as member. This project includes the installation of 1.000 SWARCO iTravel traffic data acquisition systems, which combines Bluetooth and passive infrared traffic detectors (Swarco, 2011).

Bluetooth detectors monitor the traffic flow by logging passing active Bluetooth devices, like mobile phones, GPS units, computers, in-vehicle navigation systems, etc.. These electronic devices use Bluetooth technology for short-range communication. For example, Bluetooth is used to connect a mobile phone to a car kit system for hands-free dialling during a car trip. Since each Bluetooth device has his own Media Access Control (MAC) address, this technology can be used to measure travel time and speeds. When an active Bluetooth device passes a reader, installed along the road, this reader logs the MAC address, location and time. When the same device will be detected by another reader the travel time between those two point can be calculated. If the distance between those two points is known, also the average speed can be derived. The individual travel time of one vehicle is not enough to produce accurate travel time information, therefore the penetration level of active Bluetooth devices is highly important. Data of multiple cars should be combined to calculate an average speed and travel time per road segment. Also more detectors (between the start and end point) could improve the data and provide insight into the speed distribution along the route. The number of equipped vehicle should be significant; a low number of vehicles could result in a low accuracy of the calculated speed and travel time.

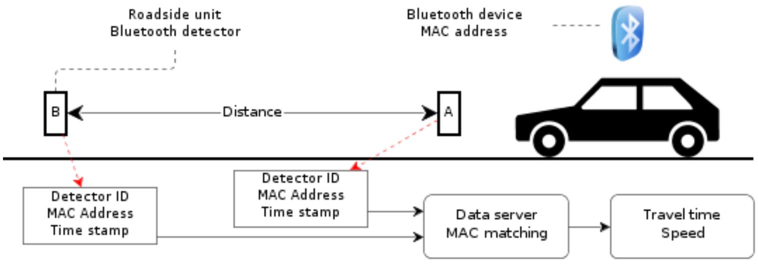

Figure 93 Bluetooth detection system

TRAVEL TIME CALCULATION

The travel/delay time calculation is currently unknown. However the VID mention at their website that the delay times are always somewhat out-dated and do not contain any predicting value (VID, n.d. a). This could be explained by the operation of Bluetooth detection based traffic monitoring; the data contain offline travel times since the travel time is known after the vehicle have passed the second detector. Next to that the current documentation tells the used models contain stability factors to improve the robustness of the provided information. In traffic conditions with rapidly growing or decreasing congestion these stability factors counteract an accurate delay time calculation (VID, n.d. a). Notice the similarity with the disadvantage of instantaneous travel time prediction, described in chapter 2.

Appendix 6 Error-files RWS

To monitor the performance of the loop detector system, RWS makes error files which present the availability of data for each measurement point. The performance indicator expresses the number of minutes the loops produce traffic data (relative to the total amount of minutes in a day). Notice this indictor only measures whether a loop is active and does not evaluate the quality of the provided data. In **Fout! Verwijzingsbron niet gevonden.** the performances of the loops on the selected routes are presented (an average of all loops at all days of the studied period). The low quality of the low density of loops at the A28 (scenario 1) and the two roads with road works (A28, scenario 1; A12, scenario 4) are clearly visible.

Table 6 Performances of RWS loops

Scenario	0		1		2		3			4
Road	A28	A28	A28	A27	A12	A20	A4/A12		N11	A12
Performance indicator [%]	74,7	75,0	75,6	95,2	96,5	98,9	92,4	98,0		75,6

Appendix 7 Overview of MATLAB scripts

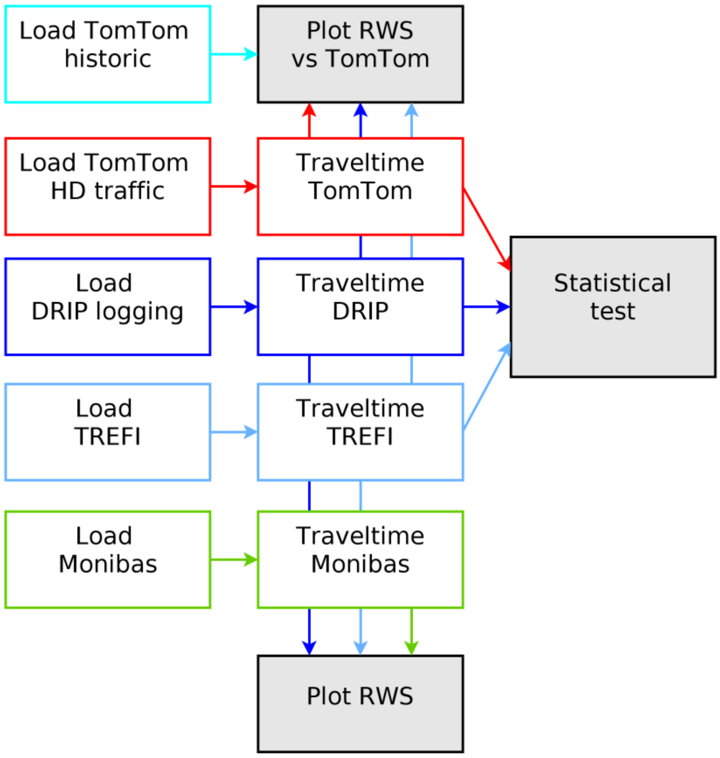

Figure 94 Overview of MATLAB scripts

Load-script

This script is used to convert the raw data (text- and excel files) to MATLAB files. Of every data sources both the travel time data and the timestamp data is loaded. To improve the loading speed this script does not make adaptations to the data nor preform any calculations.

Travel time-script

The converted data is used in the travel time script to generate a travel time of the studied route for the whole period. For the TomTom and DRIP data this means no calculations are necessary, since the travel time data does already contain a route travel time. For these source only some checks are ran to scan for missing or corrupt data.

Statistical test-script

This script is used to compare the data and calculate differences in travel times of TomTom and RWS. The first part of the script divides every day in periods of free flow, increasing and decreasing congestion. The script searches for delay in the travel time data of RWS based on the following requirements

- *Delay is present and not present in previous second*
  This rule indicate to transition from free flow to congestion
- *Delay remains for at least 300 seconds*
  This rule prevent every small adaptation of travel time is interpret as a peak.
- *Delay peak becomes bigger than 60 seconds in the following 500 seconds*
  This rule checks whether the travel time is seriously increasing or just slightly adapted.

Because during some days the travel time during daytime is varying between 0 and 1 minute delay, a peak could also start after a long period of only 1 minute of delay. The following rules are added to recognize this type of peaks.

- *Delay of the previous 1000 seconds was 60 seconds*
  This rule looks back in time to check whether the travel time was stable and slightly increased.
- *The current growth of delay is more than 50 seconds*
  This rule confirms whether the current growth is substantial.
- *Delay peak becomes bigger than 100 seconds in the following 500 seconds*
  This rules looks forward and checks whether there is a serious peak.

After defining the boundary of free flow and congestion peaks, the script creates three types of days. And uses the mode minimal travel time of all days in the database as standard free flow time.

- Free flow day: The maximal travel time of a day is smaller than or equal to 1,25 times the defined free flow time.
- Medium congested day: The maximal travel time of a day is smaller than or equal to 2 times the free flow time.
- Heavy congested day: The maximal travel time of a day is bigger than 2 times the free flow time.

Subsequently, the calculations for the MAPE and student t-test are performed a several times. Firstly, for all type of days including the complete 24 hour dataset. Secondly, for the medium congested days distinguishing free flow, increasing and decreasing congestion conditions. Thirdly, the same calculations are ran for the heavy congested days.
The final part of the statistical test-script generate plots for the results of the MAPE and t-test and an excel-sheet with the numerical results of the test.

Plot-script
This script generates a plot for every day in the studied period. The figure standardly contains the DRIP travel time, DRIP updates, TREFI measurements of RWS and the travel times of TomTom HD Traffic. The DRIP update data does not contain travel time data, but indicate when a new message is presented at the DRIP. In this way for example detour or motto messages could be easily recognized. For some scenarios the plot could also contain TomTom GPS historical data, Bluetooth data of D4T or VID or an error dataset. This latter indicates when a specific data sources is malfunctioned and produce no or unreliable data.

Appendix 8 Confidence intervals of congested days

Chapter 6 already showed the confidence intervals for the 24hour-periods of all three types of days, however this appendix presents the figures for the periods of free flow, increasing and decreasing congestion during medium and heavy congestion. Hereby the differences between TomTom and RWS instantaneous travel times could be studied in detail.

Additional results at scenario 1

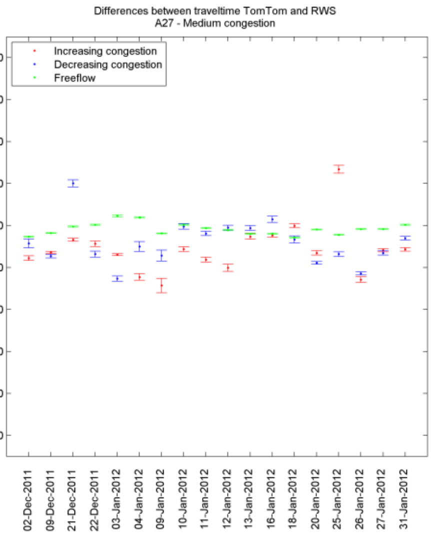

Figure 95 Confidence interval of t-test during medium congestion, A27

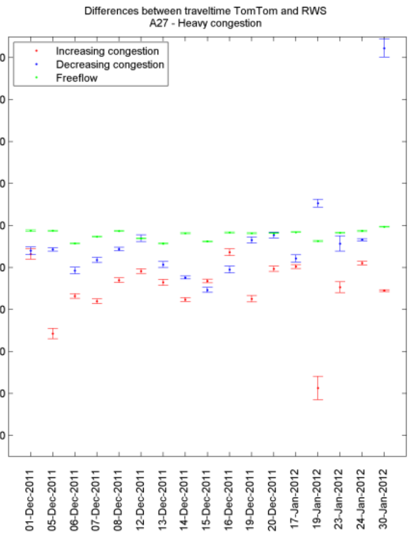

Figure 96 Confidence interval of t-test during heavy congestion, A27

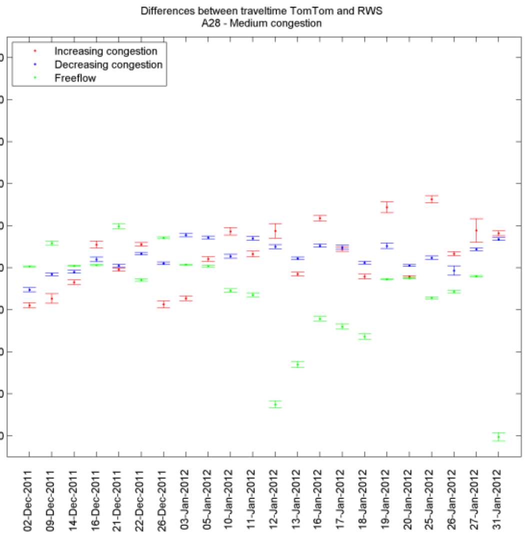

Figure 97 Confidence interval of t-test during medium congestion, A27

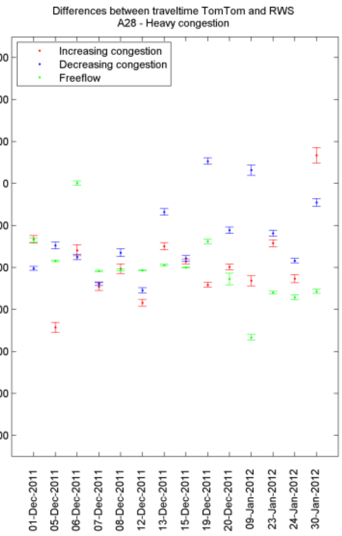

Figure 98 Confidence interval of t-test during heavy congestion, A28

Additional results at scenario 2

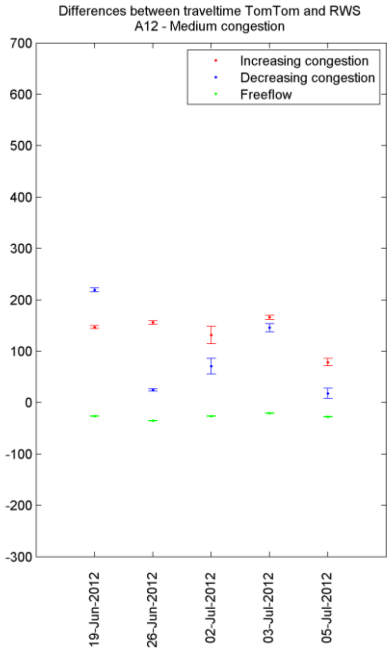

Figure 99 Confidence interval of t-test during medium congestion, A12

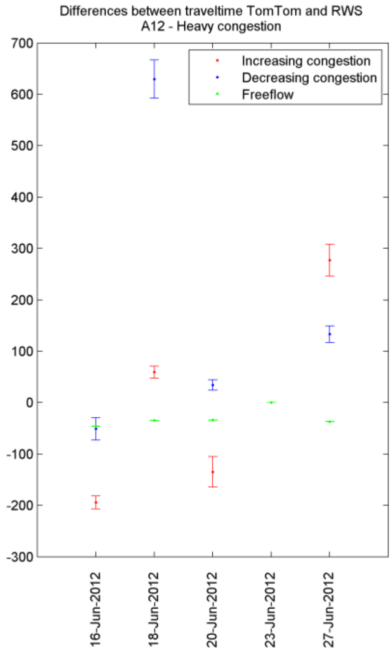

Figure 100 Confidence interval of t-test during heavy congestion, A12

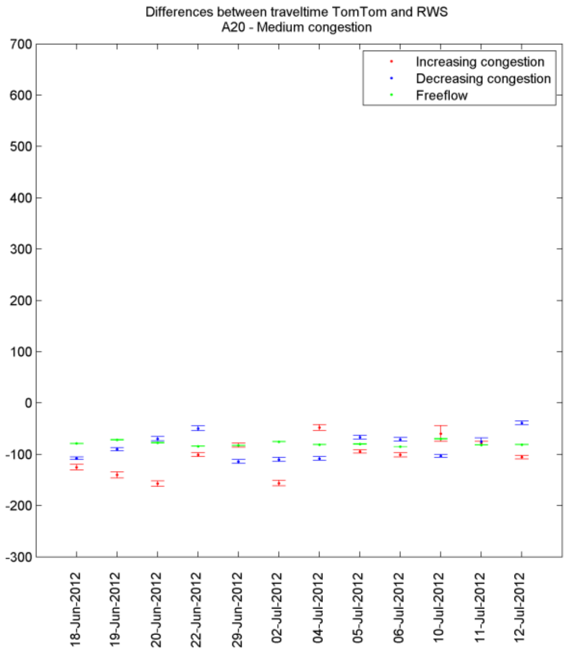

Figure 101 Confidence interval of t-test during medium congestion, A20

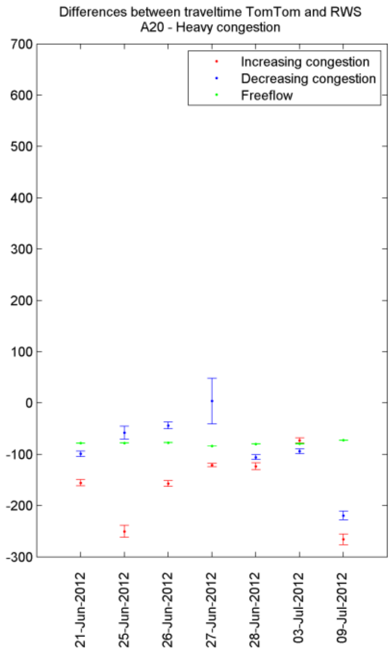

Figure 102 Confidence interval of t-test during heavy congestion, A20

Additional results at scenario 3

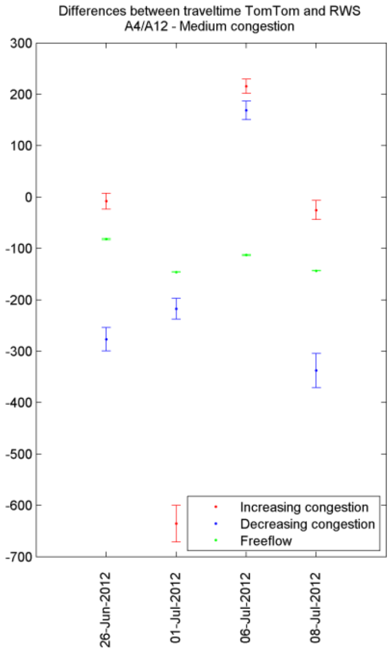

Figure 103 Confidence interval of t-test during medium congestion, A4/A12

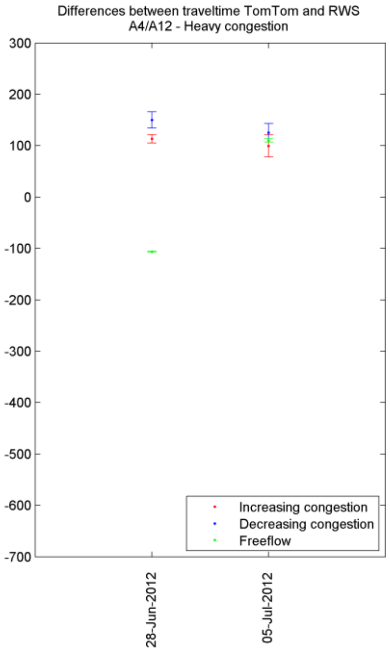

Figure 104 Confidence interval of t-test during heavy congestion, A4/A12

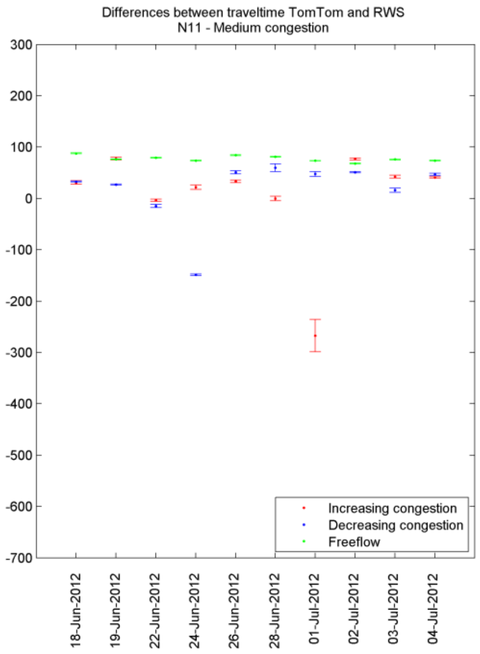

Figure 105 Confidence interval of t-test during medium congestion, N11

Additional results at scenario 4

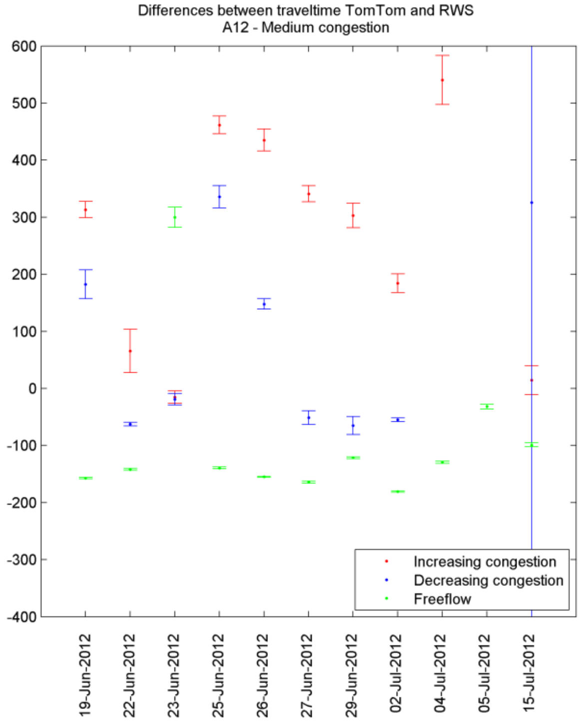

Figure 106 Confidence interval of t-test during medium congestion, A12

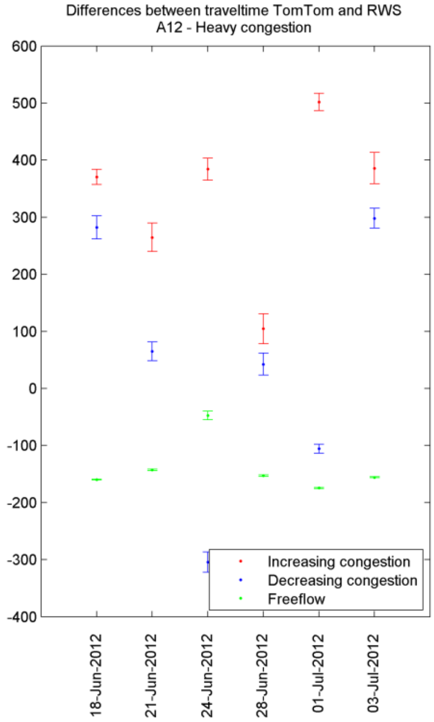

Figure 107 Confidence interval of t-test during heavy congestion, A12

Appendix 9 Plots of all studied days

Since the data analysis studied a high amount of days and only a small number of plots could be included in this report, an electronic appendix is generated which contains all results. The figures are sorted by scenario and type of day. In this way, the results could be verified by studying all results and detailed study of the differences is possible. The plots could be downloaded by the following link:

http://dl.dropbox.com/u/2930586/Electronix%20apendix_plots%20of%20all%20days.zip