

Navigating for new traffic solutions

The use of probe data from consumer GPS navigation devices
for the analysis of controlled intersections

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To measure is to know. (Lord Kelvin, 1824-1907).

Preface

This thesis is the last part of my Master studies in Civil Engineering in Delft. For my graduation project the use of probe data collected from consumer GPS navigation devices for the analysis of controlled intersections is researched. The project was fulfilled as part of a graduate internship at the TomTom offices in Amsterdam. Alongside the thesis document, a research paper was written on the results of the study and was submitted under review for the TRB annual meeting 2012. The paper is titled: “Probe data from consumer GPS navigation devices for the analysis of controlled intersections” and is included in Appendix D.

I would not have been able to fulfil my master graduation project without the advice and support of my supervisors at TomTom and at Delft University of Technology. First of all I want to thank Bart van Arem for his help during the graduation project. His enthusiasm and fresh approach on traffic management inspired me throughout my work. Furthermore I want to thank my daily supervisors Peter Krootjes and Nick Cohn at TomTom and Maria Salomons at Delft University of Technology for their continuous support and innovative perspectives. I also want to thank Bart De Schutter and Paul Wiggeraad at Delft University of Technology for their advice in the graduation committee. Furthermore I would like to thank all the employees at the Traffic Solutions team at TomTom for their help during my graduation project. In particular I would like to thank Jillis Mani and Huug Bischoff for their guidance in my travels through the TomTom technology.

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Amsterdam, September 2011

Arnold Meijer

Summary

The measurement of traffic volume, route choice and driving behaviour at intersections is needed for efficient intersection control. Optimization of road geometry, intersection control and dynamic traffic management requires up to date and accurate traffic information. The greater part of intersection performance studies are comprised of evaluation of measurements from road-side detectors and loop detection. Data collection from road-side detectors can directly be used to assess the performance of an intersection but it is expensive and requires high maintenance expenditures. Loop detection delivers accurate traffic volumes but can suffer from detection errors and missing data. Continuous use of road-side detectors requires constant availability of detection equipment at the intersection, which is often not the case at uncontrolled intersections.

Recent studies using a confined dataset have shown that probe data offers great opportunities for the determination of performance at intersections but needs a certain level of penetration of probe vehicles in the network. Probe vehicle data using a large probe dataset from consumer GPS navigation devices provides an interesting alternative.

TomTom, one of the largest manufacturers of consumer GPS navigation devices in the world, has been collecting Floating Car Data since 2007. The data comprises location measurements of navigational equipment and locations of cellular devices delivering a probe dataset on a global scale. Privacy filtering ensures that drivers remain anonymous. Map-matching algorithms are used to increase the accuracy of the measurements and link the location of vehicles to the road network, producing a network-wide probe dataset.

This report presents the results of intersection performance measurement using a large probe dataset from consumer GPS navigation devices. The data is collected at two intersections which are located in the Dutch city of Delft. The measurements are compared with loop detection traffic counts and time-dependent stochastic models using input from stationary detectors.

Performance measurement at intersections

The performance of intersections is described by a Performance Index or the Level of Service principle. A Performance Index assesses traffic flows at a road element, under a minimal level of quality for the road user. In an optimal situation, actual measurements quantify the process of arrivals and departures at an intersection. Loop detectors are often used as input for performance studies at intersections. At signalized intersections the LOS distinguishes six levels of performance based on the delay at the intersection. Next to the delay other key measures of performance are saturation, queue length and stop rate.

Route choice at intersections is derived from the OD distribution which calculates the absolute (traffic volume) or relative (percentage) distribution of vehicle movements at the intersection. Delay is defined as the difference between uninterrupted and interrupted travel times through the intersection. Measurement of travel time occurs by measuring the time difference between the arrival and the departure at the intersection. The delay of vehicles at intersections is not directly assessed by traffic counts from loop detectors which, apart from a few experimental cases, only measure traffic volume. Traffic counts from loop detectors combined with traffic control device monitoring is an alternative for expensive measurement systems. In this research study a time-dependent stochastic model by Akçelik is selected which is based on the steady-state approach by Webster. The models are used for the estimation of delay, queue length and stop rate and are a generally used input for performance studies and Level Of Service assessments.

Case study results

Route choice and penetration of probe vehicles at the intersections was evaluated with a ground truth reference from loop detection traffic counts. The study shows that the system satisfies an average penetration rate of 0.5% and applies an update frequency of 1 measurement per second. Under these conditions route choice is determined with an average error per movement of 1.3 to 3.8%, mainly caused by the error at two or three movements. At the test case intersections a sample size of approximately 1000 measurements during an eight to twelve day aggregation period shows optimal results. It is concluded that increasing penetration rates show negligible results.

The most common measure of performance is the travel time delay. The results show multiple similarities to the delay of the reference model for the greater part of the crossing movements. The probe data shows more variance than the reference model which appears to be caused by a too low sample size of 7262 observations at intersection 1 and 12980 observations at intersection 2 during the three month observation period. Smoothing filters clarify trends in the data but lower the level of detail reducing some of the peaks by 60%. It is concluded that depending on the purpose of a study, smoothing should not be used to avoid data

loss. It is also concluded that increased penetration rates result in a smaller variance.

The greatest deviation for the delay is measured during congested situations (rush hour periods) and for periods with a very low traffic demand (night time) which can lead up to differences of 20 seconds. Reference studies and the results support the conclusion that the accuracy of delay time measurement is higher for probe data than for the time-dependent stochastic delay models during congested situations.

The deviation measured during night time is caused by a difference in the calculation of delay. The reference model takes into account a minimal delay at low traffic demands (saturation <0.1) which was not included in the probe data delay. The automatic inclusion of intersection layout etc. reduces the amount of manual labour required to calculate the delay for network-wide traffic studies.

The delay of probe vehicles appears to be normally distributed for individual vehicle movements. The results indicate that the probes are randomly distributed amongst traffic, which is beneficial for the use of the data in traffic models.

It is concluded that measurement of queue length and stop rate with the probe dataset is not possible for application in performance measurement. A preliminary for measurement of queue length and stop rate with probe data is a penetration rate above 40%. Furthermore the segment lengths in the digital roadmap reduce the accuracy of the data which is unbeneficial for queue length and stop rate measurement.

The final conclusion is that probe data from consumer GPS navigation devices provides an accurate and reliable data source for selected performance studies. The probe data provides an accurate measurement method for route choice and travel time delay but queue length and stop rate are not derived from the data. Although it is not possible to determine all measures of performance, the calculation of delay provides a valuable input for Performance Index and Level Of Service assignments. With the current level of penetration the data does not enable performance measurement for individual cycles and the data is only available for studies over longer time periods. With practically no malfunction rate and the ability to measure travel times, probe data from consumer GPS navigation devices provides an added value for traffic studies at any intersection.

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Notation

ATMS	:	Advanced Traffic Management Systems
FCD	:	Floating Car Data
GLONASS	:	GLObal Navigation Satellite System
GPS	:	Global Positioning System
HCM	:	Highway Capacity Manual
ITS	:	Intelligent Transport Systems
LOS	:	Level Of Service
NAVSTAR	:	NAVigation Signal Timing And Ranging
OD	:	Origin Destination
PCU	:	Passenger Car Unit
PDA	:	Personal Digital Assistant
PI	:	Performance Index
PND	:	Portable Navigation Device
RVV	:	Reglement verkeersregels en verkeerstekens
TCD	:	Traffic Control Device
VRI	:	Verkeer Regel Installatie (Traffic Control Device)

Chapter 1

Introduction

Since the start of this century travellers are able to use in-car GPS navigation to help them with their route navigation. Specialized software on a PDA and a GPS receiver makes it possible for road travellers to plan their routes using real time location data. Software using choice models and route algorithms makes it possible for every driver to plan the quickest, the shortest or even the most fuel efficient route based on their current location.

When TomTom released a standalone Portable Navigation Device (PND) in 2004, route navigation became accessible for everyone. Consumers noticed the advantages of navigation devices for their travels and the demand for navigation devices grew substantially during these years. A recent survey shows that in the year 2010 36% of the drivers in Europe regularly use a PND and almost 60% regularly use embedded navigation equipment (Navteq, 2011). New developments of embedded navigation equipment and phone applications ensure a continuous growth in the use of GPS navigation equipment.

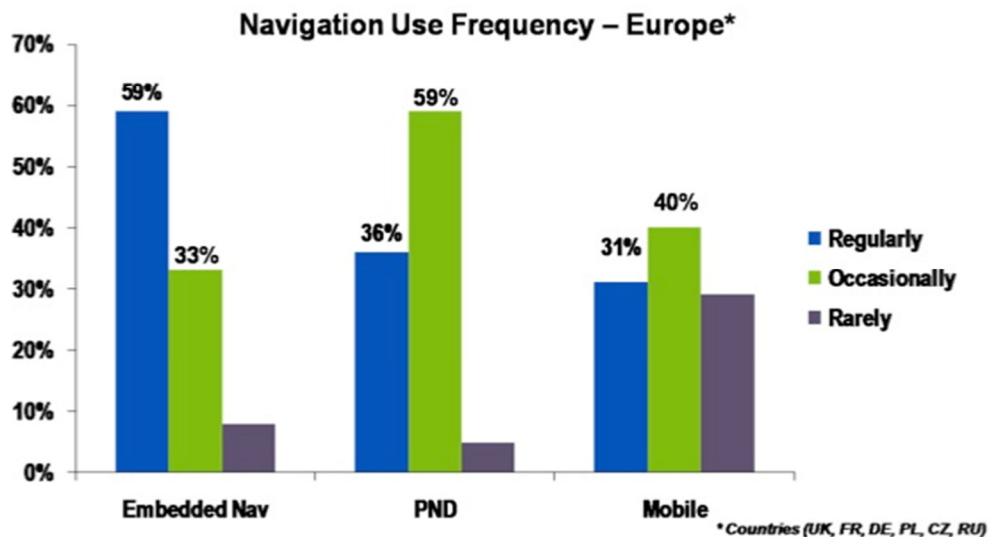


Figure 1 Navigation use frequency - Europe (Navteq, 2011)

The days that navigational devices were only used for in car route navigation are already far behind us. These days a navigation device is able to supply real time route information based on fuel usage and the expected traffic densities along the route. New services add a whole new dimension to the navigational equipment, providing not only a route planner but a complete in-car traffic information system for drivers. These developments in navigational equipment offer the possibility to track vehicles that use navigation equipment. With a GPS sensor, a navigational device can be linked to a set of GPS coordinates providing information about the movement of vehicles on the local road network. TomTom stores the information which is collected from their users, providing a database of traffic information on a global scale.

This chapter comprises the definition of the research problem and the research strategy which are chosen to examine the use of probe data from consumer GPS navigation devices for the analysis of controlled intersections. First Section 1.1 presents the context of the study. Section 1.2 presents the problem definition which describes the motivation and research question of the study. Section 1.3 comprises a description of the research strategy. Concluding section 1.4 describes the outline of the thesis.

1.1. Context

Over the years traffic congestion has become an increasingly big problem. In the Netherlands the total amount of traveller kilometres has increased with almost 30% over the last 20 years (CBS, 2011).

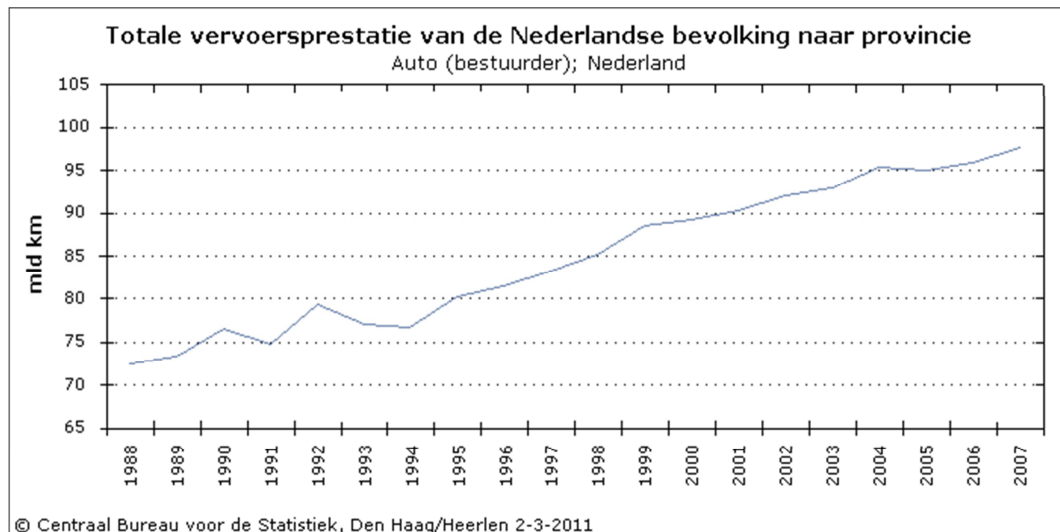


Figure 2 Total amount of Traveller kilometres (in billions) of car drivers in The Netherlands (CBS, 2011)

To cope with increasing traffic demand in urban areas, traffic operators continuously need to adapt their network and the configuration of traffic control

to the changing local traffic conditions. Congestion is often a result of capacity constraints caused by intersections and this makes them key points for traffic management in urban road networks. Network operators require accurate information about the traffic operations at intersections to create a control design that meets their requirements. The information makes it possible for network operators to optimize the traffic flows and capacity on the network. Evaluation of intersections, before the design phase and during exploitation, ensures the quality of traffic operations with a safe and efficient movement for all road users.

The analysis of traffic operations at intersections provides valuable information to network operators. Changes in road geometry, changes in traffic control and new methods of Dynamic Traffic Management are improvements that benefit from this information. Characterizing intersection performance is a specific case in the analysis of traffic operations. For intersections the definition of performance is often used instead of capacity. The capacity on an intersection depends on the traffic flows at all streams and on the crossing possibilities for the drivers. For this reason the definition of performance provides a far more complete picture. The results of performance studies strongly depend on the input data and the definition of intersection performance. The information which is stored by TomTom provides traffic operators with a new source of information about the network performance and creates an addition for existing data collection methods.

Recent studies using a confined dataset show that probe data offers great opportunities for traffic studies but needs a certain level of penetration of probe vehicles in the network (M. Chen & Chien, 2000; Cheu R L, Xie C, & Lee D, 2002; Wagner et al., 2007). Probe data for intersection performance measurement shows a lot of potential and probe vehicle data using a large dataset from consumer GPS navigation devices provides an interesting alternative for data collection from stationary detectors. In this report the calculation of performance for intersections is analysed and the use of probe data from consumer GPS navigation devices for this purpose is investigated.

1.2. Problem definition

With the increasing share of road users who use GPS navigation, the possibility to track the driving characteristics of a vehicle provides the possibility to use probe data in traffic studies. TomTom tracks and stores Floating Car Data (FCD) on the locations of TomTom GPS navigation equipment. The data is acquired for every unique device, measuring the GPS location while driving. The data acquisition includes filtering to ensure that drivers are kept anonymous and that the privacy of individual users is guaranteed. Using data processing algorithms and geographical storage techniques, the GPS locations of the devices are processed and linked to a map of the road network. This process results in a

historical traffic dataset which can be used for the calculation of a driver's trip choice, travel time and travel speed.

Evaluation of traffic operations on an intersection can be a costly and time consuming activity. The greater part of performance studies of traffic operations at intersections is carried out by analysing data which is acquired from stationary detectors and local measurements at intersections. Due to the high costs of roadside detection equipment these detectors are often only placed at a few, significant points in the road network. (Gühnemann, Schäfer, Thiessenhusen, & Wagner, 2004) Locally installed equipment is sensitive to malfunctions and requires frequent maintenance to ensure a continuous flow of data and reduce the number of errors in the data (Nihan, 1997), (C. Chen, Kwon, Rice, Skabardonis, & Varaiya, 2003) and (Hoogendoorn, 2007).

Preliminaries for the continuous use of local detection methods are the availability of logging equipment at the Traffic Control Device (TCD, Dutch: VerkeersRegelInstallatie) and loop detectors, something which is often not available in rural areas and at uncontrolled intersections. Probe data from consumer navigation can be collected at almost every intersection in the road network, even at uncontrolled intersections. Probe data provides an alternative data source for measurement of traffic operations at intersections but needs a certain level of penetration of probe vehicles in the network. Furthermore tracking the location of a driver is bound to privacy laws which ensure the privacy of an individual driver. The increasing amount of tracked GPS consumer navigation devices could provide a competitive method for measurement of traffic operations at intersections and create an alternative for intersection performance measurement. To research this problem, the following question is formulated.

“Does probe data collected from consumer GPS navigation devices provide an accurate and reliable data source for performance measurement at intersections?”

Five sub-questions are defined as a part of the main question. The following sub questions are defined:

- How is the process of arrivals and departures of traffic at an intersection characterized?
- Which parts of traffic operations at an intersection define the performance and which measures of performance are important in the analysis?
- How does data from stationary detectors provide traffic data for intersection analyses?
- How does probe data from consumer GPS navigation devices provide traffic data for intersection analyses?
- What is the accuracy of performance measurement with probe data from consumer GPS navigation devices?

1.3. Research strategy

The accuracy of probe data from consumer GPS navigation devices for intersection performance measurement is determined with a case study analysis. The results of the analysis are based on a comparison of field measurements. The analysis consists of a comparison of measures of performance derived from loop detector data, with probe data collected from consumer GPS navigation devices. The probe data from consumer GPS navigation devices consists of TomTom probe data and is compared to loop detector data from the Regiolab Delft database. The case study is confined to signalized intersections because these have the advantage of loop detection present at the intersection.

First the process of arrivals and departures at intersections is described, and the methods of performance measurement are evaluated. The definition “performance measurement” is clearly described and the measures of performance which are used in the process are derived from literature on intersection performance.

A case study is set up and field measurements from both datasets are used to calculate identical measures of performance for two intersections. The intersections that are chosen for the case study are monitored by Regiolab Delft and are located in the Dutch city Delft. Section 5.2 and Table 3 present the selected case study approach based on the performance indicators covered in Section 3.3.

The results of the study are evaluated by analysing the relation and comparison of the results derived with probe data and the loop detector data. The evaluation of the results is carried out separately for every performance indicator.

1.4. Thesis outline

Chapter 3 presents a detailed description of intersections in traffic networks. First the design and control of intersections is explained. The next section of the chapter presents the objectives of intersection control and the strategy for the implementation of intersection control. Hereafter a more detailed description of signalized intersections is provided, explaining the process of arrivals and departures of traffic at intersections.

Chapter 4 analyses the definition of performance measurement at intersections. The strategy and objectives of intersection performance measurement are derived from examples in literature. For the specific case of signalized intersections, performance measurement is further elaborated. Concluding commonly used measures of performance are explained, which are evaluated in the case study.

Chapter 5 comprises a description of the data which is used in the case study analysis. The first section of the chapter describes the measurement of traffic volume with loop detection and traffic light monitoring. The next section

describes the first dataset which comprises loop detector traffic counts and signal monitoring data collected by Regiolab Delft. Hereafter the collection of Floating Car Data is explained. The next section presents the second dataset of the case study, probe data collected from TomTom GPS navigation devices. Finally the collection approach of both input methods is compared in an example.

Chapter 6 describes the case study method used in the research study. The first section describes the case study approach. The next section presents the study location, the layout and configuration of the intersections. Hereafter the filtering and collection steps are described. The next section presents the calculation of route choice at intersections. Hereafter the calculation of delay, queue length and stop rate is described separately for the probe dataset and the loop detector data. In each section the method of assessment for the case study is included.

Chapter 7 presents the results of the study. The first section provides the route choice analysis. The next sections comprise the results of the delay, the queue length and stop rate analyses.

Chapter 8 is the concluding chapter of the report. In the last chapter the conclusions and recommendations are presented. In the first section the findings from literature and the case study are described. In the final section the recommendations for further research and application of probe data from consumer GPS navigation devices is presented.

Figure 3 shows the outline of the thesis study.

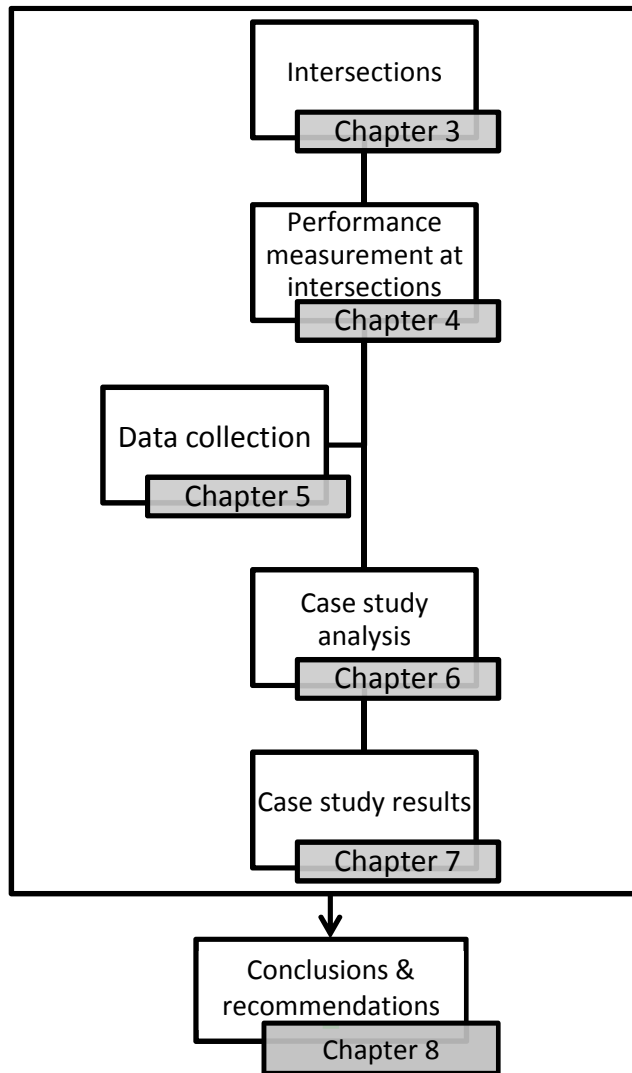


Figure 3 Thesis outline

Chapter 2

Intersections

2.1. Introduction

This chapter presents the basic principles for characterization of arrivals and departures of vehicles at intersections. The special case of signalized intersections is elaborated and the analysis of traffic flows at intersections is explained.

Definition 1. *Intersections are areas in traffic networks where two or more roads meet, cross or intersect*¹.

The design of an intersection takes into account the local traffic demand, standards of local road authorities and the geometry of the road. In urban areas the greater part of the intersections is realized with at-grade crossing facilities for vehicles and pedestrians. At-grade intersections provide complex elements in traffic networks; vehicles and pedestrians want to use the same physical space on the road. Crossings at grade level create multiple potential conflicts which have to be processed by drivers and pedestrians. Conflicts result in travel time delays, a decreased capacity of the intersection and potential safety hazards for road users. Control measures help road users to process multiple conflicts at intersections in a structured manner. Implementation of hierarchy in the intersection control structure reduces the disadvantages of conflicts at intersections.

As networks become increasingly dense, the number of intersections increases. To cope with increasing traffic demand in urban areas, traffic operators continuously need to adapt their network and the configuration of traffic control to the changing local traffic conditions. Accurate information about the traffic operation on an intersection is required to create a design that meets the requirements of the network operator. Evaluation of intersections, before the design phase and during exploitation ensures the quality of the traffic operations, providing a safe and efficient movement for all road users.

¹ (MassDOT, 2006)

This chapter introduces the elements that are crucial for the determination of traffic operations for at-grade intersections. First section 2.2 explains the theory of intersection control. The hierarchy of intersection control is described and the levels of control are examined. In Section 2.3 the objectives of intersection control are explained. The objectives for implementation of signalization are explained and the role of objectives in performance measurement is analysed. Section 2.4 comprises a more in depth analysis of the elements and design characteristics at uncontrolled intersections. Section 2.5 presents a closer analysis of signalized intersections. The basic principles of intersection signalization are examined and the characteristics of traffic movements are explained. Chapter 2 is fundamental for the understanding of intersection performance analysis studies at (signalized) intersections.

2.2. Design and control

This section provides an overview of several layout design features of intersections and the hierarchy of intersection control. First the theory of conflicting traffic streams is elaborated to explain the necessity of traffic control at intersections. Furthermore the levels of traffic control are described explaining important advantages and disadvantages of intersection control.

When two or more traffic streams cross on an at-grade level, traffic from multiple streams requires the same space on the road. Crossings at grade level create potential conflicts which have to be processed by drivers. Drawbacks of conflicts are delay in travel time, delay in capacity and potential safety hazards for road users. Figure 4 shows an example of conflict areas at a four legged at-grade intersection. The number of conflict areas depends on the layout of the intersection and the method of control. For example; a typical four-legged intersection has 12 legal vehicular movements (left turn, through traffic, right turn) and 4 legal pedestrian movements. In total these movements already create up to 32 potential conflicts.

To help road users process possible conflicts, a network operator can apply different methods of control at an intersection. A clear hierarchy in control provides the fundamental basis for safe and efficient traffic operations at intersections. The selection of an appropriate level of control is determined by the number and nature of the conflicts which a driver needs to process when crossing the intersection. When the number of conflicts becomes too large for a driver to process in a certain timeframe or if it cannot be expected that the conflicts are handled in a normal way, the level of control needs to be increased. Alternatives for increased intersection control are geometrical adjustment of the intersection, speed adjustments and prohibition of certain movements.

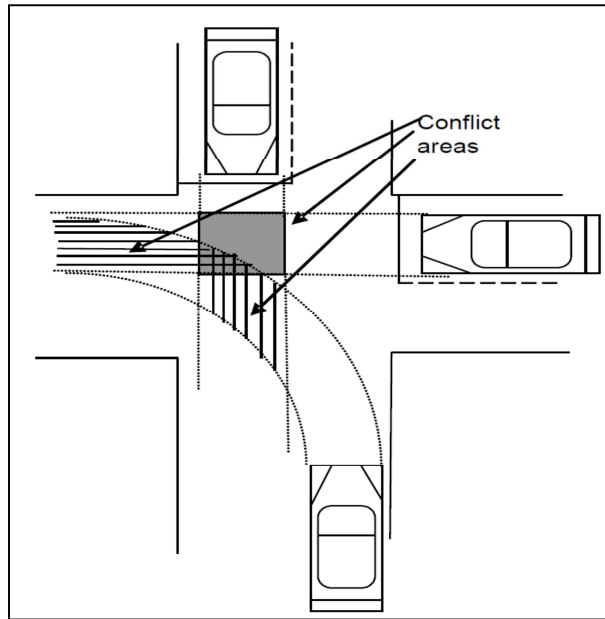


Figure 4 Conflict areas at a four-legged at grade intersection (van Zuylen, Muller, Hegyi, & Salomons, 2009)

Intersection control is categorized by the level of interference of the control tactics and by order of priority. Three levels of interference are distinguished: active control, semi control and passive control. The level of interference describes how drivers are guided at an intersection. Active control provides continuously alternating traffic instructions. Traffic is controlled based on the preferences of local road authorities. Semi control minimizes conflicts at intersections by means of channelization and traffic rotaries. The physical layout of the intersection is altered to decrease the number of conflicts at the intersection. Passive control is the most basic method of intersection control. Road users have to decide how to cross the intersection themselves based on traffic rules and possible fixed road signs at the intersection.

Intersection control on the Dutch road network is categorized in order of priority and is designed according to the Dutch regulation for traffic rules and traffic signs (Ministerie van Verkeer en Waterstaat, 1990; van Zuylen, et al., 2009). There are three levels of regulations, which are (in order of priority):

- 1 Directions
- 2 Traffic Signs
- 3 Traffic rules

1. Directions

Directions are a method of active intersection control and are only used in exceptional cases. Traffic wardens or police officers control the flow of traffic at (part) of the intersection by using hand signals and visual aids. Directions are

used at accident locations, for special convoys or when other methods of traffic control fail, e.g., when the signalization at an intersection brakes down.

2. Traffic Signs

Traffic signs are used at specific locations in the road network where basic traffic rules are not sufficient to ensure a smooth and safe flow of traffic. Traffic signs as described in the regulations for traffic rules and signs (RVV) includes three levels of control consisting of:

— Traffic signalization (Active intersection control)

Traffic lights and/or variable traffic signs provide right of way to one or more directions for a certain period of time. This enables traffic from all directions to cross the intersection. Traffic lights indicate if traffic can ‘go’ (green light), ‘stop if possible’ (yellow light), or ‘stop’ (red light).

— Fixed road side signs (Passive intersection control)

Fixed road side signs indicate the traffic control structure at a certain road section which deviates from basic traffic rules.

— Fixed signs on the pavement (Passive intersection control)

Similar as with fixed road signs, traffic signs on the pavement are used when traffic control on a road section deviates from basic traffic rules.

3. Traffic rules

Traffic rules are known as the ‘basic rules of the road’ and are a method of passive intersection control. These rules apply to any piece of road where right-of-way is not explicitly assigned through the use of traffic signs or directions. These rules are explained in the RVV and all drivers are expected to know these rules.

It is important for intersection design that the geometrical layout and the level of control are matched. This ensures that the traffic flows at the intersection meets the expectations of road users.

2.3. Objectives of intersection control

Objectives and requirements for traffic control systems are derived from the policy on traffic of the local road authority. The policy provides rules and guidelines with respect to accessibility, traffic safety and preferences. Implementation of intersection control often comes from the desire for increased capacities which meet up to the traffic demand.

The objectives for intersection control consist of qualitative goals and quantitative goals. Examples of qualitative goals are the desire for a safe intersection or an intersection with small delays. Quantitative goals are measurable parameters of the traffic control scheme, for example a maximum

allowed cycle time of 120 seconds or a minimum number of vehicles which can cross the intersection per hour. Qualitative goals are translated in normative measures to design the intersection; a qualitative goal could be low annoyance under road users which is translated into a maximum allowed red time. If a driver has to wait more than 60 seconds for a red light this will increase annoyance and decrease the credibility of the control scheme. In this case the requirement of the authority could be that red times with a maximum of 60s are required and no congestion is allowed.

The determination of the “quality” of a control scheme is evaluated with a Performance Index (PI)². A PI expresses the performance of a control scheme in a single figure based on parameters of the intersection performance. Examples of performance measures are the loss time, the number of stops, queue lengths, maximum capacity of conflicting traffic streams, fuel consumption and emissions. A commonly used PI for intersections is the total loss time of the intersection. The total loss time is the sum of all loss times (the average time that is lost at the intersection per vehicle) multiplied by the traffic volume.

$$PI = \sum_{i=1}^N Total\ loss\ time(i)$$

Equation 1 (Wilson, 2006)

PI	:	Performance Index
Total loss time(i)	:	total lost time on direction i (hours)
N	:	number of (controlled) directions
<i>i</i>	:	number of movement

This method provides a quick overview of the performance for a certain section of the traffic operations on an intersection. However the method does not provide a complete intersection performance overview and it is not complete without other measures of performance. The details of intersection performance measurement are described more extensively in Chapter 3.

2.4. Uncontrolled intersections

Uncontrolled intersections have passive intersection control. Traffic operations are controlled with the basic rules of the road and/or fixed road signs. The processing of conflicts at uncontrolled intersections is done by drivers themselves. Important factors in this process are the driver’s ability to avoid a certain conflict (a driver is required to see the conflict zone and the opposing traffic), the geometry off the road, regulations at the intersection and the volume of the crossing streams. To determine the driver’s ability to process conflicts for a

² (Wilson, 2006)

geometrical layout, the distance to a conflict zone and the possible obstruction which can limit the visibility of the collision point is observed (Figure 5).

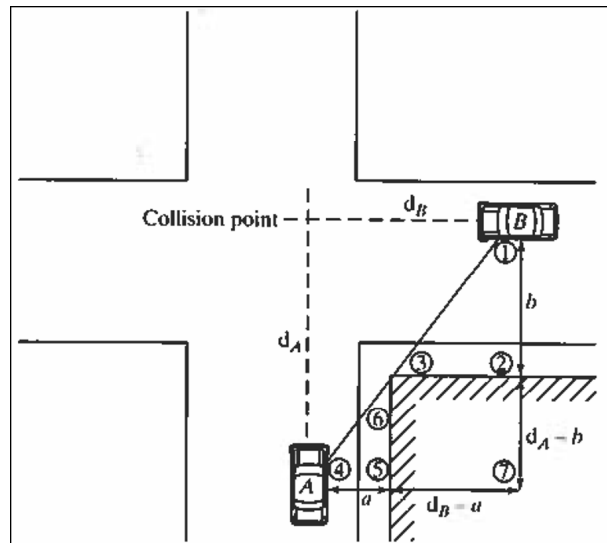


Figure 5 Visibility triangle at an intersection (Roess, Prassas, & McShane, 2011)

The relation between the distance to the conflict zone and the distance to a possible sight obstruction for drivers:

$$\frac{b}{d_B - a} = \frac{d_A - b}{a}$$

Equation 2 (Roess, et al., 2011)

- d_A : distance from vehicle A tot the conflict zone
- d_B : distance from vehicle B to the conflict zone
- a : distance from Vehicle A to the sight obstruction measured parallel to the path of Vehicle B
- b : distance from Vehicle B to the sight obstruction measured parallel to the path of Vehicle A

If the visibility at an intersection is low, priority rules and signs improve safety and traffic performance at the intersection. A common method is prioritization of the busiest stream, providing right of way on the other streams. Vehicles at side streams can enter the intersection when the time gap between two vehicles in the main stream is long enough. The number and length of the time gaps depend on the volume of the main stream. The minimum gap which is accepted by drivers depends on the visibility triangle, local circumstances and the available gaps in the priority flow which equals approximately 4 seconds (van Zuylen, et al., 2009)

If fixed signals do not provide sufficient intersection traffic control to meet up to the objectives, alteration of the geometrical layout of the intersection provides an

alternative. By changing the geometrical layout of the intersection conflict areas are separated, which makes it easier for drivers to handle conflicts. Examples of alternative geometrical layouts are roundabouts and phased crossings. If a change of the geometrical layout is not possible due to a lack of money, time and/or space, signalization can provide the solution.

2.5. Signalized intersections

In this section the basic principles of signalized intersections are described and the process of arrivals and departures of vehicles is explained. A clear description of the flow characteristics is required to understand the calculation and evaluation of intersection performance at signalized intersections.

Signalization at intersections provides a solution when uncontrolled intersections are unable to cope with local traffic demand. Deployment of signalization can provide a solution but has to be implemented carefully to minimize negative consequences. Before the deployment of signalization, evaluation studies help locate the problems at an intersection and describe the expected effects of the new control scheme. An extended analysis provides the opportunity to evaluate the effects of the new control scheme in the present and in the future situation.

2.5.1. Movements and signal phasing

Signal phasing is the control mechanism which determines the operational efficiency of signalized intersections. Traffic streams at an intersection are categorized by their direction, lane usage and right of way provision and are called movements. To distinguish the various movements at an intersection they are coded according to the Dutch standard code system. The codes are used to explain the direction and location of the movements for all traffic groups (cars, bicycles, pedestrians and Public Transport). Figure 6 shows an example of the intersection coding plan at a four legged intersection.

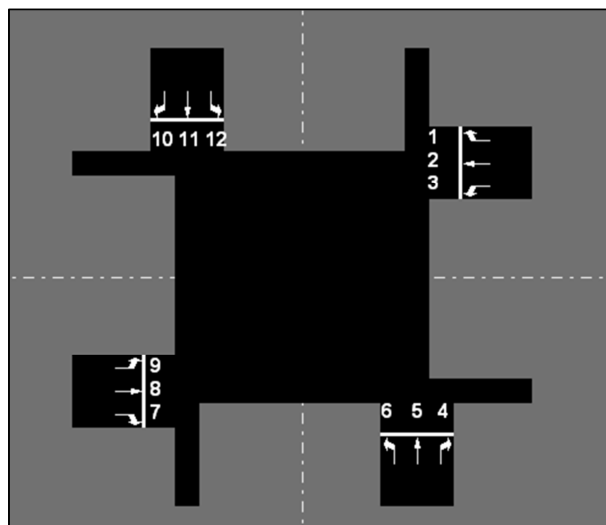


Figure 6 Standard codes on a four-legged intersection (VRIGen, 2011)

The numbers in intersection coding are categorized in the following order(van Zuylen, et al., 2009):

- 1-12 Motor vehicles
- 21-28 Bicycle traffic
- 31-38 Pedestrians
- 41-52 Right of way lanes(public transport, emergency vehicles etc.)
- 61-72 Follow-up streams

Coding of movements is used to differentiate the movements and enables the setup of signal phasing. A signal phase is the state of all signals at the intersection during which one or more movements receives right of way.

Definition 2 *A signal phase is a signal control period identified by at least one movement gaining right of way at the start of the phase and at least one movement losing right of way at the end of the phase³.*

The configuration and sequence of the signal phases is determined by the assignment of red, yellow and green time to every movement at the intersection. A complete sequence of signal phases during which all directions gain right of way at least once, is called a signal cycle. A visual example of a signal cycle for a four legged intersection is shown in Figure 7.

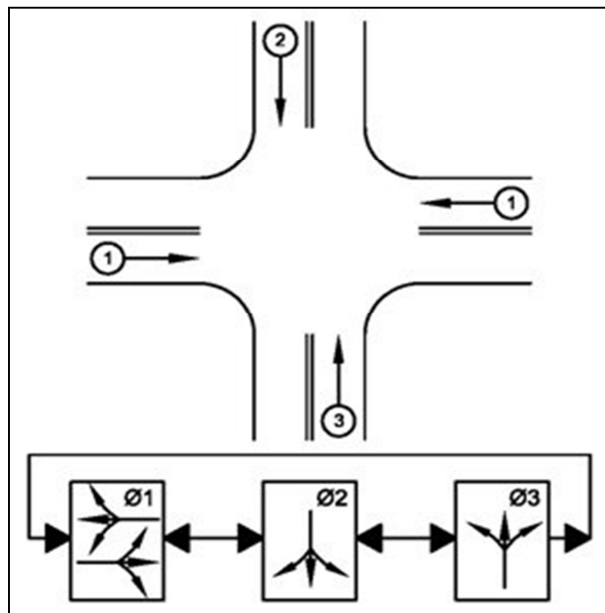


Figure 7 Three phase control sequence (Robert, Gorden, & Warren Tighe, 2005)

³ (Akçelik, 1981)

2.5.2. Control programs

The sequence and configuration of a signal cycle is stored in a control program containing the state of the signals for every phase and the transition from one stage to another. The level of control depends on the level of input for the TCD. Two levels of control are defined, fixed time control and vehicle actuated control:

- Fixed time control comprises control programs where the duration and the order of signal phases is predetermined. The cycle times are fixed and designed to match the local traffic volumes and the preferences of the road authority. Increased green time lengths and alternate signal phase sequences can optimize the flow of traffic at the intersection. Fixed time control can be adjusted to the local traffic demand by using multiple control programs depending on the time of day. An example is the use of alternate programs during rush hour periods or weekends.
- Vehicle actuated control uses the presence of traffic at the intersection as input for the traffic control program. Detectors provide information about the actual presence of road users at an intersection. The traffic demand is determined by induction loops for cars and buttons for cyclists and pedestrians. The information determines the length of the green times and the order of the signal cycles. An example is an increased green time for busy movements or skipping signal phases when no traffic is present.

2.5.3. Movement characteristics

The movement characteristics comprise the flow of traffic for a specified direction and describe the macroscopic characteristics of traffic (Hoogendoorn, 2007). The flow over time of vehicles at a movement is directly related to the signal phasing arrangement. The flow of vehicles is described in the basic discharge model (Akçelik, 1981; Webster & Cobbe, 1966). Figure 8 presents a graphical illustration of the discharge model. The model describes the departure rate of vehicles for a fully saturated green period, i.e. there is still a queue at the end of the green period.

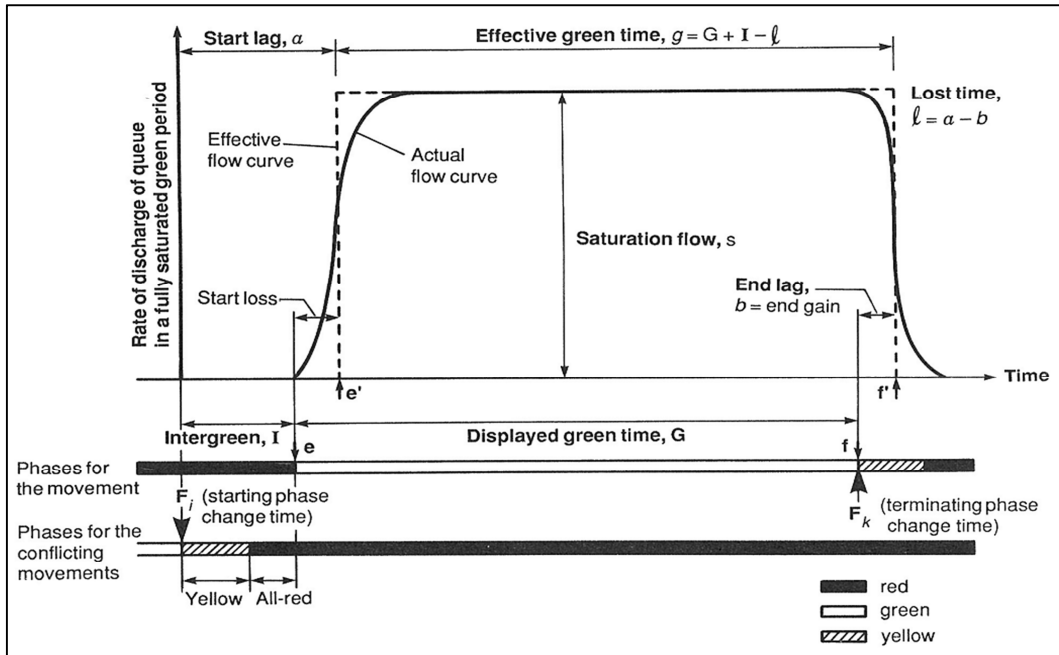


Figure 8 Movement characteristics and model definitions for corresponding signal phases. (Akçelik, 1981)

The basic model assumes that a queue builds up during the red phase of the cycle and that it discharges during the green phase of the cycle. At the start of the green phase the discharge of vehicles increases until it reaches saturation flow and remains constant until the green period ends or until the queue is exhausted. The saturation flow is the maximum departure rate at a movement which can be achieved when there is a queue.

Definition 3 *The saturation flow rate, in effect, is the capacity of the approach lane or lanes if they were available for use all of the time (i.e., if the signal were always GREEN)⁴.*

The time before and after the effective green period is the start and end lag time. The lag is indicated as the time that it takes to reach the saturation flow rate after a signal phase change, e.g., if the signal state changes to green and the saturation flow is reached after four seconds, than the start lag is four seconds.

2.5.4. Critical movements

In a complete signal cycle, a green period is assigned to every movement at least once. The conflict zones at the intersection (see section 2.2) form the basis for the order of the signal phases. Conflicting streams cannot be assigned green at the same time and the minimal cycle time is determined by the order in which green

⁴ (Roess, et al., 2011)

time is assigned to the conflicting streams. The conflicting streams determine the minimal cycle time and are the critical movements. The critical movements require the most time (green time + time lag) in a signal phase. Critical movements are located on a so called critical path in the signal cycle. Figure 9 shows an example, a signal phase diagram of a four legged intersection with the critical path indicated in red.

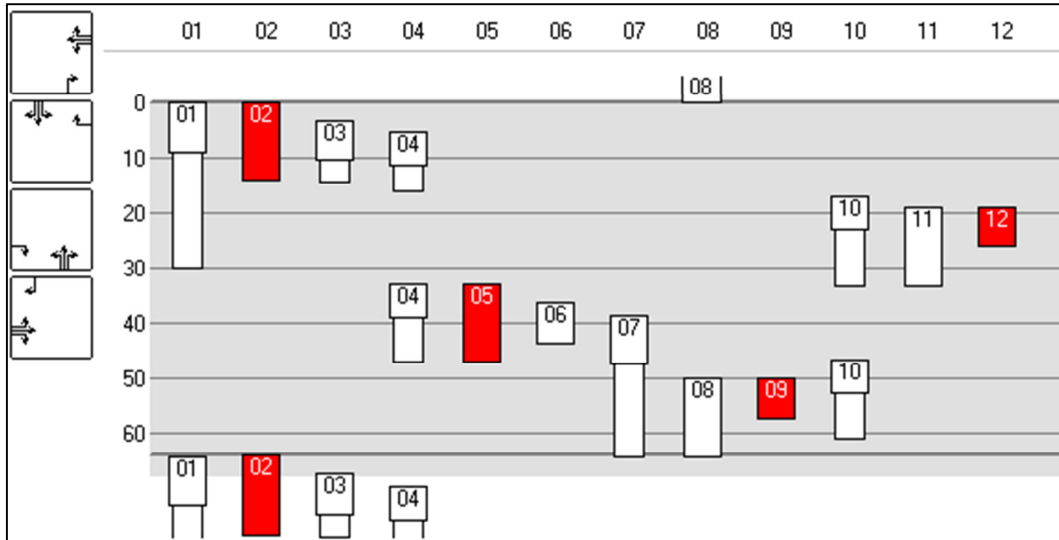


Figure 9 Critical path for a four legged intersection. (VRIGen 2011)

2.6. Summary

In this chapter the basis for the next chapter is provided by explaining the control of traffic operations at intersections and the objectives for intersection control. A description of intersections in traffic networks was presented and the design and objectives for control methods were explained. The chapter discussed the first sub-question; “How is the process of arrivals and departures of traffic at an intersection characterized?”

First the multiple levels of intersection control were shown and the hierarchy between the different levels was explained. The levels of intersection control are differentiated in their level of interference (active, semi-active and passive) and their way of regulation (directions, traffic signs and traffic rules).

Next the objectives for implementation of intersection control were explained. The objectives are described by normative goals which are translated into quantitative measures. The objectives are determined by the policy of the local road authority which provides rules and guidelines with respect to accessibility, traffic safety and preferences.

Hereafter the traffic flow operations at uncontrolled intersections were explained. At uncontrolled intersections traffic is controlled with the basic rules of the road

and/or fixed road signs. The flow of traffic at uncontrolled intersections explains the crossing behaviour of traffic at intersections which provides the basis for traffic operations at signalized intersections.

Finally a more detailed description of signalized intersections was provided, explaining the process of arrivals and departures at signalized intersections. Signal phases are used to assign right of way to traffic streams at the intersection. The length of the phases and the sequence of the signal phases determines the flow of traffic at the intersection. Signalization is divided in active and passive intersection control. Active control uses detectors to configure the signal phases and passive control uses a pre-set schedule. Per individual crossing movement the movement characteristics are derived from a basic discharge model. The model describes the macroscopic behaviour of traffic at the intersection based on the saturation flow per movement.

The movement characteristics which are introduced in this chapter are used for the performance measurement at signalized intersections. In the next chapter the measurement of these movement characteristics is analysed and the performance of intersection control schemes is investigated.

Chapter 3

Performance measurement at signalized intersections

3.1. Introduction

In Chapter 2 the process of departures and arrivals at intersections was explained. In this chapter the specific case of performance measurement at intersections is explained. Performance measurement enables the evaluation of systems and identifies potential operational problems in products or systems. In traffic systems, performance measurement allows designers and operators to evaluate the system on qualitative measures by using measured or modelled parameters.

Definition 4 *Performance measurement is the use of evidence to determine progress toward specific defined organizational objectives. This includes both quantitative evidence (such as the measurement of customer travel times) and qualitative evidence (such as the measurement of customer satisfaction and customer perceptions)⁵.*

Performance measurement is an evaluation method of traffic systems and networks with local measurements or modelling. Measurement and modelling studies analyse the local traffic volume, speed and density. These studies provide great amounts of data but without the right perspective this information is hard to understand. For performance measurement the information is divided into separate indicators which allows evaluation of a traffic network or comparison of different locations and configurations. The measures of performance can be used to locate problems in the intersection control and for this reason they are also referred to as Performance Indicators.

This chapter describes the value of performance measurement at intersections and the calculations which are needed in the process. First section 4.2 presents a description of the objectives of performance measurement at signalized

⁵ (Federal Highway Administration, 2011)

intersections and the value of performance measurement is explained. Section 4.3 comprises a closer analysis of the measures of performance for the case of signalized intersections. The available measures of performance are described and the relation to the movement characteristics is explained. Finally the measurement techniques for the calculation of the performance measures is presented.

3.2. Strategy and objectives

Traffic operations at intersections are evaluated on pre-set objectives and requirements. For controlled intersections evaluation of the signalization is an important part in the evaluation process. With intersection control evaluation (ICE)⁶, information is collected on the behaviour and traffic volume at the intersection related to the control scheme. The acquired information is used to determine the flow of traffic, the traffic safety and the environmental impact of traffic at the intersection. This information provides the opportunity to optimize the intersection and the control scheme. Evaluation of an intersection can be carried out in the design phase, or during operation. In an optimal situation, signalization at intersections is evaluated before the design phase (ex-ante evaluation) and (continuously) after the instalment of the signals (ex-post evaluation)⁷.

Ex-ante evaluations are used for the construction of new intersections or when signalization is installed at existing intersections. In these cases the signalization scheme cannot be compared to measurements from a reference situation (previous situation), but it is analysed by using traffic models or simulation. Ex-ante evaluation is used to determine if a design meets pre-set requirements or if signalization is an improvement compared to the old situation.

Ex-post evaluation is used during the operational phase of the signalization. Ex-post evaluation is carried out by measuring traffic flows at the intersection or by using traffic models. Traffic flows at the intersection can change over time due to changes in the traffic demand or shifts in driver behaviour. Evaluation of traffic operations during operation is used to optimize traffic flows which can change over time. Ex-post evaluation is valuable to measure the effects of occasional events or (temporary) changes in the infrastructure.

Traffic operations at intersections are evaluated by measuring traffic volume and route choice, or by estimation of the traffic flows with models and simulations. Commonly a combination is used where traffic models use the input from

⁶ (MassDOT, 2007)

⁷ A method which is used for the design of intersections on the Dutch road network (Adviesdienst Verkeer en Vervoer, 2002)

measured values of reference situations. The most common techniques of evaluation comprise:

- Evaluation by visual observation
- Evaluation of measurements in the field
- Evaluation with analytical models and simulation

Evaluation by visual observation

Visual observation is used to check for unexpected problems at intersections. This method provides a quick check for faults in the control program which can be used to change the signal cycle.

Evaluation of measurements in the field

Measurements in the field provide the most accurate information but the data collection can be a time consuming and costly process. Traffic counts measure traffic volume at the intersection providing the Origin and Destination(OD) of road users. Traffic counts can be done manually, or automatically with (electronic) detection equipment. The most commonly used method to acquire traffic counts at signalized intersections is the storage of the data which is collected by the signal detection loops.

Evaluation with analytical models and simulation

If there are no measurements available, evaluation with models and simulation provides an alternative. Reference situations are used to develop a model to describe the traffic operations at an intersection. Information from other intersections and models is used to calibrate the effects of certain changes in the infrastructure on the traffic flows.

Based on the available time, resources and preference a specific evaluation method is selected. A combination is also possible, for example; a model simulation enriched with measurements in the field. Evaluation of intersections analyses the measurable parameters of traffic flows (section 2.5.3), most commonly; traffic volume and travel time delay. The acquired information determines if the intersection meets up to the requirements of the operator and if the capacity of the intersection is sufficient for the local traffic demand.

Definition 5 *Capacity is the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period (usually 15 minutes) under prevailing roadway, traffic and control conditions⁸.*

⁸ (May, 1990)

For the evaluation of intersections the definition of performance is more suited than capacity. Capacity does not address the flow quality of traffic or the level of service to road users. Capacity at intersections depends on the traffic flow of all crossing movements, which changes constantly. An increase of the capacity at one movement can result in a decrease of the capacity at another movement. For this reason the definition of performance is used, providing a picture of the complete intersection.

As described in Chapter 2.3 a Performance Index provides a tool to describe the performance of an intersection. The Performance Index includes one or more quality indicators of the intersection. The indicators are measurable characteristics of the traffic flows such as travel delay or the queue lengths at the intersection. Each quality indicator is multiplied by a weight factor, which determines the weight of that specific quality indicator in the PI. For example, if the key objective of a road authority would be to reduce the delay at an intersection, than an increased weight factor for delay is preferred. The PI function for intersection performance measurement:

$$PI = \sum_{i=1}^N a_i \cdot A_i + b_i \cdot B_i + c_i \cdot C_i + \dots$$

Equation 3 (Wilson, 2006)

a_i	:	weight factor for movement i & quality indicator A
b_i	:	weight factor for movement i & quality indicator B
c_i	:	weight factor for movement I & quality indicator C
A_i	:	quality indicator A
B_i	:	quality indicator B
C_i	:	quality indicator C

Practical application of performance measurement in traffic networks and at intersections is shown in the traffic manuals of some national road authorities. The most widely used is the Highway Capacity Manual (HCM-2010) (Transportation Research Board, 2010) which is used by the U.S. and U.K. road authorities. In the HCM the performance of a specific section of the road is described including the Level Of Service (LOS). The LOS reflects the flow quality as perceived by road users. The flow quality is closely related to the travel time (and speed), the waiting times and the experienced comfort of a trip (number of stops, required acceleration and deceleration, ability to drive at a desired speed). When the LOS is taken into account, the definition of capacity is quite similar to Definition 5, but it is extended with the phrase: “while maintaining a designated level-of-service”(Transportation Research Board, 2010). The HCM indicates six service levels from A to F, each separated by the size of the control delay encountered by road users. For the determination of the LOS the delay is used as

the primary measure of performance For the case of at-grade signalized intersections this comes down to levels between 10 and 80 seconds of delay.

In the next section the most commonly used measures of performance for intersections are described. These measures of performance are used to evaluate traffic flows at intersections and can be used for the calculation of a PI (Equation 3).

3.3. Measurement of performance

The operational efficiency of signalized intersections is expressed in various measures of performance. These measures of performance are (related to) the movement characteristics as defined in Chapter 2. The choice for an appropriate measure of performance is based on the objectives of intersection control (section 2.3) and is fundamental to the method of signal time calculation (section 2.5).

Performance measures describe the traffic flows at an intersection and the effects of signalization on traffic. Many performance measures can be analysed to investigate traffic operations at an intersection. A study by TTI in 2004 shows that traffic operators use many aspects of traffic flows to evaluate the intersection control scheme (Balke & Herrick, 2004). The study shows that most common sources of information for intersections are:

- Citizen complaints
- Percent of cycle used for crossing
- Volume
- Green utilization
- Cycle failures
- Control delay
- Queue length
- Traffic demand
- Number of vehicles remaining after green
- Average duration of green interval
- Speed
- Departure headways

An interesting result of the study is that citizen complaints are the primary source of information for traffic operators to learn about problems at intersections. Complaints serve as an indication that the control scheme is not functioning optimally, but has the disadvantage that it describes the symptoms and often not the source of a problem, e.g., a complaint about large delays describes the problem but it is unknown if this is a result of oversaturation or maybe malfunctioning detection equipment.

Performance measures are divided in primary and secondary measures of performance. Primary measures of performance are directly derived from the

movement characteristics at the intersection. Common primary measures of performance are: saturation rate, delay (lost time), queue length and the stop probability. Secondary measures of performance are derived from the primary measures of performance. Secondary measures of performance are valuable for environmental studies and traffic safety evaluations. Examples of secondary measures of performance are: fuel consumption, pollutant emission and travel cost.

For the research study in this report primary measures of performance are selected for the evaluation of probe data from consumer GPS navigation devices for use in intersection performance measurement. More elaborate performance studies would require data on the primary measures of performance and for this reason the study is confined to the primary performance measures. A more detailed description of the selected performance measures is presented in the next sections. The discussed measures of performance are: saturation, delay, queue length and stop probability.

3.3.1. Saturation

The saturation flow concept provides the most important single parameter in the capacity and timing analysis of signalized intersections. The saturation flow describes the maximum departure rate of vehicles from a queue during the green phase when it has reached a constant departure rate (section 2.5.3). The saturation flow thus describes the maximum capacity of a movement.

During each complete signal cycle a movement is assigned green during part of the cycle (the Green Time). The capacity of a movement is related to the part of the cycle time which is effectively green. If the saturation flow and the fraction of green time are known, the capacity over time per movement is calculated:

$$Q = s \cdot \frac{g}{c}$$

Equation 4 (Akçelik, 1981)

Q	:	capacity over time per movement
s	:	saturation flow
g	:	effective green time per movement
c	:	cycle time

This calculation is valid for fixed signal cycles, however for dynamic cycles the capacity over time per movement changes constantly due to dynamic green times. The capacity over time is then calculated by constantly measuring the effective green time per cycle.

The effective green time per cycle is the green time ratio for the movement:

$$u = \frac{g}{c}$$

Equation 5 (Akçelik, 1981)

u : green time ratio

If the maximum capacity of a movement is known it is possible to calculate the saturation rate of the movement. The saturation rate describes the relation of the traffic demand to the local capacity and to what extent the full capacity of the road is used. The saturation rate is also known as the flow ratio:

$$y = \frac{q}{s}$$

Equation 6 (Akçelik, 1981)

y : flow ratio
q : arrival flow

The capacity and saturation of a movement are valuable for performance measurement. The information determines if the capacity of a movement is sufficient for the traffic demand. For intersection designs a maximum saturation rate of 1 is allowed, higher degrees of saturation create unstable traffic conditions which result in excessive delays and queuing. In practice a saturation rate of 1 is too high for a stable result and practical studies show that a maximum value of 0.9 provides more realistic results (Webster & Cobbe, 1966).

3.3.2. Delay

Lost time describes the time that is lost when a vehicle crosses an intersection. The lost time consists of time which is lost due to queuing, the start lag and the end lag (see section 2.5.3). The lost time is calculated per movement or for the total intersection. The lost time for the complete intersection is calculated by taking the sum of the loss times of the critical movements and not of all movements (see section 2.5.4). The lost time for a single movement is known as the (control) delay of a movement and describes the (average) delay per vehicle.

Definition 6 *Delay is calculated by comparing the time that a vehicle passes a point downstream (at a distance far enough that the vehicle has reached cruising speed again) and the time at which it would have passed if it had not stopped.*⁹

⁹ (van Zuylen, et al., 2009)

As described by Definition 6, the delay is the difference between the measured travel time and the optimal travel time. Delay is not directly measured but it is calculated by comparing the measured travel time to the optimal travel time of a vehicle. The optimal travel time is also known as the free flow travel time; the travel time of a vehicle in free flow conditions. The free flow travel time can be estimated based on the local road geometry, or it is measured by checking the travel time in optimal conditions. The travel time of a vehicle is calculated by measuring the time it takes the vehicle to travel from a point stream upwards of the intersection to a point stream downwards of the intersection. The measurement starts before the vehicle decelerates for the crossing movement and ends after the vehicle has reached cruising speed again. Figure 10 shows this concept and displays the measurement setup for a travel time measurements at intersections.

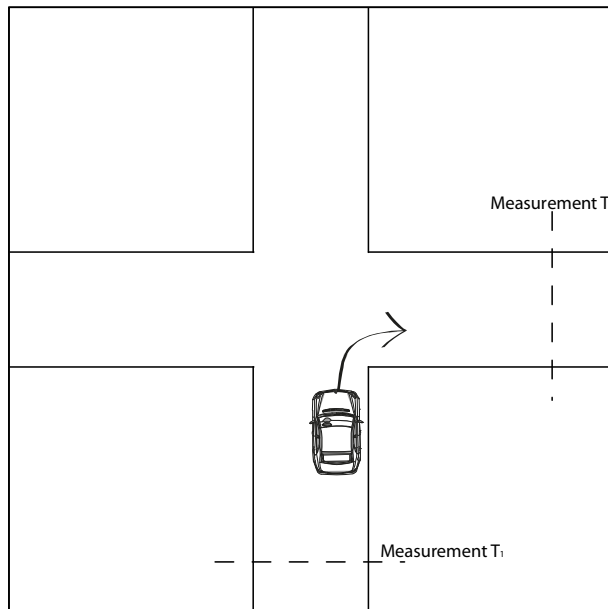


Figure 10 Measurement of delay on an intersection

With the measurement setup configured as in Figure 10, the delay is derived:

$$T_{Delay} = (T_2 - T_1) - T_{Free}$$

Equation 7 (van Zuylen, Zheng, & Chen, 2010)

- | | | |
|-------------|---|-------------------------|
| T_{Delay} | : | delay time per vehicle |
| T_1 | : | timestamp at location 1 |
| T_2 | : | timestamp at location 2 |
| T_{Free} | : | free flow travel time |

Figure 11 shows the delay trajectory for a single vehicle at an intersection.

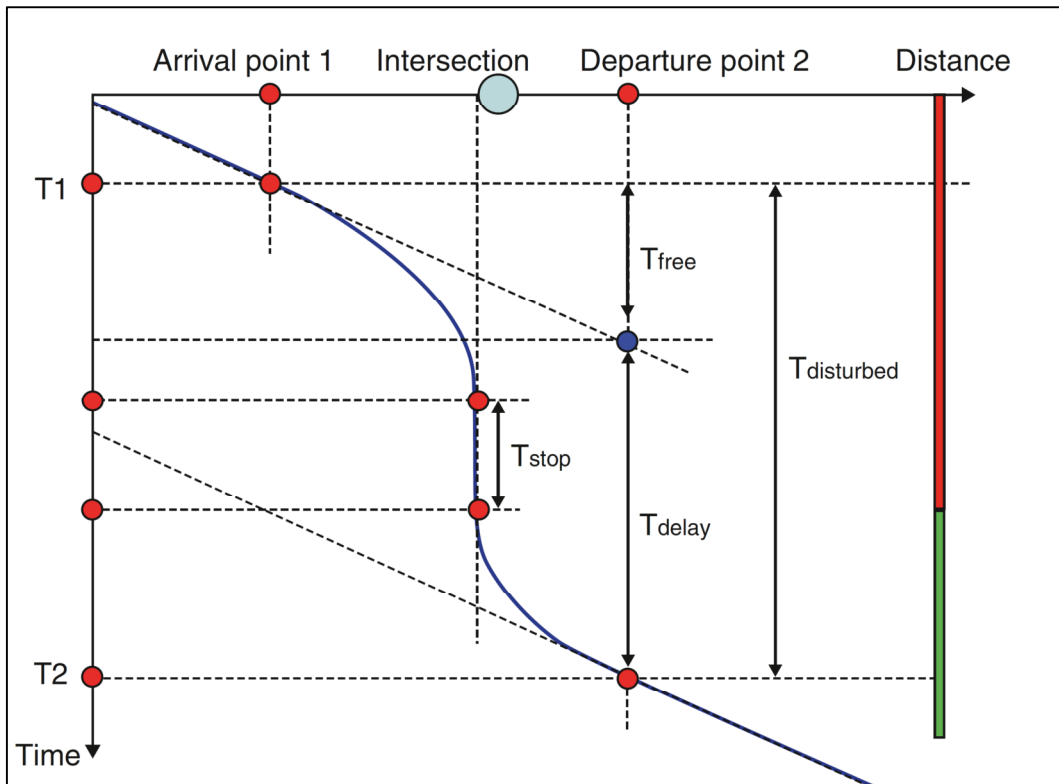


Figure 11 Delay trajectory for single vehicle (van Zuylen, et al., 2010)

There are many causes for delay at an intersection. Delay could be a result of oversaturation, congestion or a bad signal configuration. Travel time delay is often used as an indicator for problems at intersections and is directly linked to all other performance measures. Higher saturation, longer queues and increased stop probabilities result in longer delays. Delay is a clear indicator for the effects of a certain geometrical and signal configuration to road users and provides a valuable performance measure for network operators.

3.3.3. Queue length

The queue length describes the number of vehicles which are queuing in front of the stop line for a movement at a specific moment in time. The queue length describes the number of vehicles that are queuing and can be expressed in the length of the queue in meters. An estimation of the queue length is made by assuming an average length of approximately 7,2 meters per vehicle in the queue (van Zuylen, et al., 2009). The length of the queue is determined by measuring the number of vehicles starting with the first vehicle that has to wait for a red light, to the last vehicle that has to stop because of the queue. This means that the traffic light can already be green, but the back of the queue is still moving stream upwards. To this extent two queue length measures are calculated; the average queue length and the maximum queue length. The average queue length describes the average length of the queue at the start of the green phase and the maximum queue length describes the maximum length of the queue which is

reached after one signal cycle. Figure 12 shows the measurement of the queue length from the stop line.

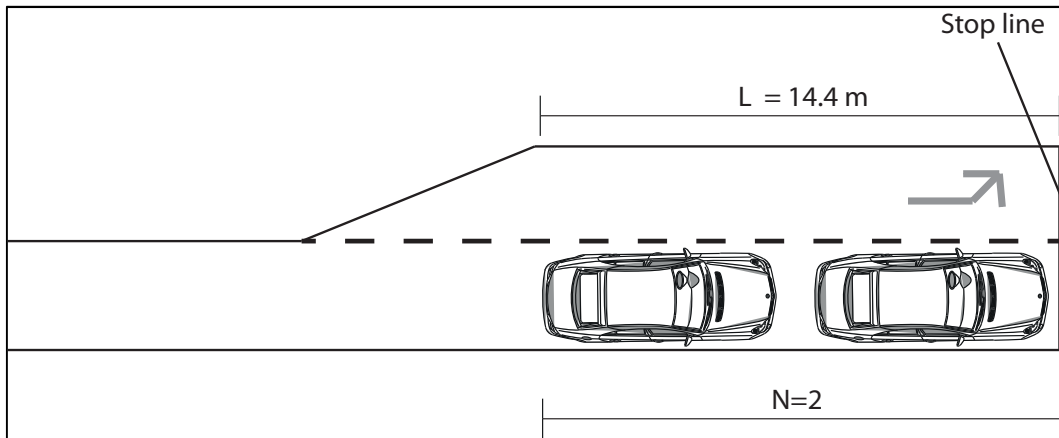


Figure 12 Queue length from the stop line

The average queue length increases if there is not enough green time assigned to a specific movement. The road authority can use the measurement of the average queue lengths to optimize the TCD. Measurement of the maximum queue length determines if the local queue discharge storage capacity is sufficient. If there is not enough space on the road to locate all waiting vehicles, congestion occurs and the delay of one movement can propagate to other movements. This effect results in lane blocking; the queue of one movement blocks the entry of another movement (Figure 13). A common guideline for the design of intersections is that they have enough queue discharge storage capacity during 95% of the time.

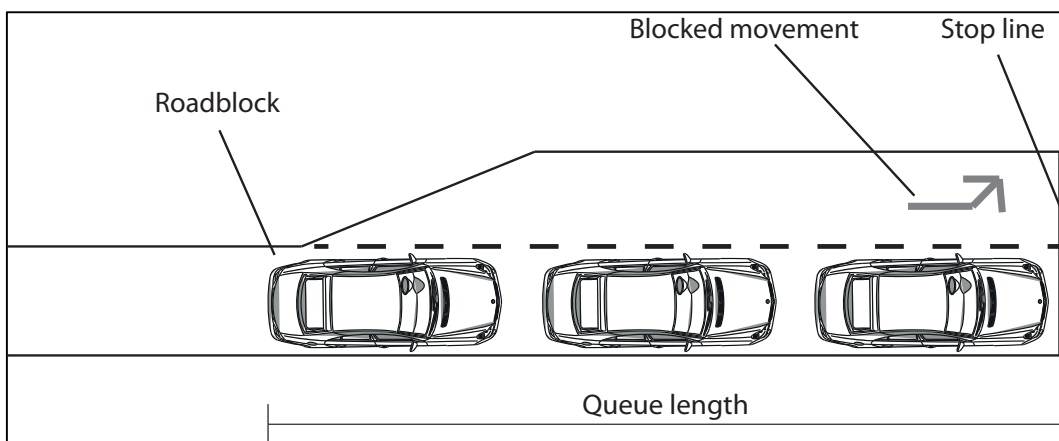


Figure 13 Lane blocking of a left turning movement due to queuing

3.3.1. Number of stops

The number of stops describes the probability that a vehicle has to stop at an intersection. The average number of stops depends on the number of arrivals during one cycle and the remaining green time after the queue has completely discharged. If the remaining green time approaches zero, the number of stops will

have a value of at least 1 (stop). In this case drivers have to wait for more than one cycle to cross the intersection resulting in more than 1 stop.

In performance measurement the number of stops is used to analyse the nature of the delay and is a key parameter for the determination of fuel usage and emissions. Fuel usage and emissions are strongly related to acceleration and deceleration of vehicles (Hammarström et al., 2008) and for this reason stopping behaviour provides important input for models on fuel usage and emissions.

3.4. Summary

This chapter gave an overview of the definition of performance measurement at intersections. The strategy and objectives of intersection performance measurement were derived from examples in literature. The chapter discussed the second sub-question; “Which parts of traffic operations at an intersection define the performance and which measures of performance are important in the analysis?”

It was shown that performance measurement provides policy makers and traffic operators with a tool to locate problems in intersection control structures. An index of the performance or a level of service indication connects the normative objectives of the traffic operator to quantifiable measures. The indicators which are used for this purpose are characterized as primary and secondary measures of performance. Primary measures are directly measured at the intersection and comprise: saturation, delay, queue length and stop rate. Depending on the purpose of the study, an adequate set of performance measures can be selected. Saturation, delay, queue length and stop rate were presented as measure of performance and it was explained how these indicators can be used to improve or optimize traffic flows at the intersection.

The conclusion is that for the research study the primary measures of performance are a key indicator to check if probe data from consumer GPS navigation devices is applicable to intersection performance measurement. The primary measures provide the first step in performance analyses of intersections and an indication on the quality of these measures is part of the construction of the answer for the main research question. In the next chapter the collection of traffic data is explained for the purpose of performance measurement at intersections. The chapter will explain the collection of road-side data and floating car data for performance measurement at intersections.

Chapter 4

Data collection

4.1. Introduction

This chapter describes traffic data collection at intersections for the purpose of intersection performance measurement. The chapter describes the data collection from loop detection and the collection of Floating Car data. In this chapter the two datasets which are selected for the case study analysis are described. The first dataset consists of travel time measurements from probe vehicles equipped with a consumer GPS navigation device. The second dataset comprises traffic counts from loop detectors and green time detection from Traffic Control Device monitoring.

In section 4.2 the collection of data from loop detection and TCD monitoring is explained. Traffic volume counts with loop detection and the monitoring of TCD equipment are described. In section 4.3 the dataset which is collected from the Regiolab Delft is described. This section consists of a description of the collection and storage process for the dataset which is used as a reference in the case study analysis. In section 4.4 the collection of FCD is described and the use of probe data in traffic engineering is explained. Section 4.5 comprises a description of the TomTom FCD database which is selected for the case study, describing how GPS measurements are used for the measurement of trajectories at intersections. In this section the extra conditions for storage and (privacy)filtering of probe data from consumer navigation are explained.

4.2. Data collection from stationary detectors

The most common method of data collection on the flow and characteristics of traffic is the use of roadside stationary detection equipment or short manual traffic counts. (Balke, Charara, & Parker, 2005) Stationary detectors at intersections comprise induction loops, TCD monitoring, infrared or wireless sensors and camera observations. The stationary equipment is used to measure traffic volume, travel times, speeds and route choice distributions. To reduce costs and increase efficiency, stationary detectors are often only placed at key points in the road network (Ehmke, Meisel, & Mattfeld, 2010). For the case study in this report, traditional data collection methods are selected as a

reference. For this reason, data collection with induction loops and TCD monitoring is elaborated.

4.2.1. Loop detection

With loop detection the passing of vehicles at a specific location on the road is monitored. The greater part of loop detection equipment consists of inductance detectors. The detector measures the inductance in a metal loop which is installed in the road. When a metal object (a condition which holds for most road vehicles) drives over the loop, a current is generated which is measured by the logging device, which is referred to as the “activation of the loop”. The size of the current depends on the size, model and speed of the passing vehicle. The number of activations measures the traffic volume at a certain road section during a specific timeframe. Local conditions such as nearby metal objects, bad weather conditions or wear and tear of the road can influence the measurement of inductance. For this reason a minimum threshold is used to level out the “noise” in the data, ensuring that only vehicles are measured. Figure 14 shows schematically how this process works, in reality the induction peaks are more smooth.

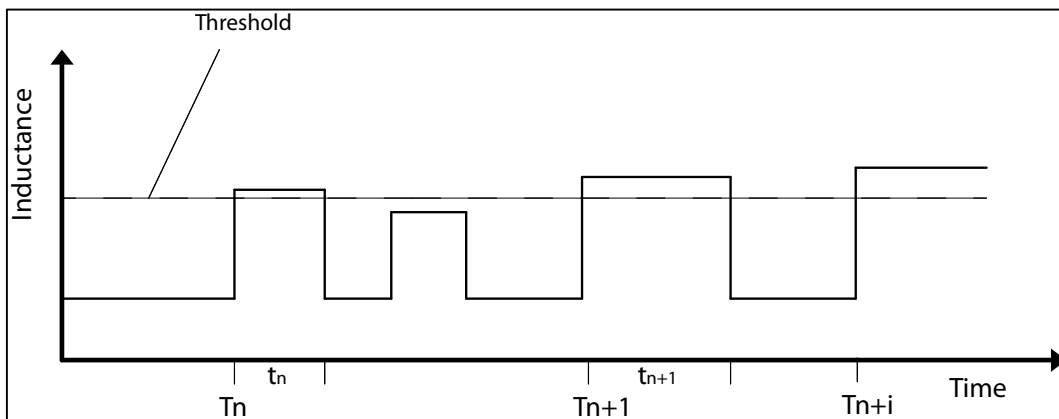


Figure 14 Inductance measurement over time from loop detection

T_n : Start time of measurement n if
inductance > threshold

t_n : Duration of measurement n

Detection loops are used for research purposes, traffic monitoring or in the case of intersections, for dynamic signal control. Detection loops are placed before the stop line to measure the traffic demand for a specific movement (group). This information is used to assign the green time on the intersection or temporarily change the control cycle sequence. Request detectors are placed upstream of the stop line. If the gap time between two requests becomes too large, the green phase is cut off and the yellow phase starts. An additional extension detector

enables the detection of incoming vehicles, which results in less unused green times. Figure 15 shows the placement of detectors at an intersection.

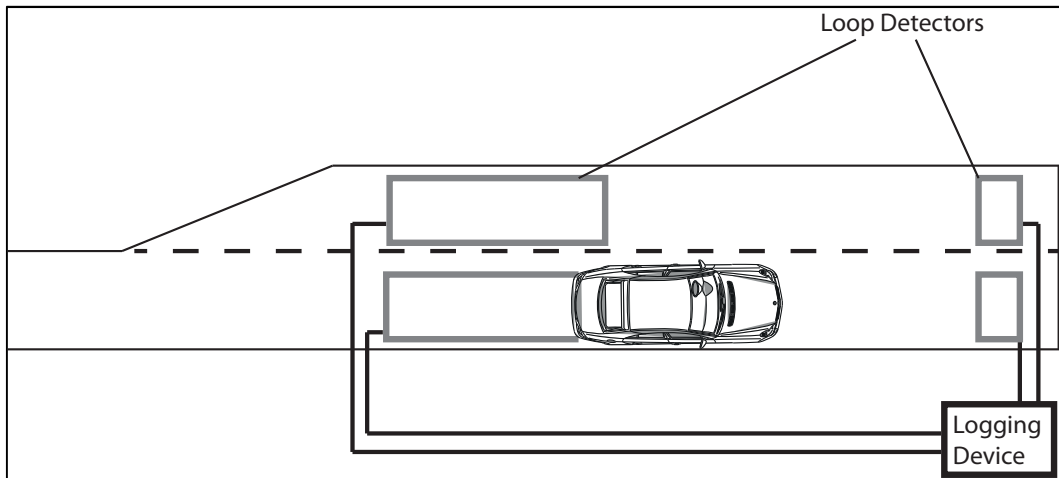


Figure 15 Request and extension detectors at a signalized intersection

If the activations of the request detector are stored by a logging device (locally or at a remote location), the traffic volume at that detector is measured. If individual detectors are placed at all movements and by using the conservation of vehicles at the intersection, it is possible to calculate the traffic volumes for individual movements.

Measurement of the travel time, route and speed of a vehicle is not possible with single induction loops. The loop inductance does not identify an unique vehicle, which makes it very hard to track the vehicle during a trajectory. Experimental setups show that more advanced inductance analyses and multiple loops can be used for an estimation of the speed and travel time of a vehicle (Coifman, 2000). The described methods do tend to be more suitable for application on highways and are less accurate at intersections. Non-ideal behaviour of the equipment and vehicles (for example lane changes) create a possible error in speed measurement of 5% and 15% for the measurement of vehicle lengths. (Hoogendoorn, 2007).

4.2.2. TCD monitoring

The signal control cycle is stored in a control program at the TCD (section 2.5.2.). The control program is used by the TCD to control the signal states and regulate the traffic at the intersection. To monitor the TCD, the state of the control program is stored locally or at a remote location. The length and the sequence of the signal phases are stored together with the date and time. For fixed time control TCD monitoring provides a constant result; the length and the sequence of the signal phases are non-dynamic. For vehicle actuated control TCD monitoring provides storage of the dynamic cycles. The storage of the length of the signal phases and the local time is used to determine the state of the intersection at a certain point in time. The monitoring of the TCD device is used

to evaluate traffic operations at the intersection and more importantly, the quality of the control program itself.

Next to optimization and measurement of traffic at separate intersections, TCD monitoring also provides opportunities for network-wide solutions. Remote monitoring of intersections is beneficial for use in dynamic traffic management. Combining the signal control state of multiple intersections enables the control of traffic flows from a network-wide perspective. Network-wide traffic management results in an overall lower total loss time for drivers due to a reduced amount of unnecessary waiting. Experimental studies in the Dutch cities Eindhoven and Nijmegen showed that network wide dynamic traffic management caused an overall reduction of 11 to 21% in loss time (Taale, Hoogendoorn, van den Berg, & De Schutter, 2006).

4.3. Dataset 1: Regiolab Delft

The data of loop detectors and TCD monitoring which are used for the case study are part of the Regiolab Delft project. Regiolab Delft is a research project of the Dutch Ministry of Transport, the province of Zuid-Holland, the municipality of Delft, Delft University of Technology, Siemens, Vialis, TRAIL and CONNEKT. Traffic data is collected in the region of the Dutch city Delft for research in traffic engineering. The data of Regiolab Delft is collected from MONICA (the loop detection system on the Dutch highway network, created by the Ministry of transport), loop detectors at controlled intersections in Delft, TCD monitoring, camera detection and other experimental means of traffic detection.

For the case study only loop detection data at intersections and the monitoring systems of the TCD are available. For both measurement systems the collection and storage of the data is elaborated.

4.3.1. Intersection loop detection

The loop detectors which are measured in the Regiolab Delft area comprise single loop detectors which are used for dynamic signal control. The loops are installed before the stop line to detect traffic at the TCD and are used to measure traffic volumes at the intersections. The detection loops are monitored and the time and date of the activation and deactivation is stored, providing the traffic volume at the detector during a selected time period. Table 1 shows an example of the data storage method.

Year and Month	Day	Time	Detector	Flank
2009Sep	1	07:02:50,71	481	D
2009Sep	1	07:03:01,12	481	U
2009Sep	1	07:03:05,67	481	D
2009Sep	1	07:03:09,69	481	U

Table 1 Example of Regiolab Detector counts

As shown in the example the activation (Down flank D) and deactivation (Up flank U) indicates the time period when a vehicle is at the detector. Aggregation of the down flanks during a time period enables calculation of the traffic volume at the detector. Depending on the detector configuration at the intersection, vehicle conservation at the intersection is used to determine the traffic volume for a single movement (section 4.2.1).

4.3.2. TCD monitoring

For the Regiolab Delft project the Traffic Control Devices at the intersections are continuously monitored by logging devices. The logging devices store the assignment of green for every movement, including the public transport movements. The data storage method is similar to the storage of traffic counts. The date and time of the start of the green phase and the end of the green phase are stored (Table 2).

Year and Month	Day	Time	Detector	Flank
2009Sep	1	07:02:45,44	451	D
2009Sep	1	07:03:10,19	451	U
2009Sep	1	07:04:10,18	451	D
2009Sep	1	07:04:39,84	451	U

Table 2 Example of Regiolab TCD Monitoring

The data is used to derive two parts of the signal cycle. First the length of the green times is derived by measuring the time between the start of the green phase (Flank Down) and the end of the green phase (Flank Up). Secondly the number of green phases is derived by counting the number of green activations in a certain period.

4.3.3. Deriving delay, queue length and stops from Regiolab data

The estimation of delay, queue length and stop rate from loop detection is not straightforward. Delay, queue length and stop rate are all directly related (Dion, Rakha, & Kang, 2004), but are not directly derived from the traffic counts measured by loop detectors. Models can provide the calculation of these parameters based on loop detection data and TCD monitoring, although direct measurement is preferred. Loop detection with TCD monitoring and modelling is often used, because it provides a cost effective alternative. The available input data and the objectives of the assessment determine the choice for a specific model. The models which are available for assessment comprise: deterministic queuing models, shockwave delay models, microscopic simulation models, steady-state stochastic delay models and time-dependent stochastic delay models.

For the reference dataset in this research study a time-dependent stochastic delay model by (Akçelik, 1981) is chosen which is based on the steady state model by

(Webster & Cobbe, 1966). The chosen model is often applied to the performance measurement at intersections when only loop detection and TCD information is available (Dion, et al., 2004). For the use in the PI and LOS assessments, macroscopic traffic characteristics are required (Chapter 3). Some of the discussed models provide macroscopic results but are more time consuming because they operate at a microscopic level. Furthermore deterministic queuing models and shockwave delay models assume uniform arrivals of vehicles which is unrealistic for intersections in dense urban areas. For this reason the time-dependent stochastic delay model is selected, assuming a random arrival of vehicles. It has to be noted that the presence of other intersections or network-wide traffic management is not taken into account by the model. In these cases platooning of vehicles can scramble the random arrival pattern.

4.4. Floating Car Data

Floating Car Data comprises a number of data collection methods, measuring traffic flow characteristics from a moving observer perspective. The term Floating Car Data arises from the fact that measurements are carried out by vehicles that “float” among the rest of traffic. Often FCD is also referred to as probe data; data measured from probe vehicles in traffic. Depending on the method of data acquisition, it is possible to measure the location, speed and acceleration of a probe vehicle continuously or with constant time intervals. Common methods of FCD collection are measurement from GPS devices (Fleet management, anti-theft devices, cell phones and in car navigation), measurement from cell phones, remote sensing technologies and tracking equipment (blue-tooth and camera). For use in this case study, FCD from GPS and cell phones is elaborated.

4.4.1. Global Positioning Systems

GPS or Global Positioning System is developed by the U.S. Department of Defense as part of their NAVSTAR program which started in 1967 (Herring, 1996). The GPS uses a network of 24 (or more) satellites to determine the location of a signal receiver on earth. The satellites are uniformly arranged in six circular orbits which makes a location on the earth visible 24 hours per day for at least three satellites (Grewal, Weill, & Andrews, 2001). Similar systems are developed by Russia (GLONASS) and the European Union (Galileo) which is still under development.

The GPS measures the distance from satellites to a location on earth. The location of the satellite is transmitted together with a time reference signal. A receiver on earth uses the distance/time measurement to calculate the exact distances at a specific moment in time. If the distance to at least three satellites is known, the location of the receiver in the X,Y,Z plane is derived. In practice there are four satellites needed for accurate location measurement. Atmospheric refraction causes interference in the clocks of the satellites and a fourth satellite is

required to adjust for small timing errors which decrease the accuracy of the results. Figure 16 shows an example of this method.

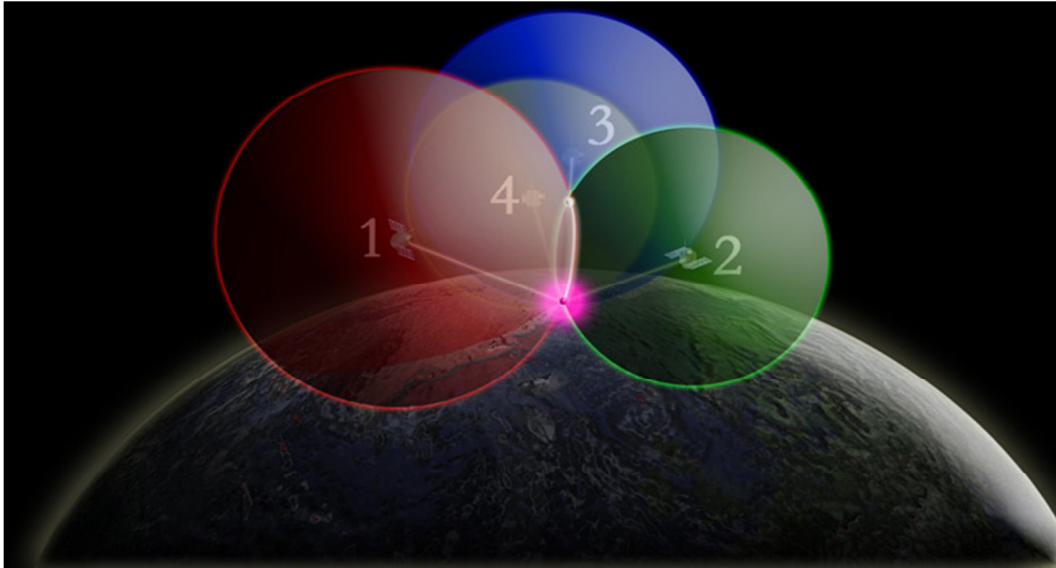


Figure 16 Determination of a location with GPS(U.S. Department of Commerce, 2011)

The accuracy of GPS equipment depends on a great number of factors and can range from 1 millimetre up to 30 meters. Important factors in the accuracy of the measurements are the amount of satellites available (visible from the receiver), the local detector that is used, the local terrain and local weather. Currently available consumer GPS products provide an accuracy of approximately 5-15 meters (www.GPSaccuracy.com), but the newest products can reach an accuracy of 3-4 meters during 95% of the time (www.tomtomgpspreview.com). Linking the measurements to a roadmap improve the accuracy of the measurements even more.

4.4.2. Cell phone positioning

Unlike GPS which is designed to calculate locations, cell phones are intentionally designed as a means of communication. Calculating the location of a cell phone is one of the extra possibilities of cell phone usage. The most common method of FCD collection from cell phones is a process of triangulation to determine the location of a driver. In the triangulation process a user is located by monitoring the cell phone towers which are closest to the cell phone. Each cell phone tower broadcasts a signal which can be received in a certain area. By checking the overlap of the broadcast area's the network operator can determine the position of a user within that area. The accuracy of these positions can range from 0.5 to 25 km depending on the number of cell phone towers available.(Figure 17).

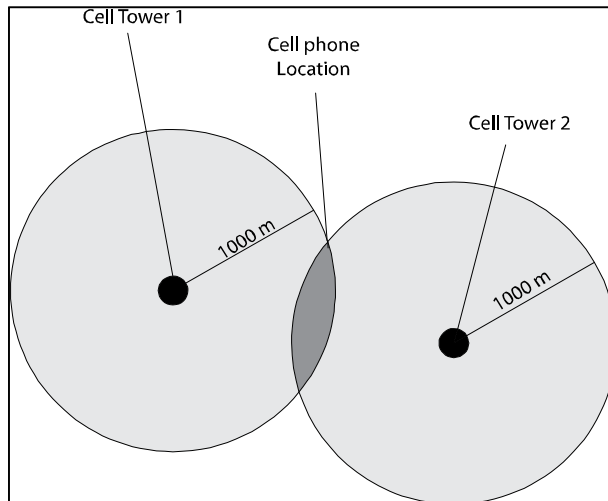


Figure 17 User location from cell phone towers

Currently network operators also use cell phone towers with directional antennas. The directional antenna's divide the broadcast area into multiple areas, enabling the operator to monitor the direction of a signal from the viewpoint of the cell phone tower. The smaller areas create more precision in the accuracy of the location, which can range from 50 to 5000 meters depending on the amount of cell phone towers available (Figure 18).

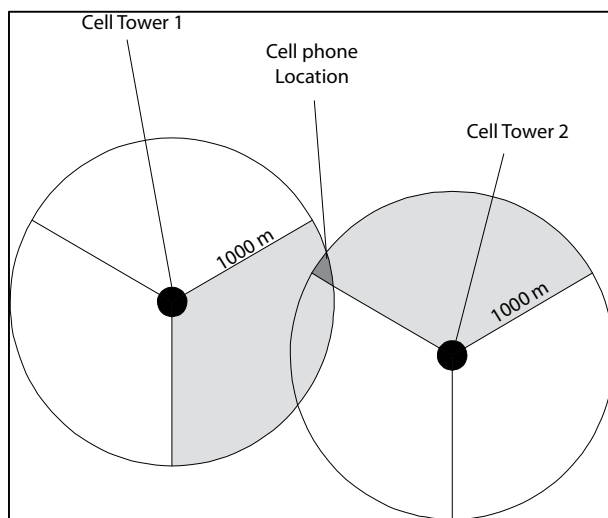


Figure 18 Driver location from cell phone towers with directional antennas

Again, linking the measurements to the local roadmap can improve the accuracy of the location by identifying the route of the user. An iterative calculation of the possible route of a driver increases the accuracy of the location, especially in rural areas. An important preliminary for triangulation is that the phone has to be active to calculate the location of the device. The phone becomes active during

phone calls, during the handover from one broadcasting tower to another or when it is activated (pinged) remotely.

4.4.3. FCD in traffic engineering

Although there are multiple systems available for FCD collection, they all operate from the same principle; the determination of a vehicle's location at a specific moment in time (van Lint, 2005). The level of accuracy and the amount of information which is collected depends on the method of data collection. Nonetheless all methods at least comprise a determination of the location of an unique vehicle, at a specific moment in time. This information is used to determine a vehicle's speed, acceleration, travel time and route choice. The determination of a location X,Y (or X if the vehicle is linked to a road) and the moment in time T, makes it possible to determine the travel time of a vehicle on a route. From the travel time the average speed and acceleration for a time interval Δt are calculated (Figure 19).

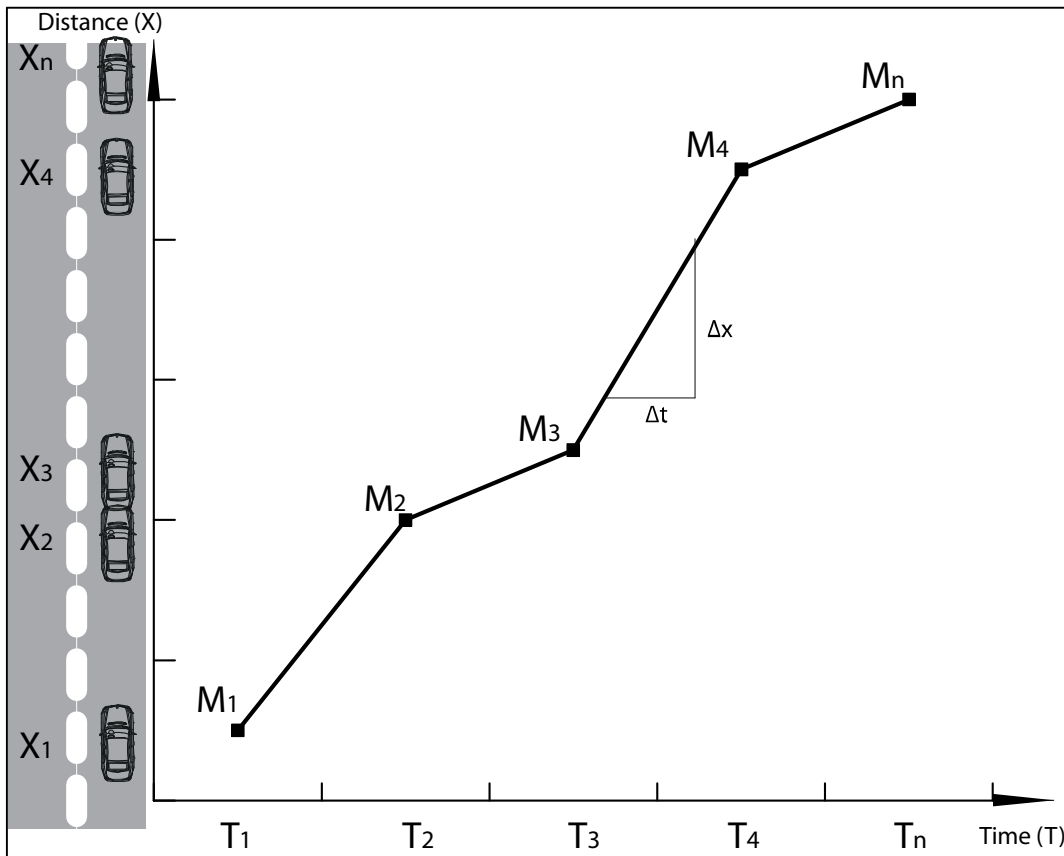


Figure 19 Determination of travel times from FCD measurements

M_n	:	Measurement point
T_n	:	Time of measurement
X_n	:	Location of measurement

From the location of the vehicle, the travel time is derived:

$$\text{Traveltime}(X_{n+1} - X_n) = T_{n+1} - T_n$$

Equation 8

The travel time is the calculated average for a single vehicle. The accuracy of the measurement depends on the accuracy of the location measurement and the time interval between subsequent measurements ($T_{n+1}-T_n$). From the travel time difference the average speed and acceleration is calculated.

FCD can be used for other purposes next to the measurement of locations which was investigated by (Huber, Lädke, & Ogger, 1997). By monitoring not only the location and the route of a vehicle but also other electronic equipment in the car, FCD is extended with additional sources of information. Data on local traffic conditions, safety issues, driving aids and the local weather are derived from the equipment in the car. An example is the measurement of the activation of the windscreen wipers or rain sensors, which would indicate local rainfall. This information can then be used for weather predictions or dynamic traffic management(Chapman et al., 2010). Another example is measurement of activation of the hazard warning flashers or airbags, which could indicate an accident, enabling much quicker response rates of emergency services.

One important factor for the practical use of FCD in traffic engineering is the penetration rate of FCD. Not all vehicles are equipped with a receiver and only a part of the traffic is monitored. A prediction for all vehicles on the road is derived from analytical methods for sample tests and data enhancements. For these methods the accuracy depends on the uniformity of the vehicle distribution and the penetration rate of measured probe vehicles. Field and model studies indicate, depending on the road category and the quality of the traffic information that is required, a minimal penetration rate of 0,1 to 5% (M. Chen & Chien, 2000; Cheu R L, et al., 2002; Neumann, 2009; Wagner, et al., 2007).

4.5. Dataset 2: TomTom probe data

TomTom is one of the leading suppliers of in-car location and navigation products and services. With a GPS location detector, in vehicle navigation is available for everyone almost anywhere in the world. Tracking the location of individual drivers makes it possible to derive the speed, location and route choice of individual drivers. Combining data of all individual drivers results in a database containing traffic information of the complete road network. The process of collecting GPS measurements, linking these measurements to the local road network and transforming them in traffic information is an extensive procedure. The accuracy of the traffic information needs to be monitored and the privacy of individual users needs to be protected.

This section explains the methods and technology which are used in the collection and storage of probe data by TomTom for the dataset which is used in the case study. Because of the lower accuracy of cellular location data (see section 4.4) the dataset which is used for the case study comprises GPS measurements from Portable Navigation Devices. In this section the collection and filtering which are used to process data from consumer GPS navigation devices is described. Furthermore the storage process is described explaining how single GPS measurements are linked to a route and the road network.

4.5.1. Probe data collection

TomTom collects probe data from multiple sources under consent of their users. The data which is collected comprises both historical and real time traffic information. The data is used to calculate travel time predictions which are used in traffic information for consumers in the products IQ Routes™ (historical) and HD Traffic™ (real-time). TomTom also provides this information for businesses and governments reducing congestion on the road network (TomTom Traffic Manifesto, 2011). Probe data is collected from PND (through connection with a home computer or real time with a mobile connection), mobile phone applications, built in navigation equipment and fleet management products. Figure 20 shows an overview of the data sources for the TomTom FCD database.

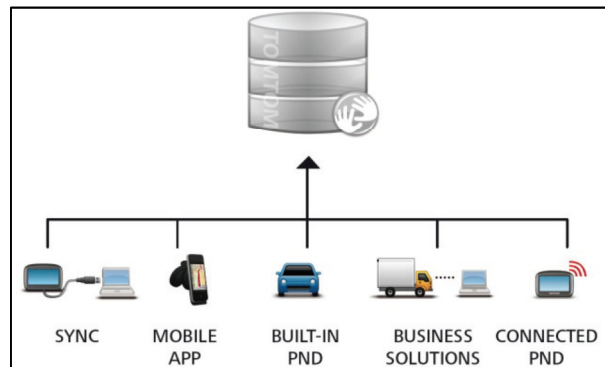


Figure 20 Data sources for TomTom traffic information

In traffic engineering probe data can be used for historical analysis (analysis from an afterward perspective) or for real time applications. Historical data is collected from TomTom PND devices which are connected with the TomTom server by users on their home computer. Collection of probe data from consumer GPS navigation devices on a real-time basis comprises connected devices, mobile phones and built-in navigation equipment. The analysis of probe data from consumer GPS navigation devices for real time applications is beyond the scope of this research and only the historical data is used. The dataset which is used for the case study consists of historical GPS measurements collected from portable navigation devices.

The data which is collected comprise GPS measurements which are sorted per trip and are stored locally on the device until they are sent to the TomTom database. The GPS measurements indicate the time and location of the device for a trip but are not matched to a specific road and do not indicate the specific user of the device. User information is not stored as part of the privacy filtering for consumer GPS data which is explained into more detail in section 4.5.2. Figure 21 shows a visual example of the collected measurements.

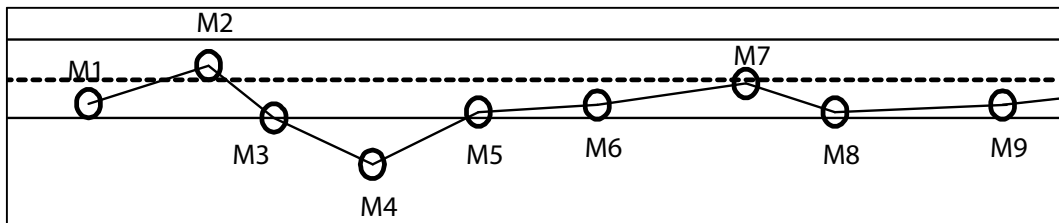


Figure 21 Example of GPS measurements before filter algorithm

4.5.2. Privacy filtering

Tracking and storing of the location of persons provides many possibilities but is also bound to rules of privacy. To a certain extent it is allowed to track someone's location, but there are restrictions by law. In The Netherlands this is stated in the Law for protection of personal data (Ministerie van Justitie, 2000) Even if there is consent of a driver to use their location for traffic products, privacy filtering needs to be applied before the data is collected and stored.

The data in the case study is processed by privacy filters at TomTom. Multiple filters are applied to ensure complete privacy for TomTom users. The most important change which is made for this case study is the removal of the device-id. The removal of the device-id is done to ensure that the device cannot be matched to a specific driver. The PND is assigned a new random device-id every day. In this way it is possible to track a device, without tracing the device to a specific individual. For intersection analyses this means that the driving behaviour of a single user can only be analysed for a single day.

4.5.3. Storage and processing

After collection, privacy filtering and storage the GPS measurements are linked to a map of the road network. The roadmap is a digital TomTom[®] map consisting of links which define the local road characteristics, i.e., the allowed maximum speed, number of lanes, the functional road class and the segment length. The links in the network as edges; line segments of one dimension joining two zero dimensional vertices in a closed shape. The edges indicate a connection between two points but they do not indicate the driving direction on the road segment. The length of the edges is determined by the geometrical layout of the road and an edge is split into smaller edges at changes in the road geometry: curves and corners, intersections and lane change areas.

Individual measurements are linked to the roadmap with a multiple step algorithm described as Map-Matching. The Map-Matching process is important for the commercial application of FCD from consumer navigation. Separate location measurements are combined to determine the route and travel time of a probe vehicle in the network. For the study in this report a schematic overview of the map-matching process is presented for historical data from unconnected Portable Navigation Devices. A more detailed description of this process is beyond the scope of this research and is described by (Bischoff, 2011).

- The first step of map-matching is the selection of a single device. As explained in section 4.5.2 an anonymous tracking id is generated daily for all devices. For the selected device the GPS measurements are categorized per day. In this first step the measurements are normalized to detect relevant stops within the movement of the corresponding vehicle.
- The next step in the process is linking the individual measurements to the roadmap. The selected GPS receivers provide an estimated horizontal accuracy of approximately 22 m with a 95% probability. This probability holds 24 hours per day in all weather conditions all over the world. Thus for every GPS position a circular region of 22 m can be defined which contains the real position of a vehicle with a probability of 95%. The selected area often contains multiple road segments which are stored as a possible location of the vehicle (Figure 22). If no segments are found the radius is increased (up to a certain boundary). If there are still no segments in the selected area, the measurement is discarded. After this process the next measurement in time is selected and the process is repeated for that measurement.

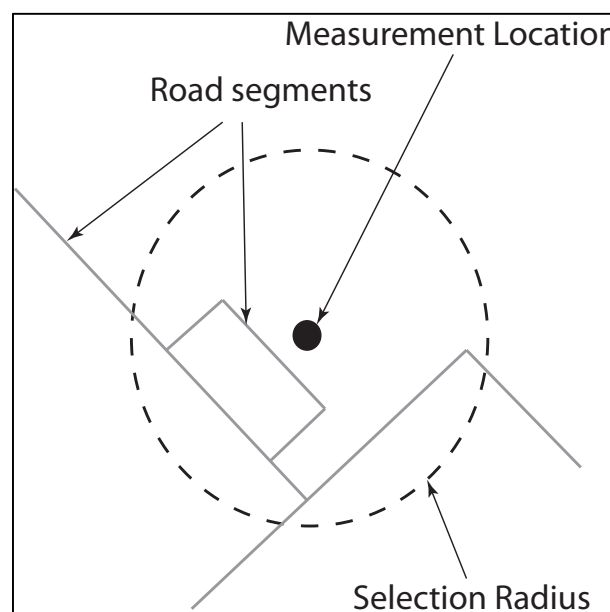


Figure 22 Segment selection in the map-matching process

- The next step in the process is determining the possible routes on the roadmap between the two measurements. Using a multi-source, multi-destination Dijkstra algorithm all possible routes between the two points are determined. The most likely route between two measurements is selected based on the distance to the segments, the local road speeds and the time between measurements.
- Hereafter the process is repeated for the next measurement in time. The process is slightly modified; with each new measurement the Dijkstra algorithm takes into account the previous most likely route. In this way the accuracy of the route is increased with every new measurement. The end of a route is set if the time between two subsequent measurements is higher than a pre-set limit, e.g., if two measurements are 10 minutes apart it is assumed that both measurements belong to two different trips. When the assessment of a route is complete, the route is analysed in a backwards direction, which increases the accuracy of earlier measurements in the route.
- The final step in the process links travel times to the route. For this step the route is transformed to a 2d stretch of road and the measurements are linked to their longitude location on the road. Combined with the time of measurement and the length of the road segments, the passage times in the route are calculated (Figure 23).

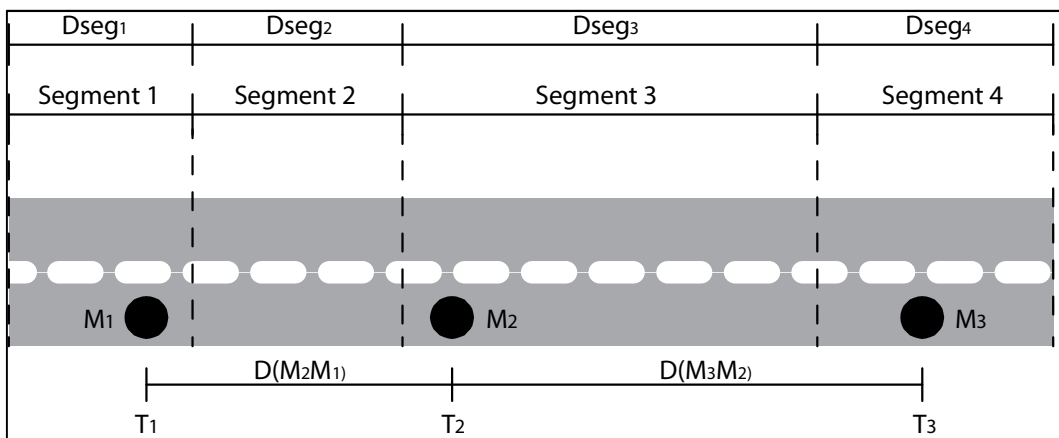


Figure 23 Matching measurements to a digital roadmap

The map-matching process transforms the GPS measurements into the final probe dataset which is used for commercial purposes by TomTom. Before the map-matching process the dataset contains information on individual measurements. After the map-matching process the information describes the travel time per segment of the route (Figure 24). The dataset thus contains per device the routes which are driven, the segments which make up the route, the entry time of the segments and the travel time on these segments. The timestamp of the measurements is stored in milliseconds but after the segmentation process measurements are stored with an accuracy of 0,1 second.

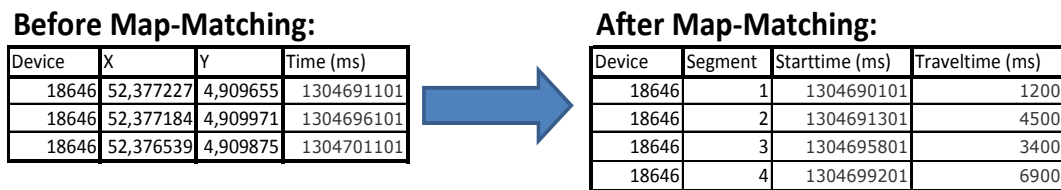


Figure 24 Transformation of probe data

After the map-matching process the location measurements are combined with the coordinates of the local road network. An advantage of the map-matching process is the increased accuracy of the location of a vehicle. A disadvantage is the fact that if the length of a segment is longer than the travel distance of a vehicle between two subsequent measurements, data aggregation causes data loss. Storage of the original data provides the opportunity to select the most suitable dataset for each purpose. Commercial application of probe data from consumer GPS navigation devices requires filtering and map-matching and the use of the original data is beyond the scope of this research project.

4.6. Data collection approach

Probe data collection and data collection from stationary detectors have a different approach to the measurement of traffic data at intersections. Both data formats are applicable for the determination of performance measures at intersections but different approaches are required to derive this information. As described in section 4.5 probe vehicles enable measurement of route choice and travel time for a part of the vehicles. Loop detection measures all vehicles but can only provide the vehicle traffic volume at a fixed location. Figure 25 shows the collection approach of both data collection methods at an intersection. For a single probe vehicle the collection and storage of data on a crossing movement is described.

Loop detectors measure the traffic volume at the location of the detector. The detectors send a signal at the activation of the loop and at the deactivation of the loop (section 4.3.1). The deactivations (up flanks) of the loop are selected as the passage time of a single vehicle at the location of the detector. Unique detectors at queuing lanes measure the passage times of vehicles for that crossing movement.

The probe data is stored as travel times on individual road segments (section 4.5). By identifying the passage time at a road segment upstream of the intersection and the passage time downstream of the intersection the entry and exit time for a specific movement are derived (Equation 7). The difference between both measurements provides the travel time.

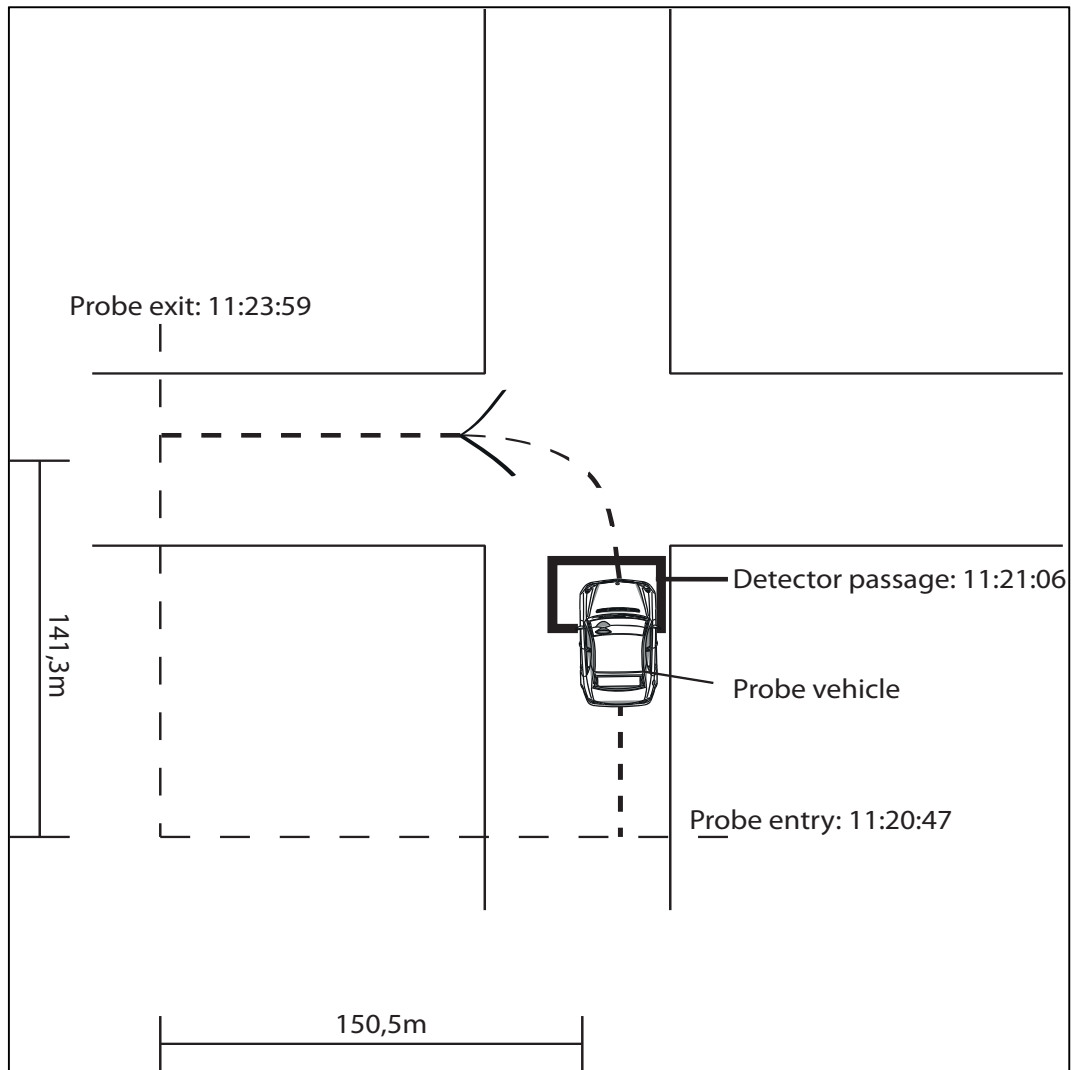


Figure 25 Data collection for the movement of a single vehicle

The datasets which are used in the case study are both used to measure passage times at the intersection. The added value of the probe data is the fact that it measures an entry and exit time, instead of the detector which only measures the passage time at the stop line. If the method is applied to both datasets it shows how a single probe trajectory fits into the total traffic volume. Figure 26 shows the data which was used to derive the example in Figure 25. It shows the entry and exit time of a probe vehicle at the intersection and the up flanks which are used as indication of a vehicle passing the detector. The arrow is used to indicate the most likely link between the measured probe vehicle and the corresponding loop detection activation. This link is derived from the average travel speed at the intersection and the length of the road segments.

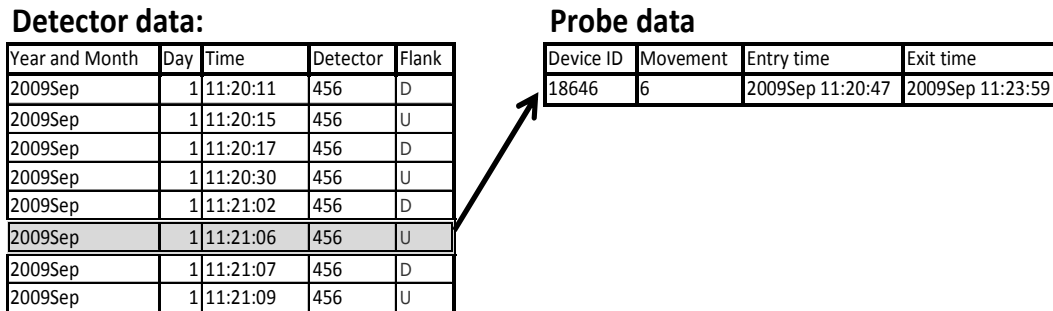


Figure 26 Linking probe data and stationary detector data measurements for the movement of a single vehicle

4.7. Summary

In this chapter the collection of traffic data at intersections was analysed and the two datasets for the case study analysis were introduced. The first dataset comprises loop detection traffic counts and green time measurement at Traffic Control Devices. The second dataset consists of historical probe data measurements collected with consumer GPS navigation devices. The chapter discussed the third and fourth sub questions: “How does data from stationary detectors provide traffic data for intersection analyses?” and “How does probe data from consumer GPS navigation devices provide traffic data for intersection analyses?”.

Stationary data collection is the most commonly used method for intersection performance studies. The presence of loop detection at signalized intersections enables the measurement of traffic volume. The green activation detectors which are installed at the signal control device measure the passage time of vehicles and this information is used to derive the traffic volume. The Traffic Control Device can be adjusted to measure the duration of the green times at the intersection which provides input for travel time delay models. The first case study dataset comprises traffic counts from loop detectors and green time measurement at Traffic Control Devices which are collected by Regiolab Delft.

The collection of Floating Car Data comprises the determination of a vehicle’s location at a specific moment in time. The measurement of the driving characteristics of probe vehicles in the network results in trajectory data or probe data. The use of consumer GPS navigation devices provides network-wide probe data but requires map-matching and privacy filtering to use the data for traffic studies. The second case study dataset is part of the TomTom Floating Car Database. The data consists of historical probe measurements from Personal Navigation Devices.

In the next chapter a case study is presented to evaluate probe data from consumer GPS navigation devices for intersection analyses. Two test case

intersections are presented and the calculation of route choice, delay, queue length and stop rate are described for the datasets which were introduced in this chapter. Chapter 6 presents the results of the case study.

Chapter 5

Case study analysis

5.1. Introduction

The case study evaluation comprises a comparison of primary measures of performance derived with the two datasets presented in Chapter 4. The comparison evaluates if probe data collected from consumer GPS navigation devices provides an accurate and reliable data source for performance measurement at intersections. The datasets comprise traffic counts from loop detection and probe measurements from consumer GPS navigation devices. Data collection from loop detection is a commonly used method for intersection analyses (Chapter 3) and is used as a reference. For the case study two intersections are analysed which are monitored by Regiolab Delft. For each intersection the route choice distribution and three measures of performance (delay, queue length and stop rate) are analysed.

In this chapter the measures of performance from Chapter 3 are applied to the datasets which are described in Chapter 4. This chapter describes the calculations of the case study analysis and the setup of the evaluation. In section 5.2 the case study approach is explained and the method of evaluation is described. In section 5.3 the location, the layout and the time period of the case study are presented. In section 5.4 the data collection process for the case study is described. In this section the uniformity, filtering and sample size for the case study are explained. In section 5.5 the measurement of route choice at the test case intersections is explained. In sections 5.6 and 5.7 the case study approach for delay, queue length and the number of stops is explained. The measurement approach is described separately for the probe dataset and for the reference dataset.

5.2. Case study approach

This section describes the study approach and the measurement setup at the intersections in the case study area. The study approach is chosen to fit the research question (section 1.3), the objectives of intersection performance measurement (section 3.2) and the reference model presented in section 4.3.3.

The evaluation of probe data from consumer GPS navigation devices for the analysis of intersections evaluates four parameters of intersection performance

measurement. An analysis of route choice, time delay, queue length and stop rate is conducted. The route choice is first assessed to determine the representativeness of the probe data compared to all traffic. The penetration rate of probe vehicles is calculated and the origin destination distribution of traffic at the intersections is compared. For the performance parameters a comparison with reference data calculated with loop detection traffic counts and TCD monitoring. The evaluation of each stage is fit to the sample size of the probe data and the availability of reference data. For the evaluation of route choice a comparison to a ground truth reference is conducted. For the evaluation of delay, probe data measurements are compared to delay estimations of a time-dependent stochastic delay model. For queue length and the number of stops a different approach is chosen. Both variables are not directly measured in the probe data and are estimated in the time-dependent stochastic delay model. To investigate the use of the probe dataset for calculation of queue length and stop rate at intersections an exploratory study is conducted. Table 3 shows the setup of the evaluation.

	Route choice	Delay	Queue length	Stops
Probe data	Measurement	Measurement	Estimation	Estimation
Reference	Measurement	Model estimation	Model estimation	Model estimation
Evaluation	Comparison to ground truth reference	Comparison of trend data	Exploratory study	Exploratory study

Table 3 Evaluation, reference data and input sources in the case study approach

5.3. Study area

5.3.1. Location

For the case study two intersections are selected which are located in the Regiolab study area. The intersections are located in the Dutch city of Delft, which is located in the West of the Netherlands and has approximately one hundred thousand inhabitants (CBS, 2010). The intersections are consecutive intersections at one road (the Westlandseweg) near the centre of Delft. The intersections are selected based on the quality of the data which is available from both datasets. For the remainder of the study the intersections are referred as intersection 1 and intersection 2 (labelled from West to East). For an overview of the location, see Figure 27.

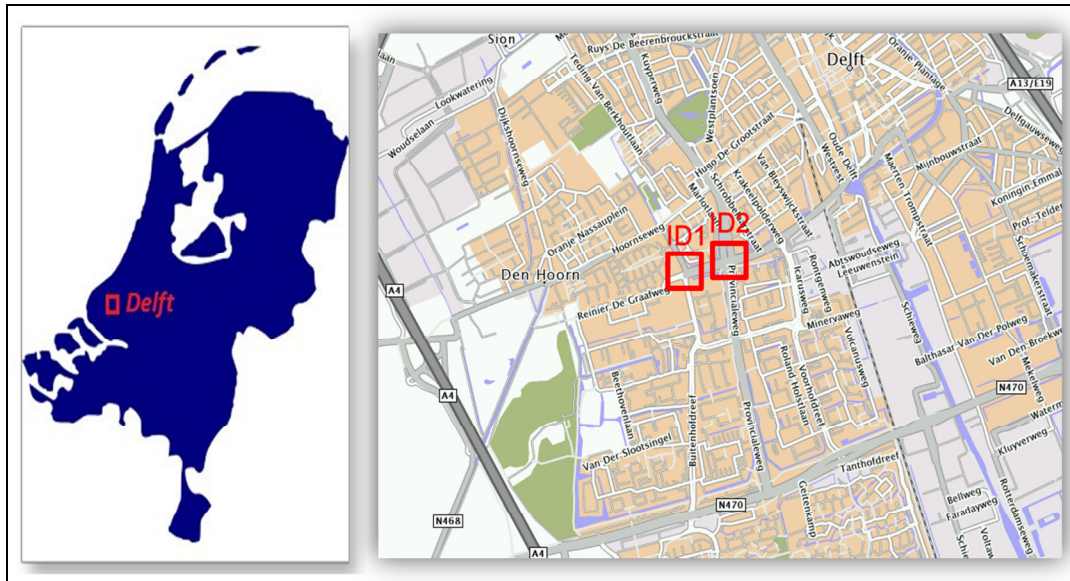


Figure 27 Location of the case study area, in the Netherlands (left), and in Delft(right)

5.3.2. Layout

The layout of the intersections is shown in Figure 28 and Figure 29. Both figures present an aerial overview of the intersections, an overview of the numbering of the movements, the edge map which is part of the TomTom digital roadmap and a map with the locations of the detectors at the intersection. For a complete overview of the location of the detectors and the lengths of the segments in the probe data map see Appendix A.

Intersection 1 is a four legged intersection with 2 pre-assigned public transport lanes for coaches. The detectors define 10 unique movements at the intersection except movement 7 and 8 which are not available from the loop detection data (Figure 28). The speed limits at the intersection comprise 70km/h on the main stream (East link) and 50km/h on the secondary streams. The intersection handles a total traffic volume of approximately 27000 vehicles per day.

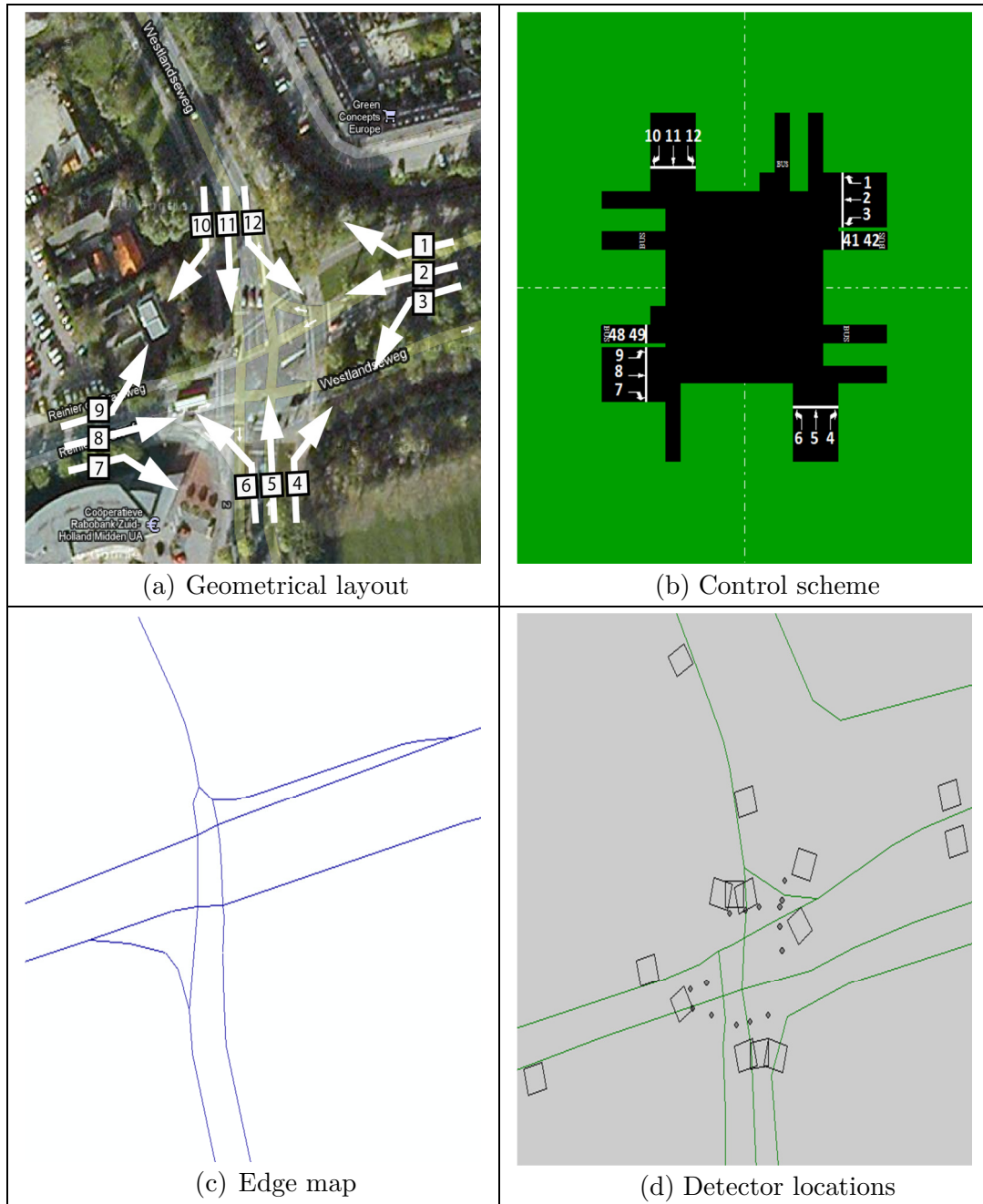


Figure 28 Geometrical layout, signal control scheme, edge map and detector locations for intersection 1

Intersection 2 is a four legged intersection with no pre-assigned public transport lanes. The detectors detect all unique movements at the intersection. For movements 2,3,6,8,9 and 12 follow-up streams are used, with extra signals and queue lanes at these movements (Figure 29). The speed limits at the intersection comprise 70km/h at all links. The intersection handles a total traffic volume of approximately 17000 vehicles per day.

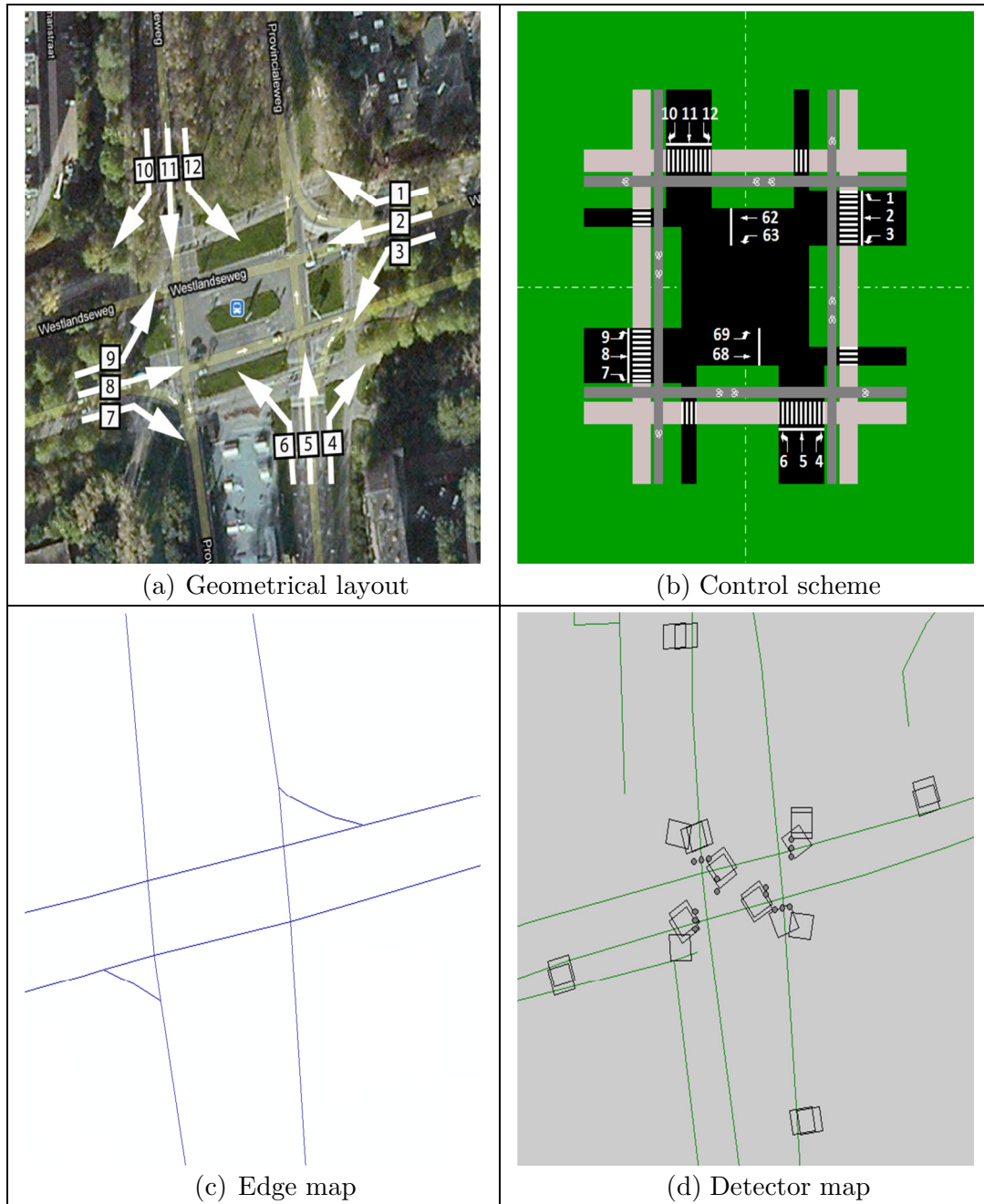


Figure 29 Geometrical layout, signal control scheme, edge map and detector locations for intersection 2

5.3.3. Time period

The time period of the case study analysis is selected by assessment of the minimal malfunction rate of the Regiolab loop detectors and the maximum coverage in the TomTom database (see Chapter 4). The time period assessment takes into account the number of measurements from probe data (Figure 30) and the malfunction rate of the loop detectors at the intersections. First a period with the maximum amount of probe measurements is selected, hereafter the detector failure rate is taken into account.

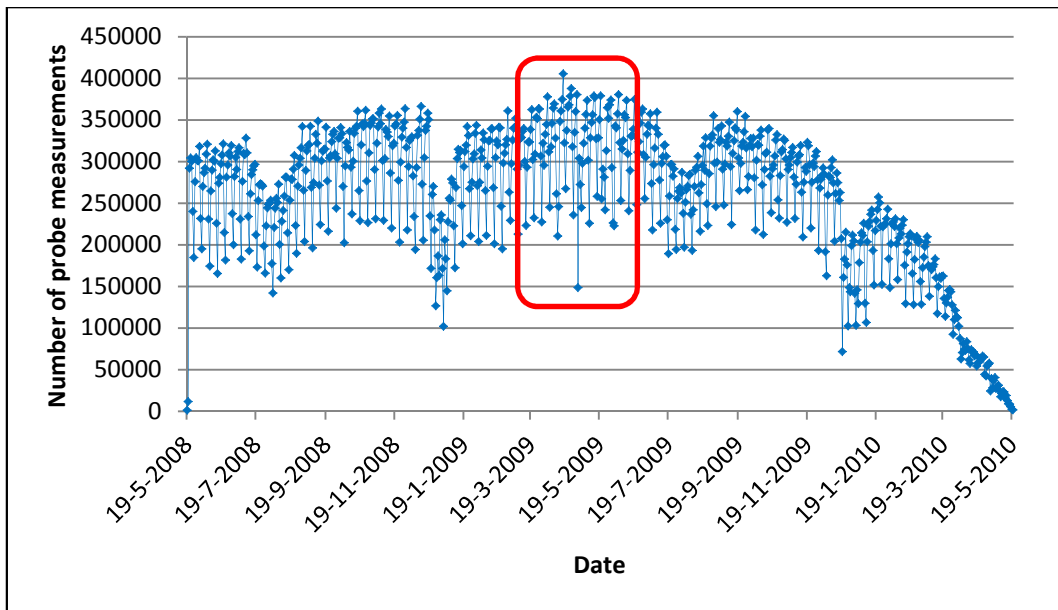


Figure 30 Number of probe measurements per day in the region of Delft (red: Selected time period)

Based on this analysis a time period of three months is selected. From the assessment of the probe measurements, April 2009 to June 2009 is selected as the time period for the case study. During the selected period the maximum number of probe measurements is available. During this period the overall malfunction rate of the detectors is 26% at intersection 1 and 59% at intersection 2. The malfunction rate is calculated as the average number of days per movement at which there are no measurements available. This calculation is done for the complete 3 month period and includes malfunctioning of single movements and also malfunctioning of the complete intersection.

	Intersection 1	Intersection 2
Single broken detectors	25%	16%
Data collection offline	1%	43%
Total malfunction rate	26%	59%

Table 4 Loop detection malfunction rate calculation

5.4. Data collection

5.4.1. Uniformity

The first step of the data collection process filters both datasets to ensure a correct and uniform dataset. Uniformity is desired to ensure that the results of the case study are representative for general traffic conditions. To this extent, certain dates are extracted from the data within the selected time period. The selected dates comprise (official) holidays in the Netherlands (Table 5).

Holiday	Date
Good Friday	10-04-2009
Easter	12-04-2009 & 13-04-2009
Queensday	30-04-2009
Libertyday	05-05-2009
Ascension day	21-05-2009
Pentecost	31-05-2009 & 01-06-2009

Table 5 Holidays during the case study period

The next step in the data collection process is the analysis of weekday patterns in the data. Based on traffic volume measurements from loop detection, the traffic volume is analysed per weekday. Travel patterns of workdays and weekends are clearly visible at most movements and at both intersections. Figure 31 shows a clear example of the weekday patterns at movement 5 at intersection 2.

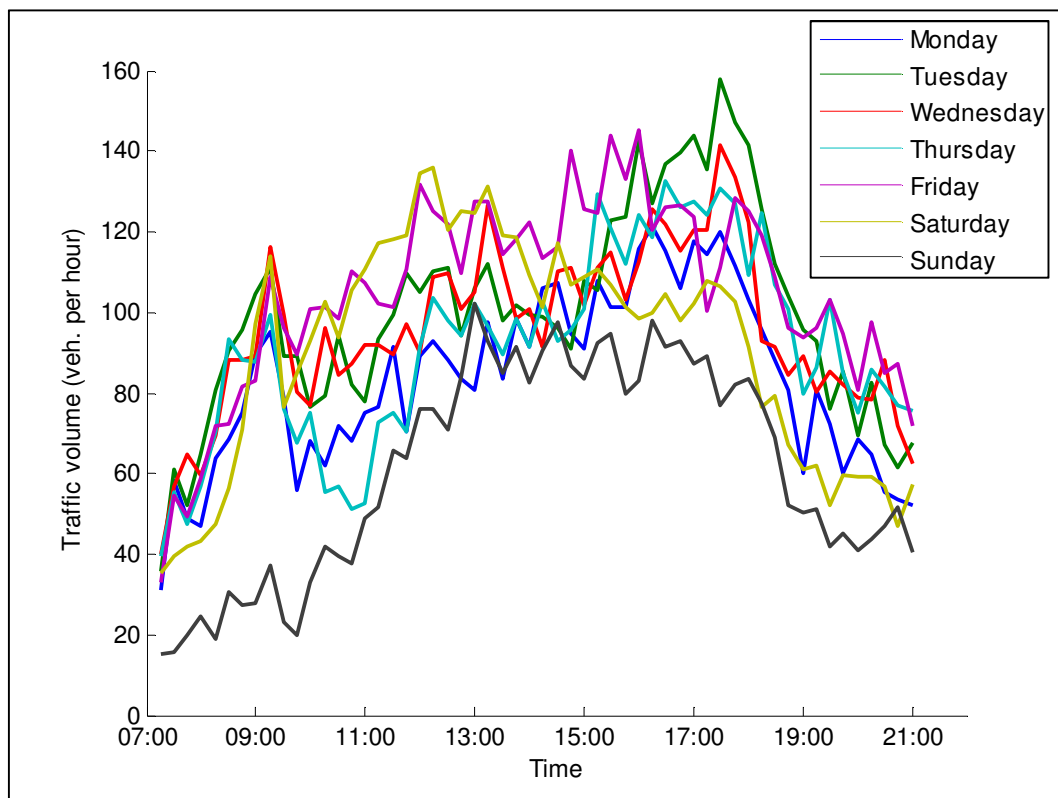


Figure 31 Average traffic volume per day for movement 5 at intersection 2

The weekday analysis shows that (most) weekends do not include the strong representation of the morning and evening rush hour periods. For this reason only work days are selected for the case study.

5.4.2. Filtering

After uniform data collection the quality of the data is assessed. Measurement systems are not 100% accurate and for this reason filtering is used to reduce the level of error. By setting a bandwidth for the measurements, errors and oddities in the data are identified and removed. For both datasets a separate filtering process is used to clean up the measurements. In this section the filtering steps is described and the results of the filtering process are provided.

For the loop detection data two filtering steps are used. The first step comprises the removal of data from broken or malfunctioning detectors. Malfunctioning detectors either produce traffic counts which deviate strongly from other measurements or produce no traffic counts at all. A visual analysis compares the traffic counts to results from other movements and time periods. If results deviate strongly or if no counts are measured during some part of a day, the complete day is marked as a faulty measurement period. In this case the complete day is removed from the data for that specific detector.

For the filtering of traffic signal monitoring a similar approach is used. The difference between both filters is the fact that the number of green times per hour is assessed instead of the traffic counts.

For the filtering of probe data two filtering steps are conducted. Both steps comprise an assessment of the measured movements and the length of the measured travel times. The first step removes travel times which are recognized as too low and the second step removes travel times which are marked as too high. For the low value clean-up, individual probe vehicle travel times are compared to an estimation of the minimal clearance times at intersections on the Dutch road network (CROW, 1992). Minimal clearance times describe the travel time required to cross the intersection based on the nature of the movement and the speed category. The filter removes probe vehicle measurements for measurements more than 20% lower than the minimal clearance time of the movement. The 20% margin is selected because the minimal clearance time provides an estimation of the minimal travel time. The margin ensures that only errors are removed from the data and not correct measurements. The filter results in an average removal of 0.2% of the measurements.

The second step of the probe data filtering is the removal of outliers from the measurements. Some of the travel time measurements in the data are very high (some over 10 minutes) and are assumed as a faulty measurement. A possible cause for these measurements are users who park their car and do not switch of their device during a travel time measurement. Because a clear maximum travel time is not defined, a sample test method is used to remove outliers in the data. For the selection of outliers the Grubbs test, a maximized normed residual test, is selected as described in (Salomons, 2010). The sample test method is used to

identify and remove outliers based on the deviation of a travel time measurement with the mean travel time of all samples. For each measurement the test statistic Z_i value is determined:

$$Z_i = \frac{|T_i - \mu|}{\sigma^2}$$

Equation 9

Z_i	:	test statistic value
T_i	:	travel time measurement
μ	:	sample mean
σ	:	sample standard deviation

The measurement is rejected if the value is higher than the critical test statistic value Z_{crit} . This value is determined by the reliability percentage which is set to 95%; a measurement is rejected with a 95% certainty that the measurement is actually wrong. If a measurement is rejected it is removed from the sample group and the test is repeated. The test is repeated until no outliers are detected and only the adjusted dataset remains.

After uniformity and error filtering, both datasets are used for the determination of the route choice and the performance measures: delay, queue length and stop rate at the test case intersections. For both datasets a different approach is selected for the calculation of these parameters as explained in section 5.2. For each parameter the calculation method is described.

5.5. Route choice

The first stage of the case study comprises the evaluation of route choice measurement at intersections. Route choice describes the division of traffic flows at the intersection which is represented by the Origin and Destination of traffic. This evaluation step provides the background for the results of the performance study and describes the level of penetration and the distribution of probe vehicles in traffic.

For both datasets the traffic volume is calculated per OD movement within a certain time period. The traffic volume is described in the OD ratio of traffic at the intersection. The probe data OD ratio is compared to OD distributions from traffic counts with loop detectors.

5.5.1. Probe data

The route choice distribution is derived from the number of probe observations per movement. The volume of probe vehicles per movement results in the OD distribution per unit of time. The volume per movement provides the input for

the OD ratio of traffic at the intersection and is used to describe the percentage of all probe vehicles for each movement.

5.5.2. Loop detection

The reference for the probe data results comprises OD distributions derived from loop detection traffic counts. Individual traffic counts from loop detectors combined with the conservation of vehicles result in the OD distribution at the intersection. Not all movements are measured with a unique detector which requires extra processing to calculate the OD distribution. The conservation of vehicles is used to calculate the traffic volume for each separate movement. At the test case intersections loop detectors are sometimes placed upstream and downstream of the intersection measuring the traffic volume of all vehicles. Because no vehicles are “lost” at the intersection the traffic volume at individual movements is derived. An example of this calculation is shown in Figure 32.

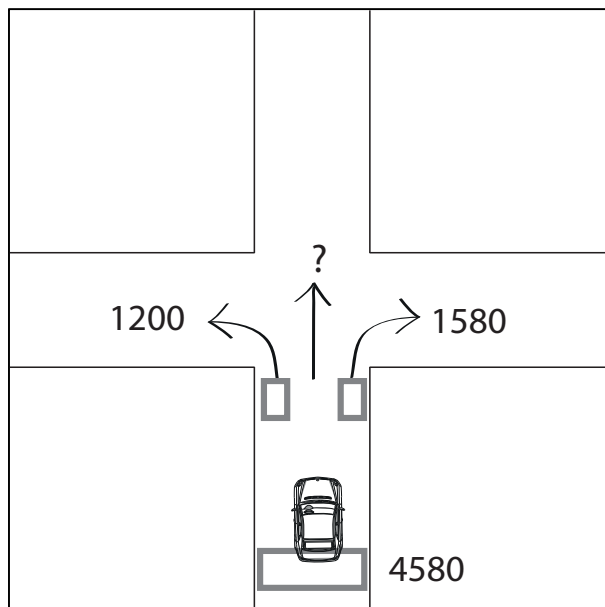


Figure 32 Loop detection traffic volume measurement at movement 10, 11 and 12 at intersection 2 during a one day period

As shown in the example the traffic volume is measured at the left and right turning movement with unique detectors. The total traffic volume on the link is also measured. The resulting traffic volume on the through movement is derived: $4580 - 1580 - 1200 = 1800$ vehicles/day

The resulting traffic volume distribution at the intersection is used to derive the OD ratio. The OD ratio describes the percentage of the total traffic volume per movement in the measurement period.

5.5.3. Assessment

For the assessment of route choice the OD distribution is compared to the distribution derived from loop detection data. Based on reference studies (C. Chen, et al., 2003) the level of error for the loop detection data is assumed to be close to zero and the distribution is assumed as a “ground truth” reference for the probe data results.

The difference between both distributions is considered as the error in route choice measurement of the probe dataset (for n movements):

$$\mathcal{E} = \frac{1}{n} \sum_{i=1}^n \text{abs}(V_{ref,i} - V_{prd,i})$$

Equation 10

\mathcal{E}	:	Average absolute error per movement
$V_{ref,i}$:	Traffic Volume ratio derived from reference data for movement i
$V_{prd,i}$:	Traffic Volume ratio derived from probe data for movement i

The definition of error determines the accuracy of probe data for the measurement of route choice at intersections. To investigate which factors (sample size, penetration rate, measurement frequency) influence the outcome of the study an analysis of the error related to these parameters is conducted.

The assessment of the sample size comprises a calculation of the error while iteratively increasing the sample size. The assessment provides the optimal sample size for route choice analysis at the test case intersection. The probe data is collected on a historical basis and the penetration rate and measurement frequency of the probes cannot be changed. The measurement frequency remains constant but the level of penetration changes over time. It is possible to measure the error compared to the penetration rate. An assessment of the penetration rate comprises calculation of the error for each individual day in the study period. From these results the influence of the level of penetration on the level of error is derived.

5.6. Delay

The delay at intersections is described as the difference between uninterrupted and interrupted travel times through the intersection (Section 3.3.2, Definition 6). Measurement of travel times occurs by measuring the time difference between the arrival and departure of a vehicle at the intersection. The measurement of delay from consumer GPS navigation devices is evaluated by using a comparison with results from a time-dependent stochastic delay model (section 4.3.3), traffic counts and signal monitoring.

5.6.1. Probe data

With probe data the travel time of vehicles is directly measured. Travel times of probe vehicles are measured by comparing the difference between the passage times upstream and downstream of the intersection (section 4.6). To ensure minimal influence of external factors and driving behaviour, the arrival and departure locations should be far enough from the intersection to include the braking and acceleration behaviour in the measurement of the travel time. The measurement of delay requires knowledge about the free flow travel time of a movement. A method is proposed for the measurement of the free flow travel time at the intersection. Based on the local speed limits and the nature of the crossing movement (left, right or through), a reference free flow travel time is calculated with the Dutch clearance time guidelines (CROW, 1992). In an iterative process 2% of the lowest measured travel times are selected and are identified as free flow movements if it is within an accepted 95% probability interval of the reference free flow travel time. The average travel time of the free flow movements is set as the free flow travel time.

The proposed method ensures that a maximum sample size is used for the calculation of the free flow travel time, which increases the reliability of the measurement. An advantage of this method is that the calculated free flow travel time is actually measured and is fit to a specific intersection and movement. Factors which influence the free flow travel time such as the layout and surroundings of the intersection are automatically taken into account. A downside of the proposed method is the fact that the calculated free flow travel times already take into account the delay caused by the signal control device.

Implementation of the free flow travel time in Equation 7 provides the delay per probe vehicle crossing:

$$T_{Delay} = (T_{Departure} - T_{Arrival}) - T_{Free-flow}$$

Equation 11

T_{Delay}	:	delay time per vehicle
$T_{Departure}$:	departure time downstream of intersection
$T_{Arrival}$:	arrival time upstream of intersection
$T_{Free-flow}$:	free flow travel time

The individual probe vehicle delays are combined to create the average delay distribution which is suited for LOS and PI performance studies. The aggregation of multiple probe movements lowers the variance of the measurement and increases the reliability of the distribution.

5.6.2. Reference model

The delay of vehicles at intersections is not directly assessed by traffic counts from loop detectors which, apart from a few experimental cases, only measure traffic volume. In this research study a time-dependent stochastic delay model (section 4.3.3) is selected for the estimation of delay based on traffic counts from loop detectors and signal monitoring. The average delay is calculated to serve as a comparison for the probe data delay distribution.

The approximate value of total delay (delay rate) for a movement at isolated fixed time signals (D in vehicle hours per hour, or ‘vehicles’) is expressed as follows:

$$D = \frac{qc(1-u)^2}{2(1-y)} + N_0x$$

Equation 12 (Akçelik, 1981)

D	:	mean travel delay time
qc	:	effective red time
u	:	green time ratio (Equation 5)
y	:	flow ratio (Equation 6)
N_0x	:	overflow factor

For the determination of the flow ratio the saturation rate is used to determine the traffic demand and capacity of a link (Equation 6). The saturation flow of a movement at the intersection is derived from measurement in the field or from estimation. The loop detection data does not enable the measurement of the saturation flow and calculation by estimation is selected.

An estimation method for the calculation of the saturation flow on a movement at an intersection on the Dutch road network is described in (van Zuylen, et al., 2009). The expression for the saturation flow is based on the saturation flow of a single lane road under standard conditions. The standard saturation flow is set to 1800 passenger car units (pcu) per hour. With an adjustment factor for the geometric conditions of the intersection the final saturation flow is calculated:

$$s = \beta_1 \cdot s_0$$

Equation 13 (van Zuylen, et al., 2009)

β_1	:	adjustment factor for geometric conditions
S_0	:	basic saturation flow (1800 pcu/h)

For the value of the adjustment factors there are multiple reference guides but the HCM is advised. For the case study the standard HCM values are selected and adjusted to fit the local road geometry if possible. For the case study the

adjustment factor is changed to include the effect of left and right turning movements on the saturation flow.

The final stage of the calculation comprises the calculation of the average delay per vehicle. To this extent Equation 12 is divided by q (the flow in vehicles per second).

$$d = \frac{D}{q}$$

Equation 14 (Akçelik, 1981)

Equation 14 provides the average delay per movement per cycle. To create an equal comparison the results are matched to the probe data distribution. The average delay per individual cycle is aggregated in 15-minute intervals which is equal to the probe data distribution.

5.6.3. Assessment

For the assessment the average delay distribution of both datasets is compared. In the case study no ground truth reference is available for comparison. The time-dependent stochastic delay model provides an estimation of the average delay and acts as a guideline to analyse the credibility of the results. The time period between 07:00 and 21:00 is examined which provides the most interesting period for delay performance analysis. The average delay is calculated for 15-minute aggregation intervals. An analysis of the number of probe measurements shows that 15-minute intervals provide more granularity than one-hour intervals and for smaller intervals do not provide complete data coverage. Based on the available measurements at both intersections a 99% data coverage is acquired at both intersections for 15 minute aggregation periods between 07:00 and 21:00.

The evaluation of the delay distributions focuses on the deviation between both distributions, the influence of the sample size, the variance of the derived results and the total distribution of delay. The results are presented by means of examples.

5.7. Queue length and number of stops

Queue length and the number of stops as a measure of performance are not directly derived from the probe data. The data is stored as segment travel times which provides the delay of probe vehicles but not the location of a probe vehicle during the delay period. For queue length and stop rate a method is proposed to estimate these measures of performance from the probe dataset. For comparison the time-dependent stochastic delay model provides a guideline reference.

5.7.1. Probe data

The queue length is described by the number of vehicles in the queue or the length of the queue in distance (section 3.3.3). The probe data does not enable the measurement of queue length. The segment travel times do provide queue times which could be indirectly used for the calculation of queue lengths. Furthermore the stop rate is described by the average number of stops of a vehicle during a crossing movement (section 3.3.1) which is also not directly derived from the probe data.

To investigate how queue length and stop rate are represented in the probe data an exploratory study is selected. Reference studies demonstrate that the delay of vehicles at intersections is related to the length of queues and the number of vehicle stops (Comert & Cetin, 2008; Heidemann, 1994; Mung, Poon, & Lam, 1996; Neumann, 2009). To see if this is also represented in our probe data, a comparison is conducted.

In the digital map the length of the road segments is stored. For the comparison the length of the segment(s) before the stop line is combined with the delay at these segments. Assigning queue length intervals to the delay intervals provides an experimental queue length distribution (Figure 33). Defining stop rate intervals provides a similar approach for the determination of the average stop rate.

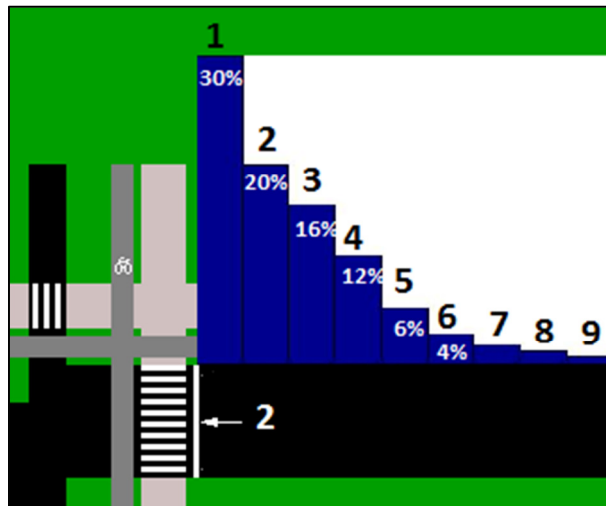


Figure 33 Experimental queue length distribution in vehicles for a movement derived from probe vehicle delay

For the application of this method the size of the delay intervals need to be defined. Without clear knowledge of the traffic signal state, the queue length or stop rate cannot be determined. Recent studies show that it is possible to identify the signal state with probe data by using Virtual Trip Line (VTL) technology (Ban, Herring, Hao, & Bayen, 2009; Y. Chen, Qin, Jin, Ran, & Anderson, 2011).

The use of sampled travel times and a penetration rate of 40% was found to be sufficient for reliable signal time detection. An exploratory study into the application of shockwave modelling showed signal timing detection at lower penetration rates (Y. Chen, Qin, & Ran, 2010). The presented studies use the unique locations of the probe vehicles to detect the signal timing. With only segment travel times available and a penetration rate which is a factor 80 below the indicated 40%, the determination of queue length and stop rate is not possible.

Although the probe data does not enable direct calculation of queue length and stop rate, a comparison of the delay distribution to the time-dependent stochastic queue and stop rate results is available. The comparison is selected to evaluate the probe data measurements compared to the estimations from the time-dependent stochastic delay model. Linear scaling is used to fit the probe measurements to the queue length and stop rate reference results.

5.7.2. Reference queue length

The calculation of the average number of vehicles in the queue at the start of the green period is defined in (Akçelik, 1981). The method assesses the arrivals at the stop line during the red phase of the signal cycle. The method assumes a build-up of the queue during the red phase which, together with the remaining queue from the previous cycle, determines the average queue length.

$$N = q \cdot r + N_0$$

Equation 15 (Akçelik, 1981)

N	:	average number of vehicles in the queue at the start of the green phase
r	:	effective red time in seconds (c-g)
N ₀	:	overflow queue in vehicles

It is possible for the queue to increase in size after the start of the green phase. To calculate the maximum back of the queue, the arrival of vehicles during the start of the green phase is also taken into account:

$$N_m = \frac{q \cdot r}{1 - y} + N_0$$

Equation 16 (Akçelik, 1981)

N _m	:	maximum back of the queue in vehicles
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The maximum back of the queue is expressed by the number of vehicles which are in the queue. Assigning an average length of 7.2m per vehicle in the queue provides the maximum back of the queue (section 3.3.3). The average

(maximum) queue length over a longer period of time is obtained by aggregating the results for each separate cycle.

5.7.3. Reference number of stops

The average number of complete stops per vehicle is defined in (Akçelik, 1981). The method assesses the stop rate at isolated fixed-time signals and is calculated from:

$$\bar{h} = 0.9 \left\{ \frac{1-u}{1-y} + \frac{N_0}{q \cdot C} \right\}$$

Equation 17 (Akçelik, 1981)

\bar{h} : average stop rate per vehicle
 N_0 : Overflow queue

It should be noted that the first term gives the proportion of stopped vehicles irrespective of how many times they are stopped. The second term allows for multiple stops in oversaturated cycles using the average overflow queue as a parameter. The effect of multiple stops becomes significant for degrees of saturation greater than about 0.8 (Akçelik, 1981).

The average number of vehicles stopped per cycle also corresponds to the maximum back of the queue N_m . The stop rate given by Equation 17 is obtained from N_m by applying a correlation factor of 0.9:

$$h = 0.9 \frac{N_m}{qc}$$

Equation 18 (Akçelik, 1981)

For the case study the average number of stops per vehicle is obtained over a longer period of time. The analysis is carried out for each separate cycle and the results are aggregated to match the intervals of the probe data delay distribution.

5.7.4. Assessment

For the assessment of queue length and the number of stops a scaling method is used. The average delay distribution of the probe dataset is scaled and compared to the average queue length and stop rate distribution of the time-dependent stochastic model. In the case study no ground truth reference is available for comparison. The time-dependent stochastic delay model provides an estimation of the queue length and stop rate and acts as a guideline to check for similarities or deviations. The time period between 07:00 and 21:00 is examined which provides maximum coverage for the probe data delay distribution. The average delay is calculated for 15-minute aggregation intervals and scaling provides an

experimental queue length and stop rate distribution. The evaluation examines the deviation between the probe data and the reference models. The comparison is carried out at a visual level and the results are presented by means of examples.

5.8. Summary

This chapter presented the setup of the case study for the evaluation of probe data from consumer GPS navigation devices in intersection analyses. The method for the case study and the calculations which are selected for this purpose were presented. The case study evaluates route choice, delay, queue length and stop rate measurement at two intersections in Delft. The chapter discussed the last sub-question: “What is the accuracy of performance measurement with probe data from consumer GPS navigation devices?”

The evaluation of route choice compares probe observations with loop detector traffic counts collected from traffic signal activation detectors. The evaluation of route choice serves as a background for the measurement of performance as it provides a clear overview of the distribution of probe vehicles in traffic. The reference which is used in this comparison is set as a ground-truth reference, which clearly defines the error of the probe data results.

Delay describes the difference between measured travel times and the undisturbed travel time at intersections. The probe data is used to calculate the delay and is compared to the results of a time-dependent stochastic delay model. The time-dependent stochastic delay model calculates delay from traffic volume and signal cycle analysis and does not provide a ground truth reference. The results of the model are used as a guideline reference for the analysis of the probe data.

Queue length and stop rate are not calculated from the probe dataset. These measures of performance are derived by assessing the traffic volume and the signal state at the intersection. The signal state is not measured from the probe observations which requires a higher penetration rate of probe vehicles. The use of segmented travel times can reduce the accuracy of the vehicle location, which makes the data less suited to measure the vehicle location in the queue. To evaluate the probe data for calculation of queue length and stop rate a comparison to a time-dependent stochastic model is performed. Scaling is applied to the probe data delay distribution and it is evaluated with an exploratory analysis.

The case study provides the basis for the evaluation of probe data from consumer GPS navigation for intersection analysis. The study focuses on performance measurement and the calculation of route choice. In the next chapter the results of the case study analysis are presented.

Chapter 6

Case study results

6.1. Introduction

Based on the case study method and the assessment approach presented in Chapter 5, the results of the case study are derived. The results of the case study are evaluated in a comparison study. The results of the study are elaborated in examples and hypothesis are presented and tested as part of the case study.

First in section 6.2 the measurement of route choice at intersections is evaluated. In section 6.3 the calculation of delay is evaluated. Section 6.4 presents the exploratory study for the determination of queue length and stop rate with probe data.

6.2. Route choice

The first stage of the case study comprises the evaluation of route choice measurement at intersections. The ratio of the traffic volume is calculated per crossing movement (section 5.5). The setup of the route choice analysis starts with the selection of an appropriate sample size i.e., the number of measurements for the probe data.

6.2.1. Sample size

The sample size is determined by the number of probe measurements and increases with the length of the data collection period. Small sample sizes do not provide a smooth distribution, e.g., if only four probes are measured a division for 12 movements is not possible. Larger sample sizes require longer collection periods which lower the level of detail and enable seasonal changes to affect the OD distribution. The assessment provides the optimal sample size for route choice analysis with the selected probe dataset.

The optimal sample size is derived by iteratively measuring the absolute error of the OD distribution from the probe data compared to the reference situation (Equation 10). At both intersections the sample size is increased by expanding the aggregation period with one day per iteration. Figure 34 shows the results of this analysis with the absolute error related to the sample size.

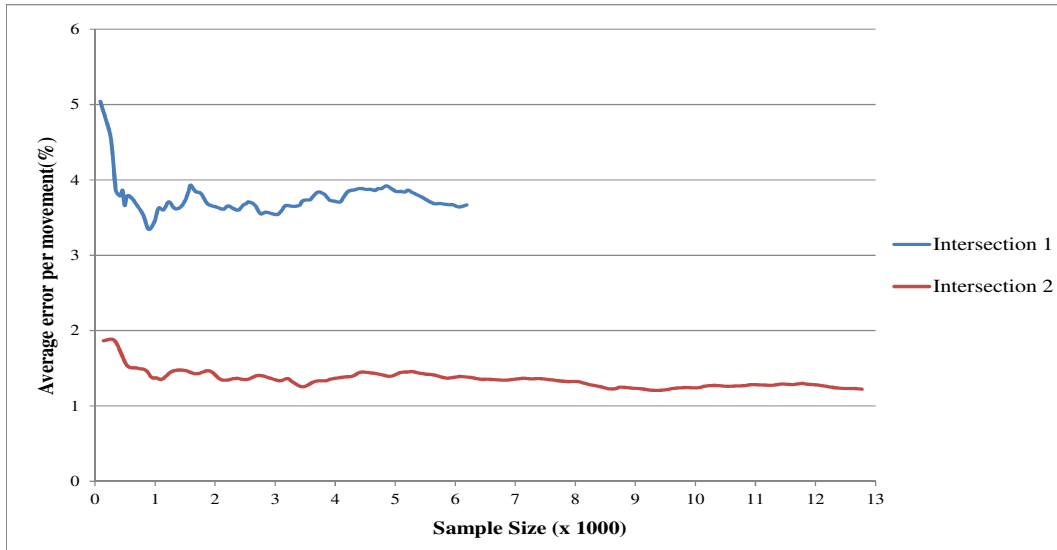


Figure 34 The average error per movement compared to the sample size of the research study

It becomes clear that the total error at both intersections approaches a constant level at approximately 1000 measurements. If the relative change in error is observed within a boundary of 0,1%, the stable region for the error at the intersections is found . At intersection 1 this is achieved after 12 days with a sample size of approximately 1100 measurements. For intersection 2 this comprises 8 days with a sample size of 900 measurements. It appears that the minimal error is obtained if the length of the collection period is fit to the optimal sample size. For smaller timeframes (for example morning rush hour) the calculation of the OD distribution requires a longer collection period to reach the optimal sample size. An analysis of the sample size in the morning rush hour shows that an aggregation period of 11 weeks is required for intersection 1 and this comprises 7 weeks for intersection 2.

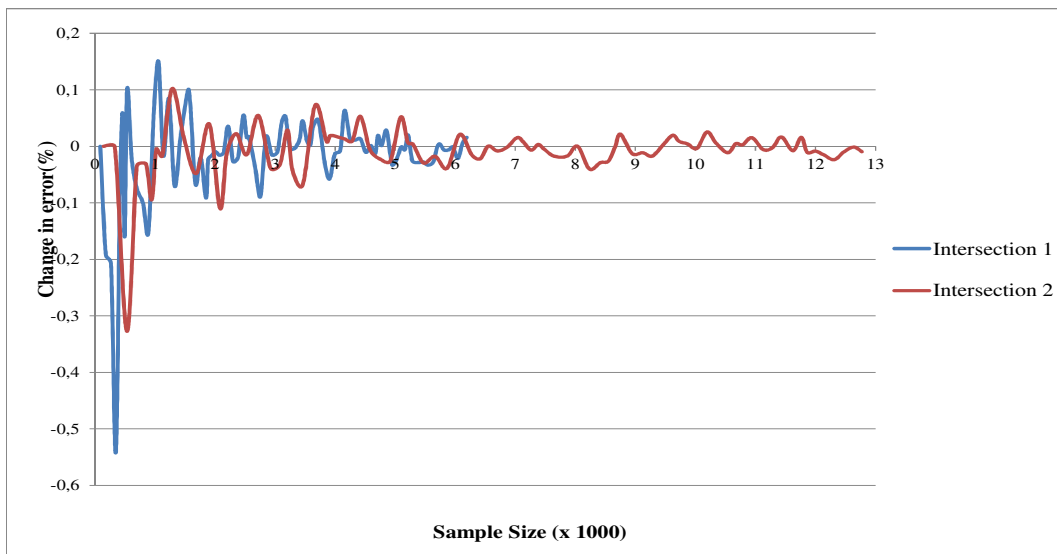


Figure 35 The average change in error per movement

6.2.2. Penetration rate

To investigate the relation of the penetration rate and the error of the route choice measurement, the absolute total error and penetration rate are measured for each day in the three month case study period. For intersection 1 the average penetration rate equals 0.35% and the average error per movement equals 3.76%, for intersection 2 the average penetration rate equals 0.49% and the average error per movement equals 1.35%. In this case an increase of 0.14% in the level of penetration is accompanied with a decrease in error of 2.41%.

A logarithmic regression of the results indicates that an increase in the penetration rate results in a decrease of the error; however the goodness of fit is negligible. Figure 36 shows the results of the analysis.

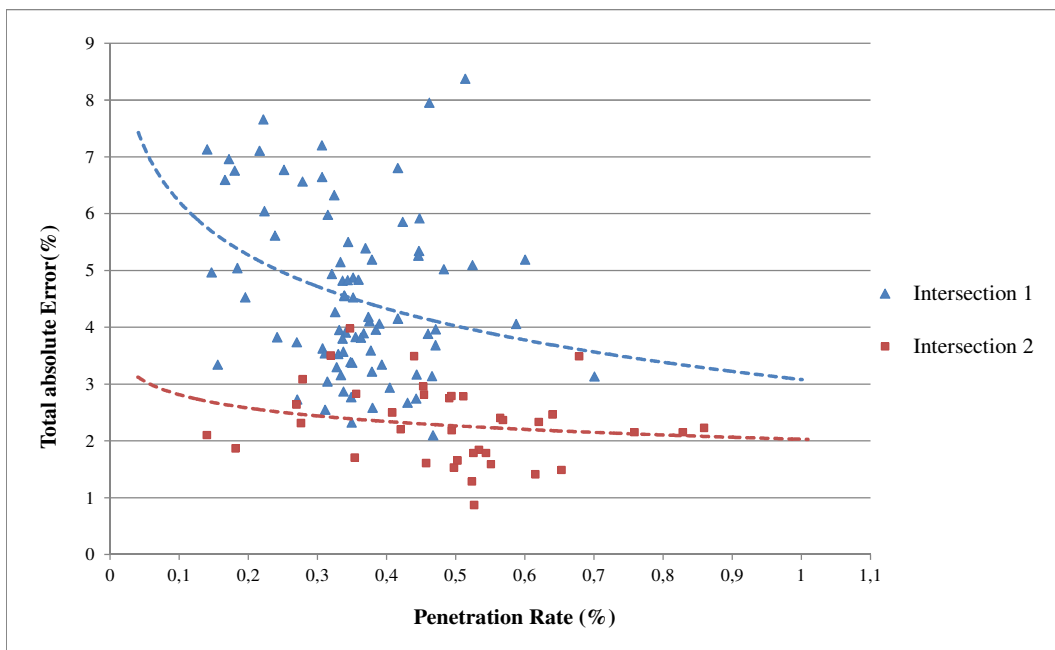


Figure 36 The average error per movement per day compared to the penetration rate of probe vehicles

The penetration rate influences the error of the analysis and directly determines the speed at which the sample size increases. During different parts of the day the penetration rate changes caused by the ratio of probe vehicles. The average penetration rate distribution over a complete day shows that the penetration rate decreases during the rush hour periods (Figure 37).

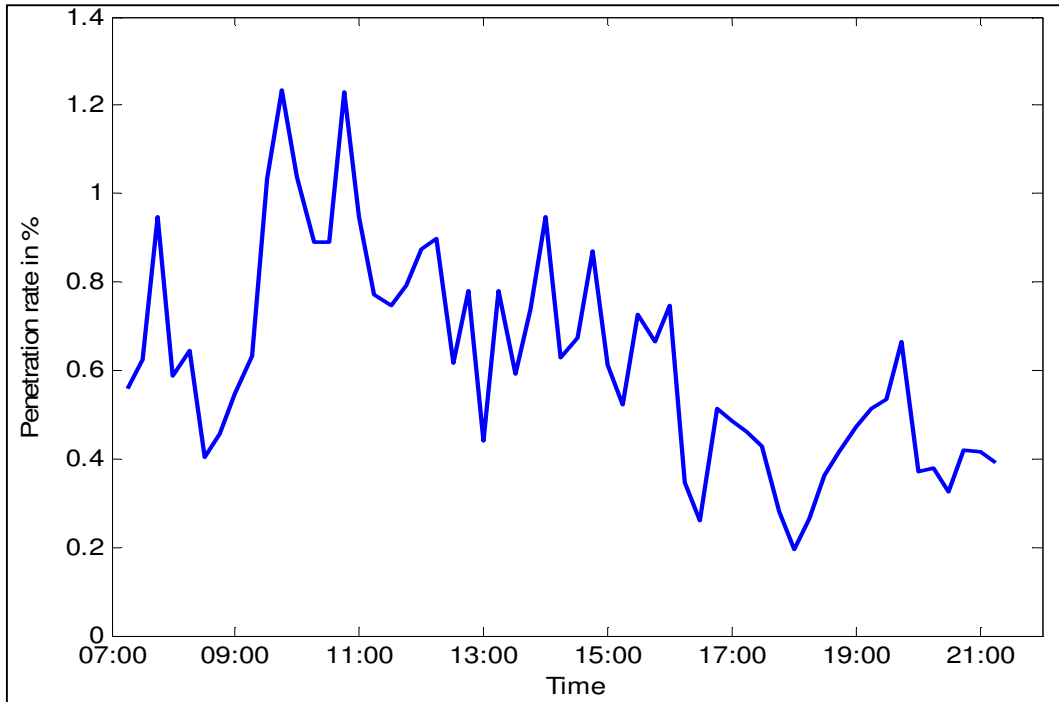


Figure 37 Average penetration rate for right turning Movement 1 at intersection 1 (April - June 2009)

On average between 07:00 and 21:00 the number of probe observations reaches a maximum at 14:30. The traffic volume measured with the loop detection however increases significantly during the rush hour periods. The strong increase of volume during rush hour periods results in a decrease of the penetration rate during the rush hour periods.

6.2.3. Distribution of error

To investigate the nature of the measured error, the OD ratio for the individual crossing movements is calculated. The OD distribution is derived for both intersections with a sample size of 1000 measurements and the absolute error is calculated. Note that the movements which are not measured by loop detectors are left out of the OD distributions. The loop detector data is used as a reference for the error which requires the removal of these movements.

It becomes clear that a great part of the total error is caused by over- and underrepresentation of only a couple of movements in the OD distribution. At the first intersection movements 1 and 2 account for 48% of the total error and on the second intersection movements 1 and 9 account for 56% of the total error. The results indicate that the error is caused by over- and under representation of probe vehicles in these Movements. Figure 38 and Figure 39 show OD ratio and the related error for intersection 1 and 2.

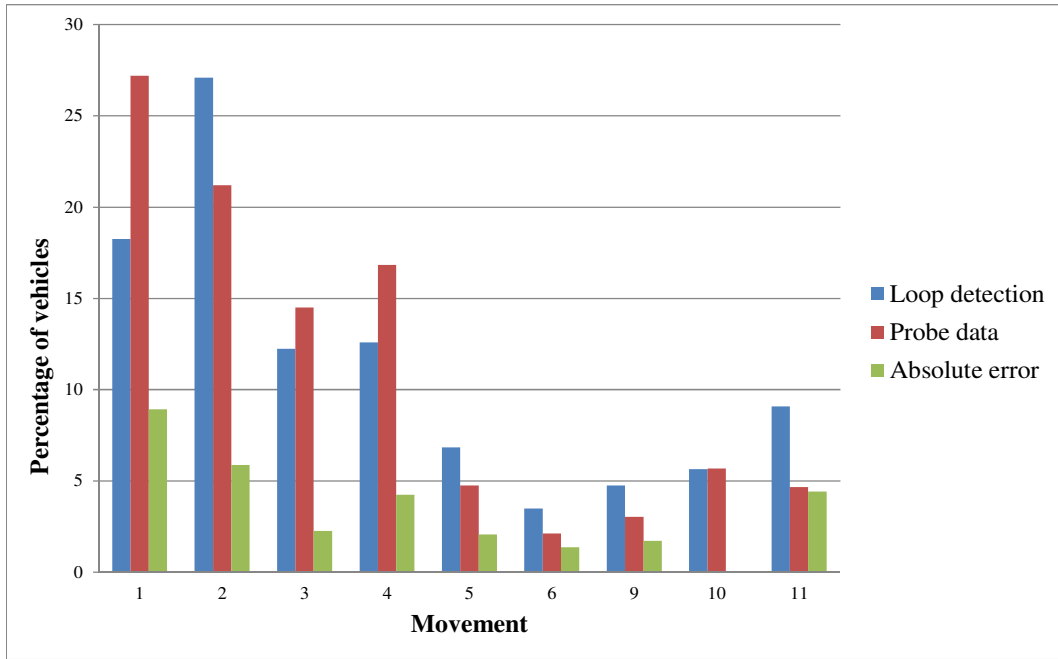


Figure 38 The OD ratio for intersection 1 derived from loop detection, probe data and the absolute error per Movement

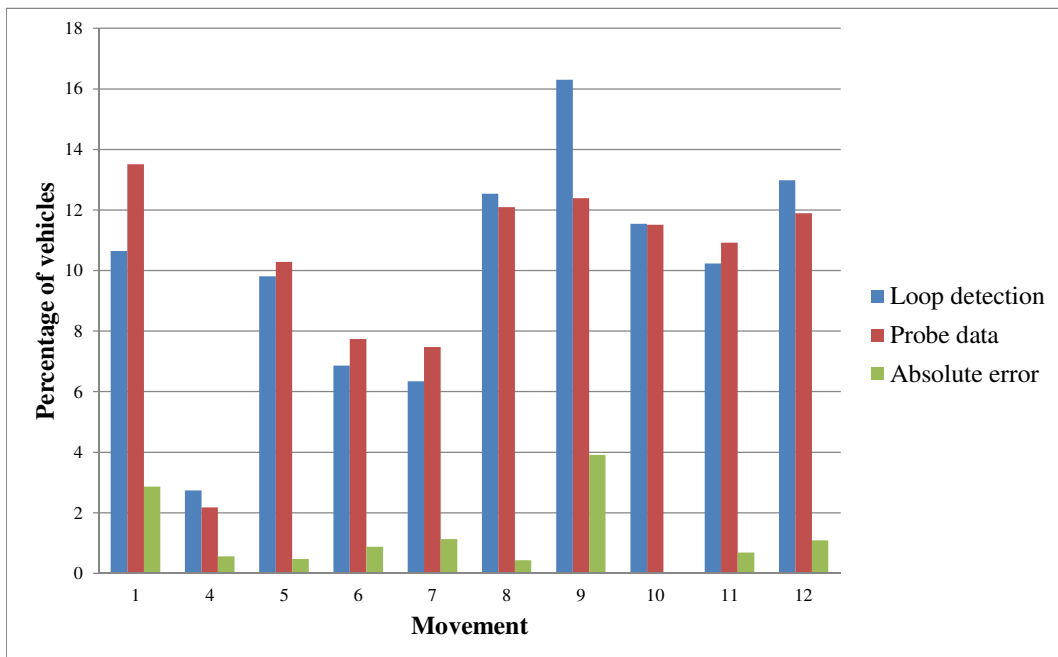


Figure 39 The OD ratio for intersection 2 derived from loop detection, probe data and the absolute error per Movement

To investigate the nature of the error the loop detection counts per movement are more closely analysed. At the first intersection, traffic counts on the deviating movements are conducted with the same detector which may cause an error in the measured traffic counts and result in a shifted distribution. At the second intersection traffic counts are conducted with separate detectors and for this case

it is likely that the error is caused by a shift in the probe vehicle distribution. To test this hypothesis, loop detection counts are calculated for the per movement. Figure 40 and Figure 41 show the average traffic volume per movement in pcu per hour for both intersections.

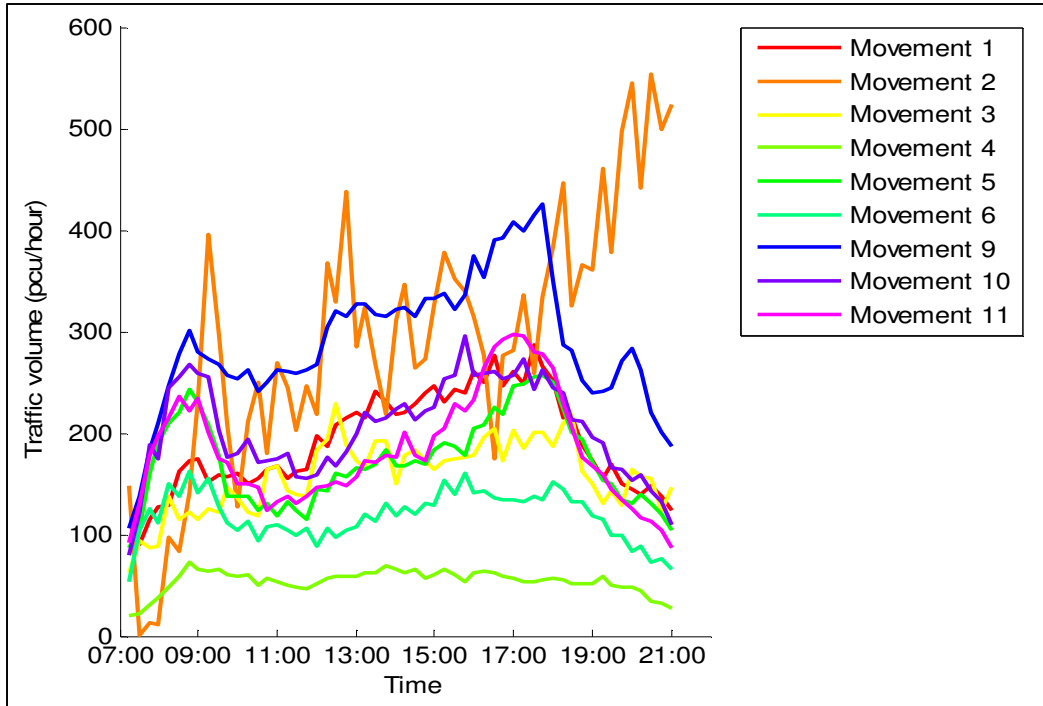


Figure 40 Average traffic volume per movement(pcu/hour) at intersection 1 derived from loop detection

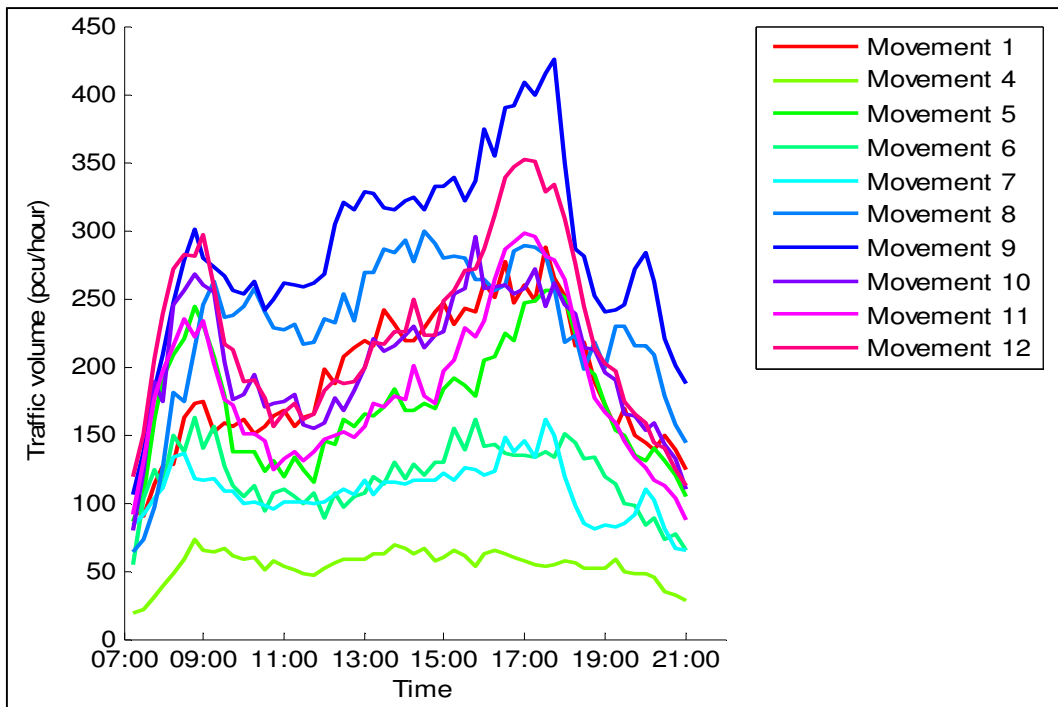


Figure 41 Average traffic volume per movement(pcu/hour) at intersection 2 derived from loop detection

The results show that movement 1 and 2 at intersection 1 do indeed have deviating traffic volumes. Compared to other movements at the intersection movement 1 shows less representation of the rush hours but not less than the other movements. For movement 2 the measured traffic volume appears to be completely random. The traffic volume for movement 2 seems to accumulate over the day and volumes of more than 1000 pcu during night time indicate that one of the detectors used to calculate the traffic volume is broken. The overall average traffic volume at movement 2 does not deviate strongly from other movements and this is probably why it is not detected in the filtering stage (section 0).

Movement 2 at intersection 1 is removed from the data and the average error is recalculated. The average error per movement is 3.65%, this is a relative decrease of 3% compared to the original calculation. The error however is still caused by two movements; movement 1 and 11 comprise 55% of the total error.

6.3. Delay

The evaluation of the delay starts with the calculation of the average delay distributions. The time period between 07:00 and 21:00 is examined and the average delay is calculated for 15-minute aggregation intervals (section 5.6).

6.3.1. Reference

The time-dependent stochastic delay model provides the average delay distribution for all movements at both intersections. The results show a distribution which resembles the traffic volume at the intersection but also takes into account the effect of the signal scheme. Figure 42 shows the average delay per vehicle and the traffic volume for movement 5 at intersection 2.

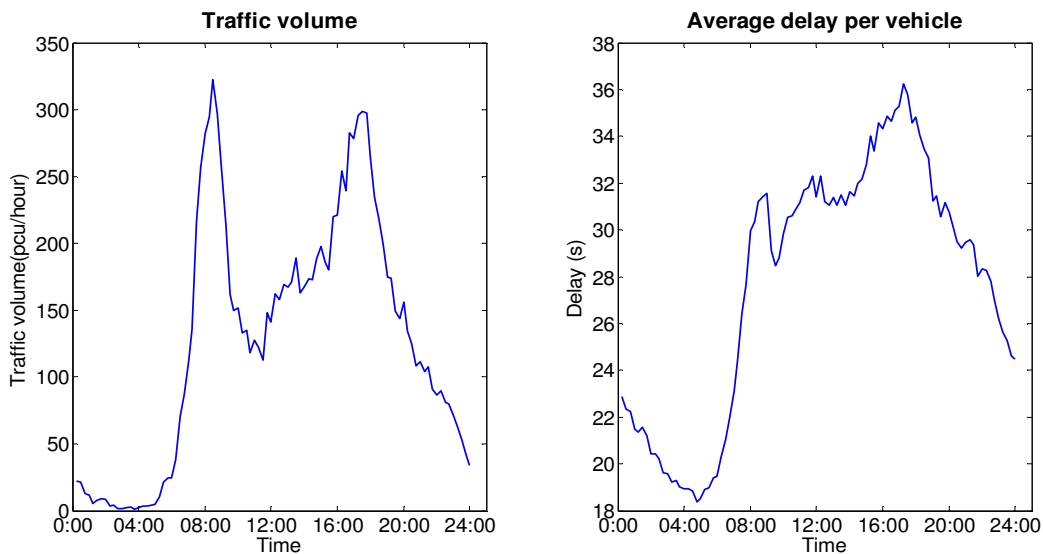


Figure 42 Traffic volume(pcu/hour) and the average delay per vehicle derived from the time-dependent stochastic delay model for Movement 5 at intersection 2

The delay model greatly resembles the traffic volume distribution, but the example also shows the representation of the signal configuration. Longer green times during the morning rush hour result in a reduction of the delay during this period compared to the evening rush hour. The model takes into account a minimal delay even when the intersection is empty, which equals an average delay of 19 seconds for all movements.

6.3.2. Probe data

The delay distribution derived from probe is calculated for a complete day with probe measurements from April, May and June 2009. Using aggregation intervals of 15 minutes a 97% coverage is obtained and the only “gaps” in the data occur at night time. The delay distribution shows no clear resemblance to the volume of the probe vehicles. The maximum number of probe vehicle observations occurs between 12:00 and 17:00 at most movements. Figure 43 shows an example of the delay and the total number of probe observations per hour collected in April, May and June 2009 for movement 5 at intersection 1.

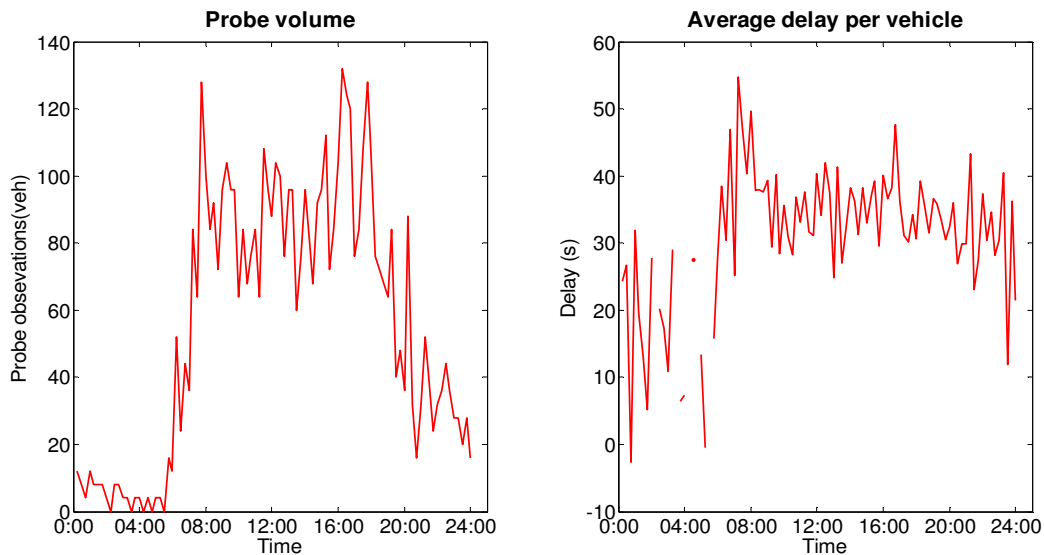


Figure 43 The total number of probe observations per hour collected from April 2009 to June 2009 and the average delay per vehicle derived from probe data for Movement 5 at intersection 1

For the average delay distribution, the variance of the results is evaluated. A higher variance can indicate less significance of the calculated value. The variance is expressed as the standard deviation of all delay measurements during a 15-minute period compared to the average delay in this period. On average 20 measurements per interval are assessed. The results show a relative high variance. In some cases the standard deviation is 100% larger than the average delay. Figure 44 shows an example of the average delay distribution and the variance for movement 5 at intersection 1.

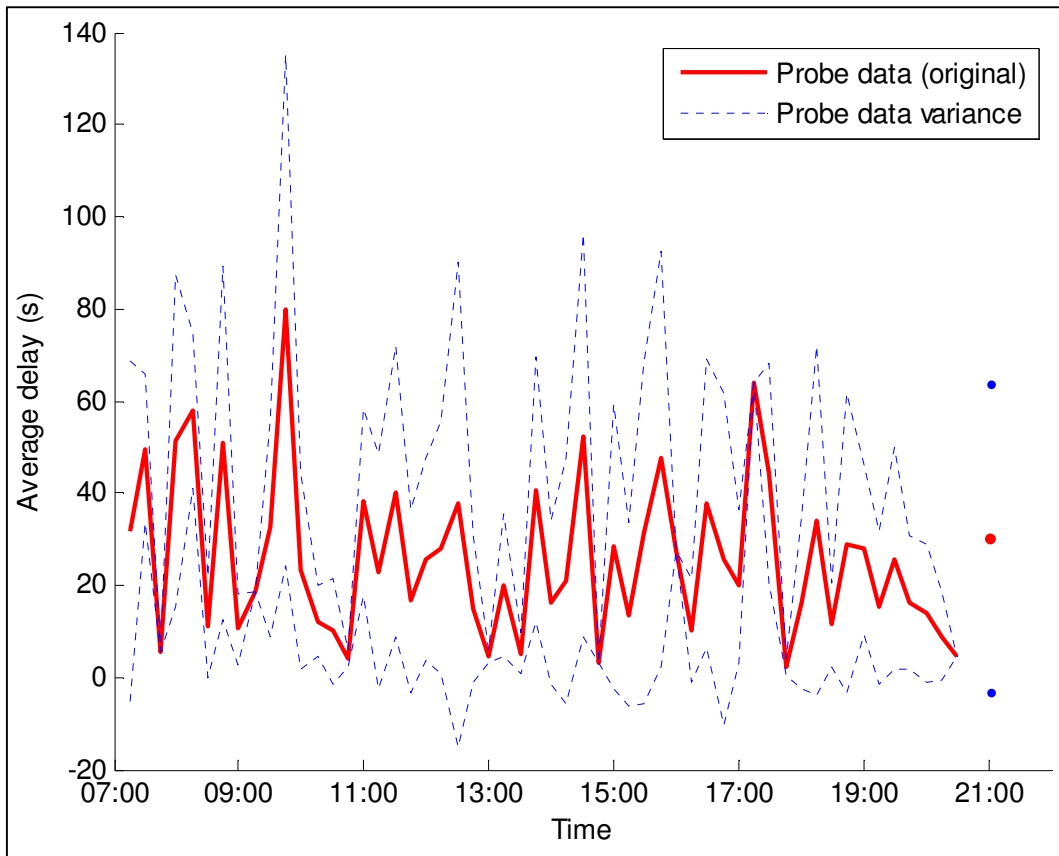


Figure 44 The average delay per vehicle and the deviation of observations derived from probe data for Movement 5 at intersection 1

A possible explanation for the high variance is the number of probe vehicle observations per interval. It is assumed that the probe vehicles arrive randomly at the intersection and the delay per crossing movement depends on the moment of arrival during the signal cycle. Delay times between 0 and 160 seconds are possible which causes high variance in the delay distribution.

6.3.3. Comparison analysis

The next stage of the analysis comprises the comparison of the probe data results and the calculations from the time-dependent stochastic delay model. The delay distribution calculated from the probe data shows a resemblance with the results of the time-dependent stochastic delay model, but has more noise in the distribution. A logical explanation for the greater variance compared to the time-dependent stochastic delay model is that the sample size is too low (section 6.3.2). During the three month period 7262 observations were observed at intersection 1 and 12980 observations at intersection 2. It is possible that these values are too low to create a smooth distribution. A quick analysis with smaller sample sizes confirms this hypothesis. The analysis is confined by the length of the collection period and cannot be increased to increase the sample size. To demonstrate the results a representative movement is selected and the average

delay distribution is calculated. Figure 45 shows the results for left turning movement 4 at intersection 1.

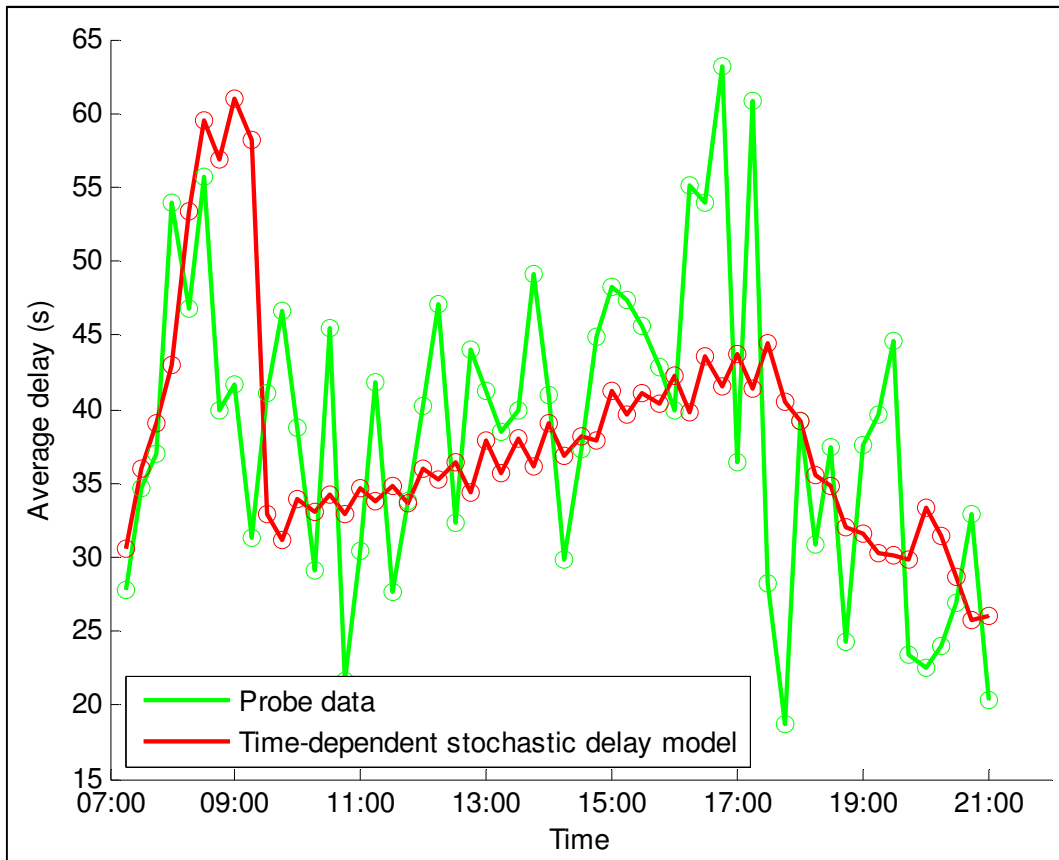


Figure 45 Comparison of the average delay per 15-minute time period for left turning Movement 3 at intersection 1 between 07:00 and 21:00

Although the example shows great variance, the overall average delay shows a strong resemblance to the time-dependent stochastic delay model. The model measures an overall average delay of 37.6 seconds compared to the delay of 38.1 seconds measured with the probe data, a difference of 1.3%. In order to clarify the results, a method is proposed to reduce the amount of noise and locate trends in the distribution. A moving average filter and a Savitzky-Golay filter are selected for the smoothing of the probe delay distribution. Clearly the smoothing process results in a reduction of noise and the probe distribution shows more resemblance to the time-dependent stochastic delay model. The trends in the distribution are clearly visible and the variance is lowered. However the smoothing process also reduces peaks in the distribution resulting in data loss. In the example this results in a maximum peak reduction of 35% for the Savitzky-Golay filter and 60% for the moving average filter (Figure 7). At this level of reduction, the question arises if smoothing provides an added value, however, smoothing does decrease the deviation between the results and the reference. Depending on the purpose of a study, smoothing should be avoided to reduce data loss.

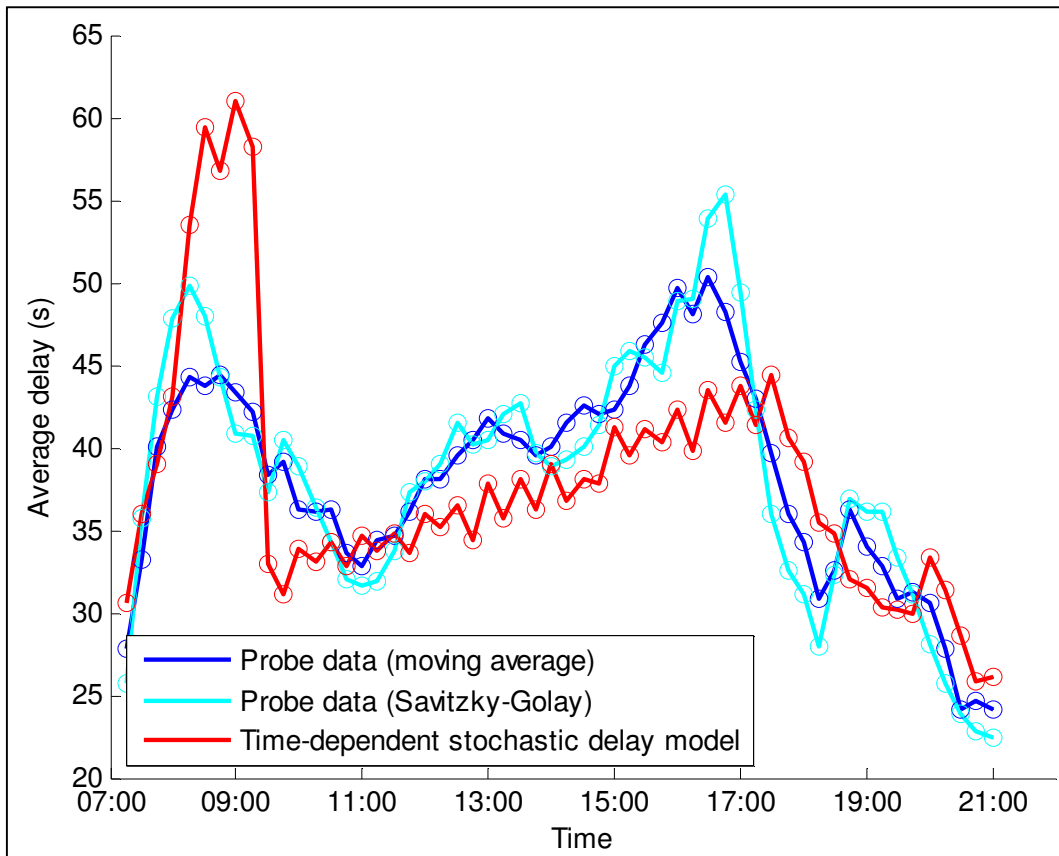


Figure 46 Application of a moving average and a Savitzky-Golay filter to the average delay per 15-minute time period for left turning Movement 3 at intersection 1 between 07:00 and 21:00

The greatest deviation between the probe delay distribution and the reference data is measured during rush hour periods. During these periods, probe data shows substantially higher or lower delays than the time-dependent stochastic delay model, which can lead to differences of up to 20 seconds. It is difficult to locate the source of this deviation. The measured deviation is different for each movement and both positive and negative deviations are measured.

The calculated free flow travel time takes into account the delay caused by the signal control device (section 5.6.1) and the results show the effect of this assumption. At periods with a very low traffic demand (night time) the delay distribution approaches zero seconds at some of the movements. The time-dependent stochastic delay model however indicates a delay of 10 to 15 seconds during these periods. Figure 47 shows an example of this trend which starts at approximately 19:00 for movement 11 at intersection 2.

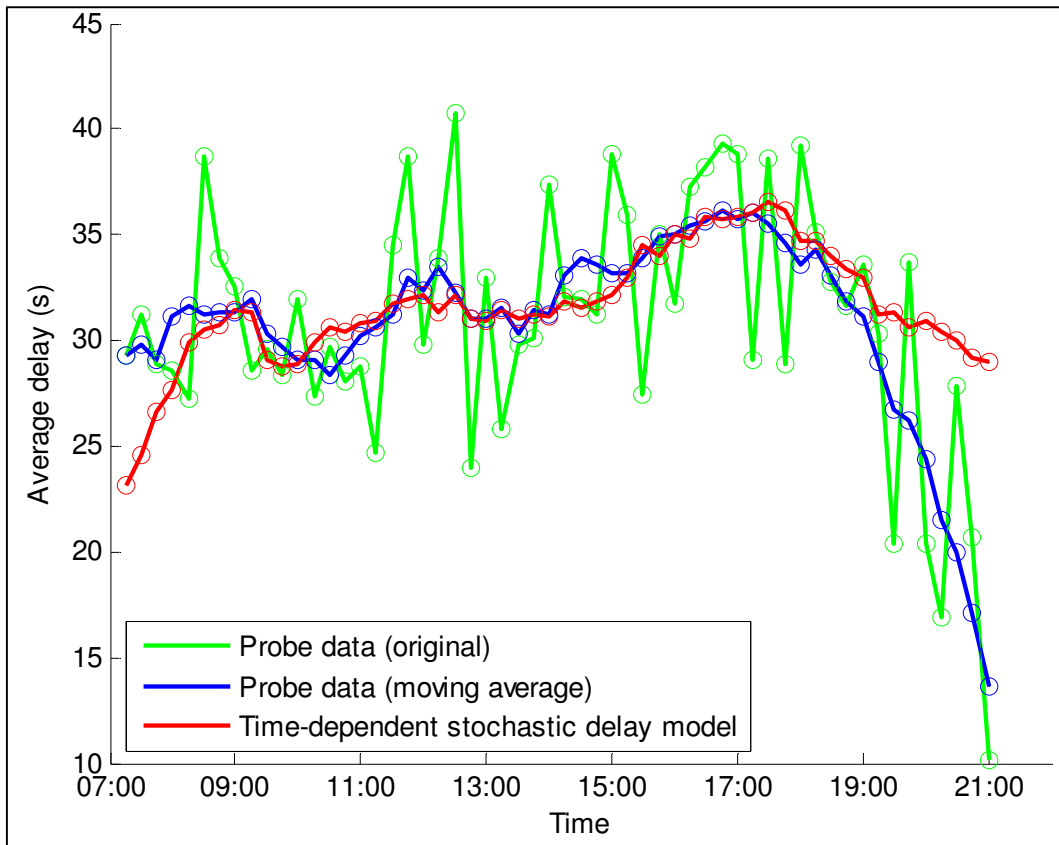


Figure 47 The average delay per 15-minute time period for trough Movement 11 at intersection 2 between 07:00 and 21:00

The probe data delay distribution on four movements at intersection 2 shows a shift in the results compared to the time-dependent stochastic delay model. The delay calculated with the probe data is on average 20 seconds higher than the delay which is derived with the time-dependent stochastic delay model. The trend lines show resemblance but a constant difference of 20 seconds is measured. The movements at which the effect is measured comprise movement 3,6,9 and 12. Figure 48 shows an example of this effect at movement 9.

An analysis of the movements at which the effect occurs clarifies the difference in the calculated delay. At intersection 2, follow-up streams are used at movements 2,3,6,8,9 and 12 (section 2.5.1). At the main stream of the intersection (movements 2 and 8) no difference is measured but at the other four movements, the deviation does occur. It appears that the control scheme is configured in such a way that movement 2 and 8 are linked to the follow-up streams, resulting in no additional delay. At the other four movements the green time is not matched to the follow-up streams which results in higher delays. A visual analysis at the intersection confirms this hypothesis and shows that the follow up streams are not linked for movements 3,6,9 and 12. The “extra” delay is measured with the probe data but not with the time-dependent stochastic delay model. Additional

effort could be taken to include this in the model, however it should be checked manually which movements require adjustment in the model.

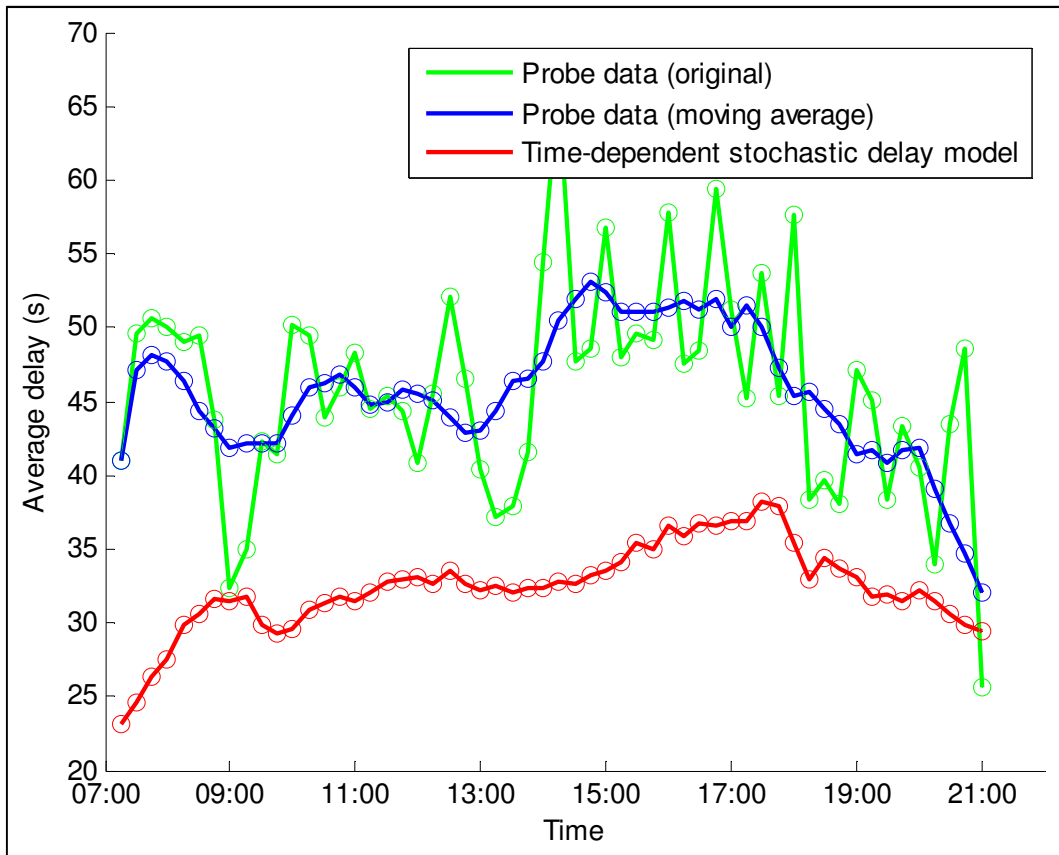


Figure 48 The average delay per 15-minute time period for left turning Movement 9 at intersection 2 between 07:00 and 21:00

6.3.4. Delay distribution

To investigate the variance of the average delay, the distribution of the delay amongst all individual probe measurements is calculated. The sample of probe vehicles is compared with the accounted delays at a single movement. The comparison shows a random arrival pattern for the collected probe data. The accounted delay of the probe vehicles appears to be normally distributed, most likely caused by a random distribution of probes amongst traffic. It is calculated from the results that the error of fit decreases if the number of probe observations is increased. Figure 49 shows an example of this distribution for left turning movement 9 at intersection 2 with $\mu=43.7$ and $\sigma=23.3$.

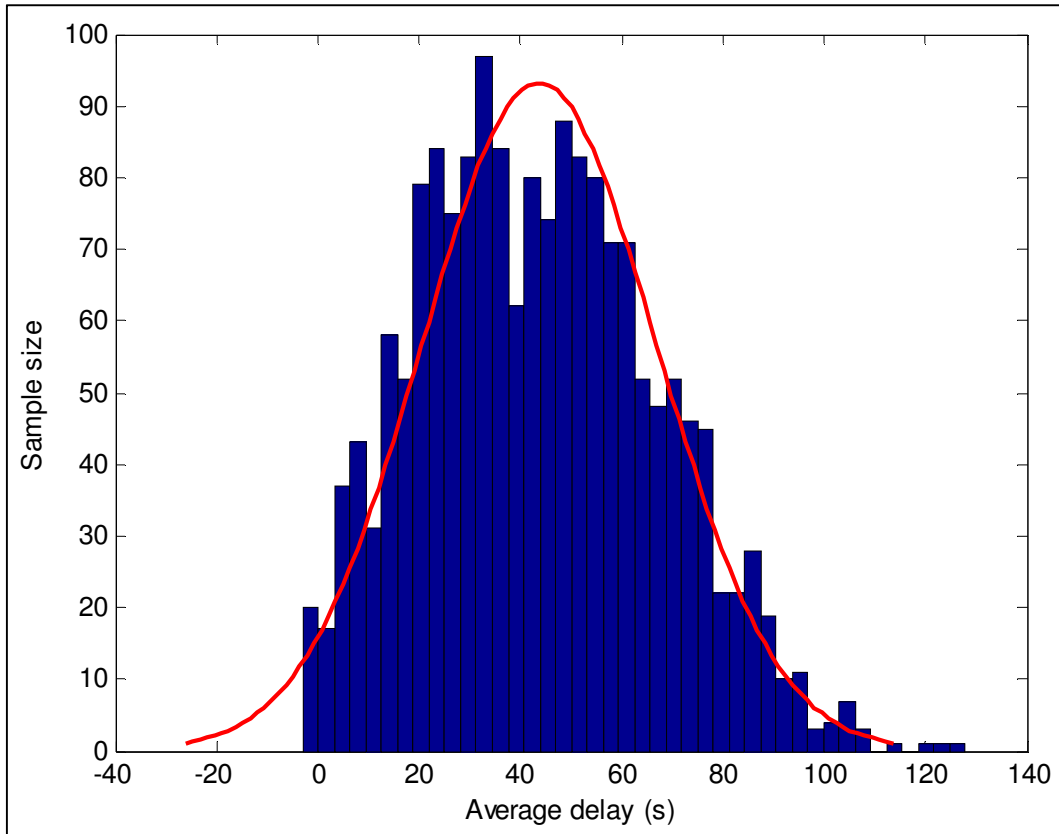


Figure 49 Distribution of delay amongst observations for left turning Movement 9 at intersection 2

6.4. Queue length and number of stops

For queue length and the average number of stops, a scaled probe data delay distribution is examined next to the time-dependent stochastic queue and stop rate models (Section 5.7). The time period between 07:00 and 21:00 is examined and the distributions are calculated for 15-minute aggregation intervals similar to the probe data delay distribution. A moving average smoothing filter is applied to clarify trends in the results (section 6.3.3).

6.4.1. Queue length

The time-dependent stochastic model provides the average queue distribution per movement at both intersections. Multiplication with 7,2 meters per vehicle provides the queue length distribution (Section 3.3.3). The results show a distribution which very strongly resembles the traffic volumes measured at the intersection. Figure 50 shows an example of the average queue length the and the traffic volume for movement 5 at intersection 2.

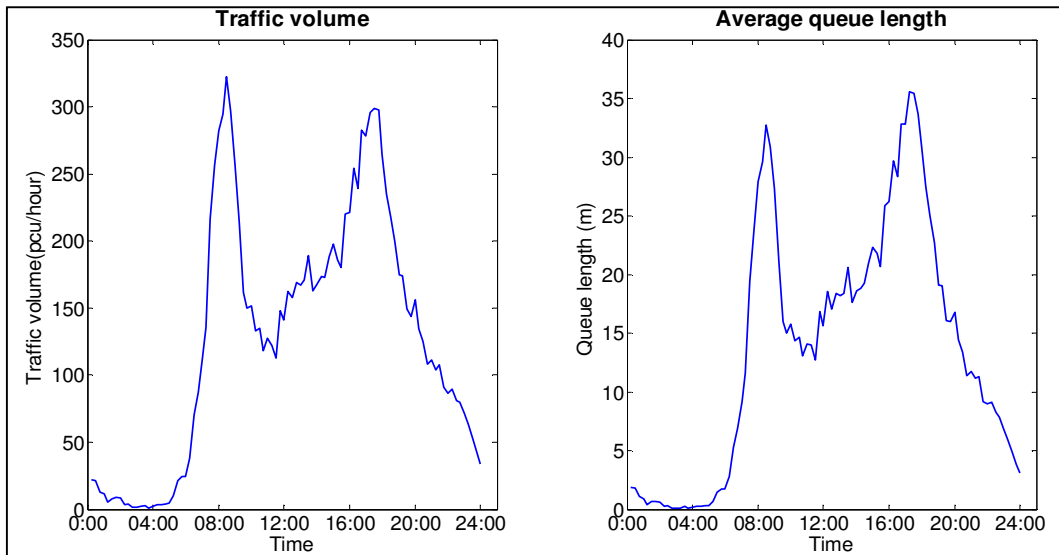


Figure 50 Traffic volume(pcu/hour) and the average queue length derived from the time-dependent stochastic delay model for Movement 5 at intersection 2

The time-dependent stochastic model is used to scale the probe data delay distribution. The average queue length is derived from the distribution and the scaling ratio is calculated. Figure 51 shows an example of the scaled queue length distribution compared to the model results for movement 5 at intersection 2.

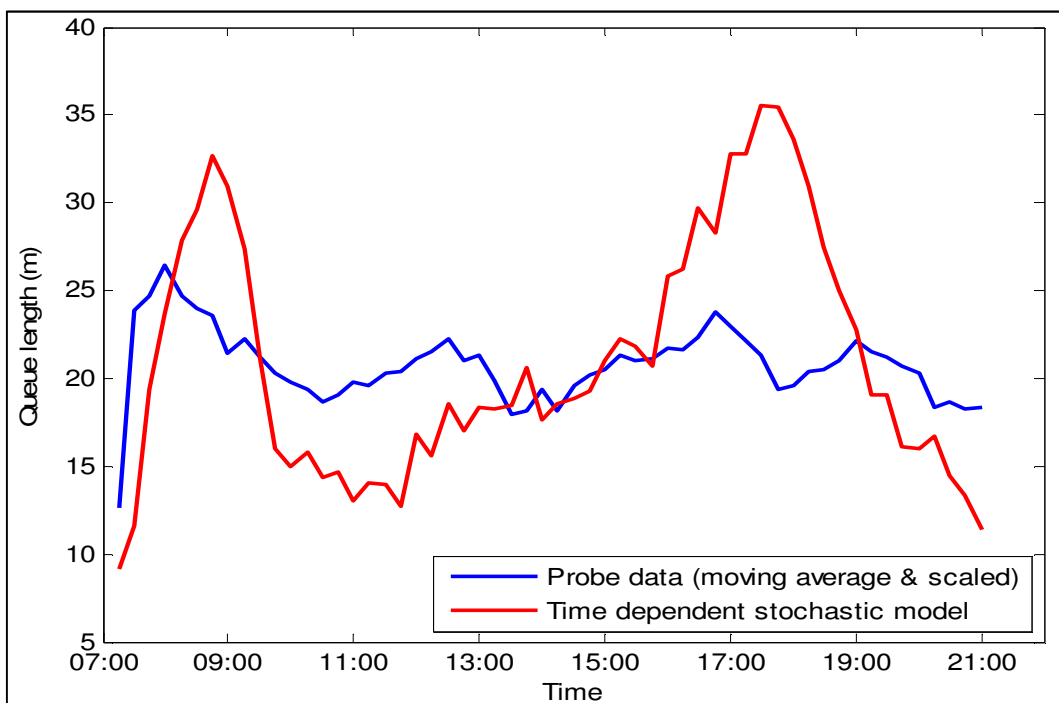


Figure 51 The scaled probe data delay distribution and the average queue length derived from the time-dependent stochastic delay model for Movement 5 at intersection 2

The results of most movements show similar results as in the delay analysis. Compared to the delay analysis however, the probe data shows smaller peaks which are reduced by 10 to 20% on average. The reason for the peak reduction is unclear but it appears from the distributions that no clear relation is derived by using the selected scaling method.

6.4.1. Stop rate

The time-dependent stochastic model provides the average stop rate distribution for all movements at both intersections. The results show a distribution which is similar to the traffic volumes which are measured at the intersection. The stop rate distribution has less variance than the traffic volume, the delay and queue length distributions from the reference model. Figure 52 shows the average stop rate per vehicle and the traffic volume for movement 5 at intersection 2.

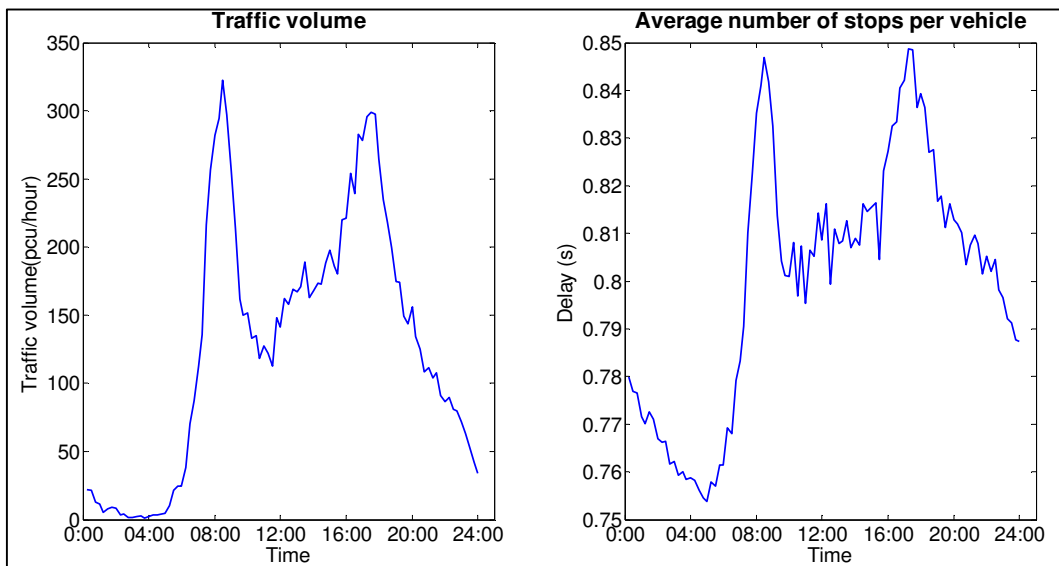


Figure 52 Traffic volume(pcu/hour) and the average number of stops derived from the time-dependent stochastic delay model for Movement 5 at intersection 2

Similar to the queue length approach, the time-dependent stochastic model is used to scale the probe data delay distribution. The average number of stops is derived from the probe delays and the scaling ratio is calculated. Figure 51Figure 52 shows an example of the scaled stop rate distribution compared to the model results for movement 5 at intersection 2.

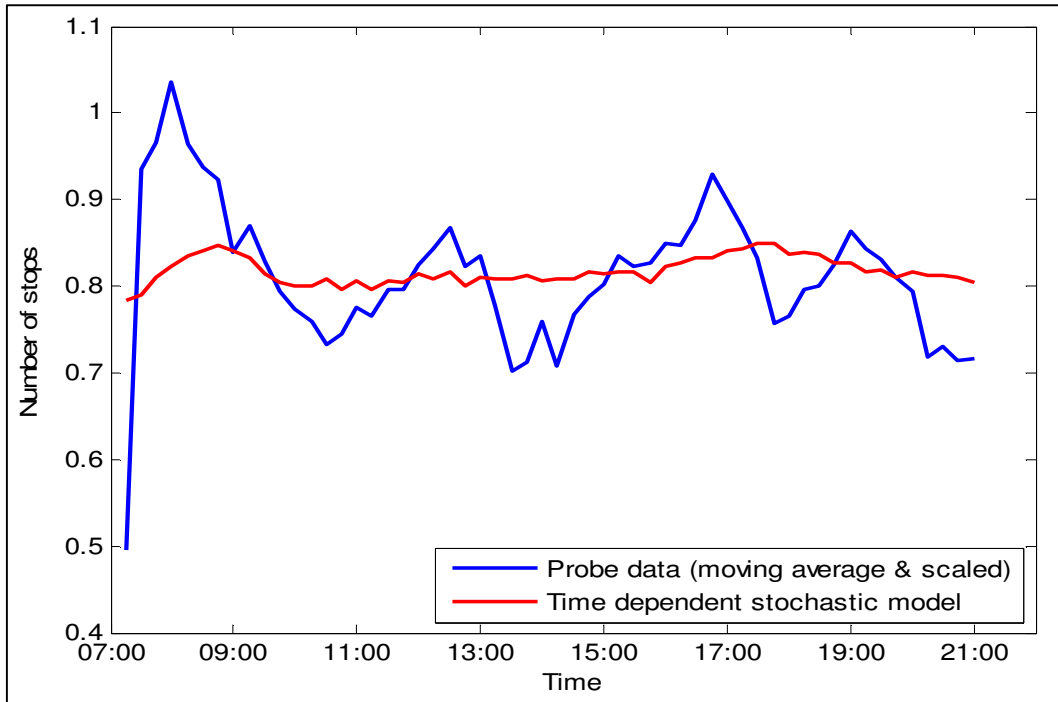


Figure 53 The scaled probe data delay distribution and the average stop rate derived from the time-dependent stochastic delay model for Movement 5 at intersection 2

The comparison shows the opposite of the results derived at the queue length analysis. The probe data distributions shows much stronger peaks compared to the results from the time-dependent stochastic model. In the reference model a minimal stop rate is maintained which equals 0.75. The maximum measured stop rate at both intersections varies between 0,8 and 1,2. The question arises which of both methods actually provides the best results, because both distributions appear to provide quite random results.

6.4.2. Discussion

The results of the time-dependent stop rate model show very little variance. The average number of stops only becomes significant if the degree of saturation increases to a level higher than 0.8 (Akçelik, 1981). At this degree of saturation the change of vehicles having to wait for more than 1 cycle increases. When the degree of saturation at the intersection is observed, the maximum value approaches 0.6 at some intervals but higher values are not found. Normally values higher than 0.6 are expected and visual observations at the intersection do show this during rush hour periods. Although visual observation shows cycles with oversaturation, this is not found in the data. A hypothesis is that saturation rates lower than 0.6 come from the fact that the intervals observe 15 minutes of traffic cycles and take into account multiple days. The chance of constant oversaturation during all cycles in the 15 minute period, during all days is very low. The aggregation results in an average value for the saturation rate and this will always be below 0.8. It is the question if the time-dependent stochastic model

provides a good reference for the study. Performance measurement of stop rate is interesting for shorter analysis periods but longer aggregation periods result in an average value of the stop rate.

6.5. Summary

In this chapter the results of the case study analysis were presented. With the method which was introduced in Chapter 5, the use of probe data from consumer GPS navigation devices for intersections analysis was evaluated. The chapter is the basis for the final conclusion of the report and is used to answer the main question: “Does probe data collected from consumer GPS navigation devices provide an accurate and reliable data source for performance measurement at intersections?”

The study indicates that probe data from consumer GPS navigation devices provides a data source for measurement of delay and route choice at intersections but not for measurement of queue length and stop rate. The systems satisfy an average penetration rate of 0.5% and apply an update frequency of 1 measurement per second. Under these conditions route choice is determined with an average error per movement of 1.3 to 3.8%, mainly caused by the error at two or three movements. At the test case intersections a sample size of approximately 1000 measurements during an eight to twelve day aggregation period shows optimal results. The results indicate that increasing penetration rates result in a lower level of error but this trend is negligible.

For the delay a resemblance to the time-dependent stochastic delay model was found for the greater part of the crossing movements. The greatest deviation for the delay is measured during congested situations (rush hour periods) and for periods with a very low traffic demand (night time) and can lead up to differences of 20 seconds. The average delay distribution shows more variance than the time dependent stochastic delay model which appears to be caused by a too low sample size of 7262 observations at intersection 1 and 12980 observations at intersection 2 during the three month observation period. Smoothing filters can considerably clarify the trends in the data but lower the level of detail reducing some peaks by 60% and it is suggested to avoid smoothing to reduce data loss. Interesting effects which are observed from the data are follow-up signal streams which are not measured in the reference model. The delay of probe vehicles appears to be normally distributed for a single movement indicating that the probes are randomly distributed amongst traffic.

The exploratory study for queue length and stop rate measurement indicates that probe data from consumer GPS navigation devices does not provide an accurate data source for these measures of performance. The comparison of scaled delay distributions with references from time-dependent stochastic models shows no

clear similarities and it is suggested that the relation of probe delay with queue length and stop rate is too weak to detect.

Chapter 7

Conclusions and recommendations

The final chapter presents a discussion on the research approach of the study and the conclusions of the project. The results of the case study make up the answer of the main question and are presented in section 7.2. Section 7.3 presents the recommendations for further research and practical applications of probe data from consumer GPS navigation devices, based on the findings of the research study.

7.1. Discussion

The study shows that a minimal number of probe measurements is required for performance measurement at intersections. For the practical application in PI and LOS assessments, the number of probe measurements defines the minimal length of the analysis period. In this case the selected methods result in intersection performance on an aggregated level. For traffic studies on a per-second level an increased amount of probe data from consumer GPS navigation devices is required. It can be discussed if the research approach which is selected for this study is the appropriate method for a complete evaluation. The method calculates results at an aggregated level and the evaluation of individual trajectories could provide a better method for the data.

For the research study a time-dependent stochastic model was selected specifically to match the aggregated character which was used for the probe dataset. The time-dependent stochastic delay model provides an estimation of delay but does not provide actual travel time measurements. Taking this into account, the question arises if the model is applicable as a reference for the evaluation of delay from probe data. The probe data measures actual travel times and the model provides delay estimations from aggregated data. It is discussable if the selected model is an appropriate reference for the evaluation of the accuracy for delay measurement compared to accurate travel time measurements such as camera travel time measurement.

7.2. Conclusions

This report analysed the use of probe data from consumer GPS navigation devices for the analysis of intersections. The study approach for this purpose was formulated in Chapter 1 and the research question was presented:

“Does probe data collected from consumer GPS navigation devices provide an accurate and reliable data source for performance measurement at intersections?”

To answer the research question, the definition of performance measurement for intersections was analysed and a case study was proposed to evaluate the accuracy with measurements in the field. The main research question was divided into five sub-questions which make up the conclusions of the study and provide the answer to the main research question:

- How is the process of arrivals and departures of traffic at an intersection characterized?
- Which parts of traffic operations at an intersection define the performance and which measures of performance are important in the analysis?
- How does data from stationary detectors provide traffic data for intersection analyses?
- How does probe data from consumer GPS navigation devices provide traffic data for intersection analyses?
- What is the accuracy of performance measurement with probe data from consumer GPS navigation devices?

The first sub-question provides the background for performance measurement at intersections. The flow of traffic at (controlled) intersections is characterized:

“How is the process of arrivals and departures of traffic at an intersection characterized?”

The measurement of traffic volume, route choice and driving behaviour provides the input for traffic studies at intersections. The optimization of road geometry, intersection control and dynamic traffic management requires up to date and accurate traffic information from intersection analyses. The definition of performance measurement at intersections is used to create a complete picture of traffic operations providing information on the traffic volume, speed and densities.

The second sub-question investigates the use of performance measurement at intersections. The sub-question is used to select the sections of performance measurement which are evaluated in a case study:

“Which parts of traffic operations at an intersection define the performance and which measures of performance are important in the analysis?”

The definition of performance measurement at intersections is used to create a complete picture of traffic operations at intersections. Generally a Performance Index or Level Of Service assessment is used for traffic studies to incorporate multiple characteristics into a single assessment of the intersection. The most commonly used indicators of performance are the vehicle time delay, queue length and stop rate at intersections.

The third sub-question and the next step of the study describes the analysis and collection of traffic data for performance measurement at intersections from stationary (road-side) detectors:

“How does data from stationary detectors provide traffic data for intersection analyses?”

Data collection from stationary detectors is directly used to assess the performance of intersections. The greater part of traffic data collection at intersections is comprised of traffic signal monitoring and traffic counts from loop detectors. Loop detection is used to measure traffic volumes per OD movement at the intersection. A combination of both stationary detection methods with traffic models provides input for delay, queue length and stop rate models. Although the data collection with stationary detectors is generally selected for traffic studies, it is expensive and requires high maintenance expenditures. Loop detection delivers accurate traffic volumes but can suffer from detection errors and missing data. In the case study the average malfunction rate of the loop detectors is 43% which confirms the unreliability of loop detection equipment.

The fourth sub-question is used to investigate the collection of traffic data at intersections from probe data which is collected with consumer GPS navigation devices:

“How does probe data from consumer GPS navigation devices provide traffic data for intersection analyses?”

Probe data provides trajectory data at intersections but is confined to a certain number of vehicles in the network. Data enhancement methods and sample size calculations are used to improve results, but the outcome depends on the quality of the probe data. The level of accuracy and reliability is determined by the primary measures of performance which are input for performance studies. Building on the research question; probe data is an accurate and reliable data

source for performance measurement at intersections if it provides input for performance studies comparable to currently accepted reference data sources.

The fifth and final sub-question makes up the final section for the answer to the main research question. The sub-question forms the basis for the case study approach:

“What is the accuracy of performance measurement with probe data from consumer GPS navigation devices?”

A case study comparison of probe observations with data collection from stationary detectors provides an answer for the fifth sub-question. The study is separated in multiple measures of performance. It shows that the system satisfies an average penetration rate of 0.5% at the test case intersections and the probe vehicles apply an update frequency of 1 measurement per second. For these conditions it is concluded that the accuracy of route choice is measured with an average error per movement of 1.3 to 3.8%, mainly caused by the error at two or three movements.

The penetration rate of the probe vehicles determines the minimal aggregation period for the calculation of route choice. The optimal sample size for route choice analysis of 1000 measurements is obtained after a waiting period of 8 to 12 days. For the accuracy of performance measurement the sample size is leading in the size of the error and not the aggregation period. For practical applications this indicates that the number of probe measurements defines the minimal length of the analysis period. Shorter analysis periods will require higher penetration rates (for similar traffic volumes). This also implies that shorter analysis periods are required for intersections with higher traffic volumes and similar penetration rates. It is concluded that increasing penetration rates do not result in a lower level of error.

The most common measure of performance is travel time delay. Probe data delay measurement was compared with input from loop detection traffic counts and signal monitoring. The results show multiple similarities to the reference model for the greater part of the crossing movements. The probe data results show more variance than the reference model which appears to be caused by a too low sample size of 7262 observations at intersection 1 and 12980 observations at intersection 2 during the three month observation period. Smoothing filters can considerably clarify the trends in the data but lower the level of detail, reducing some of the peaks by 60%. The conclusion is that depending on the purpose of a study, smoothing should not be used to avoid data loss. The results also show that increased penetration rates and higher traffic volumes result in a smaller variance.

During congested conditions an average difference of 20 seconds is measured in the probe data compared to the reference model. The nature of the difference is unclear. Reference studies show that the accuracy of loop detection decreases at congested situations, which possibly explains the difference. Furthermore, the variance of delay during congested situations is expected to be higher than in uncongested conditions (there is a larger spectrum of delay times). The higher variance is taken into account by the probe data which measures the travel times and the hypothesis is that the difference is caused by the fact that the reference model produces averaged values. Both theories support the conclusion that the accuracy of delay time measurement is higher for probe data than for the time-dependent stochastic delay model.

During night time a difference in delay time is measured which leads up to 20 seconds. The reference model takes into account a minimal delay at low traffic demands (saturation <0.1) which is not included in the probe data delay. Optimally measured conditions are assumed as a “zero-delay” situation for the probe data which includes the lowest measured signal delay in the free-flow travel time. An advantage of this method is that the calculated free-flow travel time is actually measured and is fit to a specific intersection and movement. Factors which influence the free-flow travel time such as the layout and the surroundings of the intersections are automatically taken into account. A downside of the proposed methods is the fact that the calculated free flow travel time already takes into account the delay caused by the signal control device. It is concluded that the probe data provides better accuracy than the time-dependent stochastic model for the inclusion of intersection layout characteristics.

The study shows that smoothing filters can considerably clarify the trends in the probe data delay distributions, but lower the level of detail which reduces some of the peaks by 60%. At this level of reduction, the question arises if smoothing provides an added value for the data analysis.

Queue length and stop rate measurement with the probe dataset appears to be not possible. A preliminary for measurement of queue length and stop rate with probe data is a penetration rate above 40% (Comert & Cetin, 2008; Heidemann, 1994; Mung, et al., 1996; Neumann, 2009). Furthermore the length of the segments which are used in the digital roadmap reduce the accuracy of the location of a vehicle before the stop line which is unbeneficial for queue length and stop rate measurement.

Finally the conclusions of all sub-questions are combined to answer the main research question and provide the final conclusion of the study:

“Does probe data collected from consumer GPS navigation devices provide an accurate and reliable data source for performance measurement at intersections?”

Probe data from consumer GPS navigation devices provides an accurate and reliable data source for selected performance studies. The probe data provides an accurate measurement method for route choice and travel time delay but queue length and stop rate are not derived from the data. Although it is not possible to determine all measures of performance, the calculation of delay provides a valuable input for Performance Index and Level Of Service assignments. The penetration rate of vehicles and the storage of segment travel times do not enable measurement of performance measures other than delay. With the current level of penetration the data does not enable performance measurement for individual cycles and the data is only available for studies over longer time periods. With practically no malfunction rate and the ability to measure travel times, probe data from consumer GPS navigation devices provides an added value for traffic studies at any intersection. The real strength of the data lies with route choice and delay measurement at intersections without fixed detectors or where data from stationary detectors is not easily accessible.

7.3. Recommendations

In this section the recommendations for further research on the use of probe data from consumer GPS navigation devices for the analysis of intersections is presented. Furthermore the practical applications for probe data from consumer GPS navigation devices is discussed.

The study shows the strengths and limitations of probe data from consumer GPS navigation devices for the analysis of intersections. A combination with other probe data sources and a growing market share could increase the possible applications of the data. Currently 40% of the vehicles on the road are equipped with some sort of navigation equipment and the number of vehicles is constantly growing. This trend provides a key factor for the use of probe data in traffic studies. To prepare for future application of the data, theoretical or test case studies should be used to identify the added benefit of the growing share of traceable GPS navigation devices.

For the research study two intersections are examined. Additional effort is advised to investigate the accuracy of the probe data at intersections with different layouts and under deviating traffic conditions. The effect of the number of probe measurements should be analysed at multiple intersections to check the network-wide representation of the data. By performing the study at a great

number of intersections, the individual character of the results is lowered and a evaluation of the use of probe data from consumer GPS navigation for intersection performance measurement can be presented.

The results show that storage of probe data as segment travel times reduces the possibility to accurately measure queue length and stop rate at intersections. The current data format is determined by the storage and retrieval capacity of the data servers which store the probe data. For the practical application of the data it is advised to investigate the possibility to use the 'raw' location measurements for queue length and stop rate calculations which would be beneficial for Performance Index studies with multiple measures of performance.

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Appendix A

Case study measurement setup

This appendix provides a background of the case study measurement setup and the layout of the intersection. The transformation of the physical layout of the intersection and the location of the detectors for digital model calculations is elaborated.

A1. OD layout for probe travel time measurement

For the calculation of travel times at the intersection all movements (12) are categorized by their respective origin and destination. Both test case intersections have 4 origins and 4 destinations, numbered clockwise starting at the Eastern link (Figure A.1)

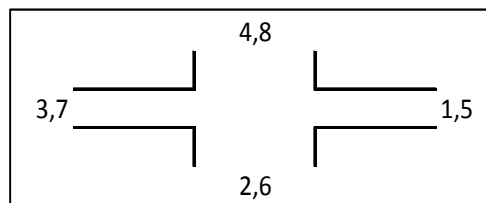


Figure A.1 Layout of origins and destinations for the calculation of the travel time and free flow speed

A2. Measurement setup probe data for intersection 1

For the calculation of the travel times the segment location and lengths which define the route of the movement are stored in the model. A separation is made between the total length of the movement trajectory and the length of the entry point to the stop line, which provides extra information for the experimental queue length and stop rate calculation. Next to the information from the

TomTom© map, the free-flow travel time per movement is calculated from CROW guidelines (CROW, 1992) and the corresponding free-flow speed is calculated to check the calculated travel times.

Intersection 1: Westlandseweg-Buitenhofdreef							
TomTom© map						CROW+Filter	
Movement	Entry segment	Exit segment	Matrix	Length(m)	Entry distance to stopline (m)	FF Speed (m/s)	FF Time(s)
1	1487450	2495476	1,8	364,5	242,5	14	26
2	1487450	2617598	1,7	287,5	242,5	17	17
3	1487450	1194881	1,6	429,9	242,5	15	29
4	1198041	1488802	2,5	109,3	29,4	15	7
5	1198041	2495476	2,8	181,9	29,4	14	13
6	1198041	2617598	2,7	97,3	29,4	12	8
7	1194766	1194881	3,6	281,3	151,7	12	23
8	1194766	1488802	3,5	231,9	144,2	14	17
9	1194766	2495476	3,8	304,7	144,2	11	28
10	2495476	2617598	4,7	168,7	130,7	12	14
11	2495476	1194881	4,6	311,1	130,7	15	21
12	2495476	1488802	4,5	239,1	130,7	15	16

Figure A.2 The measurement setup and crossing length used for the calculation of the travel time, delay and free flow travel time at intersection 1

Intersection 2: Westlandseweg-Provinciale weg							
TomTom© map						CROW+Filter	
Movement	Entry segment	Exit segment	Matrix	Length(m)	Distance to stopline (m)	FF Speed (m/s)	FF Time(s)
1	1960591	2581825	1,8	425,9	145,8	17	25
2	1960591	1487450	1,7	387,1	141,3	17	23
3	1960591	2581834	1,6	290,8	141,3	12	24
4	2581822	1189937	2,5	318,9	288,5	14	23
5	2581822	2581825	2,8	618,2	288,5	22	28
6	2581822	1487450	2,7	562,4	288,5	15	37
7	1488801	2581834	3,6	248,5	196,1	14	18
8	1488801	1189937	3,5	274,7	191,4	18	15
9	1488801	2581825	3,8	574	191,4	15	38
10	2581832	1487450	4,7	498,5	310,1	14	36
11	2581832	2581834	4,6	406,7	310,1	18	23
12	2581832	1189937	4,5	420,5	310,1	15	28

Figure A.3 The measurement setup and crossing length used for the calculation of the travel time, delay and free flow travel time at intersection 2

A3. Detector locations intersection 1

For the calculation of traffic volume and signal timing at the test case intersections, the location and numbering of the detectors is examined. A reference table is created to link the numbers of the detectors and lights in the Regiolab project to the numbers of the model used for traffic volume and green time calculations.

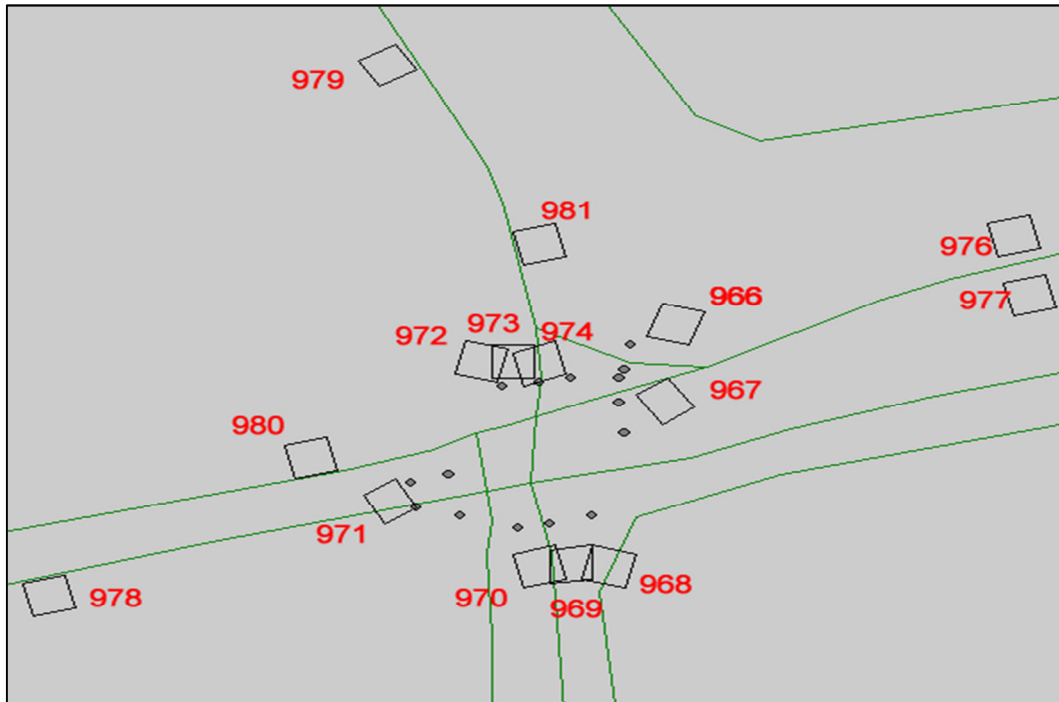


Figure A.4 Regiolab loop detectors at intersection 1

A4. Movement calculation intersection 1

Intersection 1: Westlandseweg-Buitenhofdreef				
Regiolab input				
Movement	Detector input	Error	Light	Model code
1	966		951	16
2	977		952	26
3	967		953	17
4	968		954	18
5	969		955	19
6	970		956	20
7	978-971	8	957	27-21
8	978-971	7	958	27-21
9	971		958	21
10	972		959	22
11	973		960	23
12	974		961	24

Figure A.5 The movement calculation from Regiolab detector input at intersection 1

A5. Detector locations intersection 2

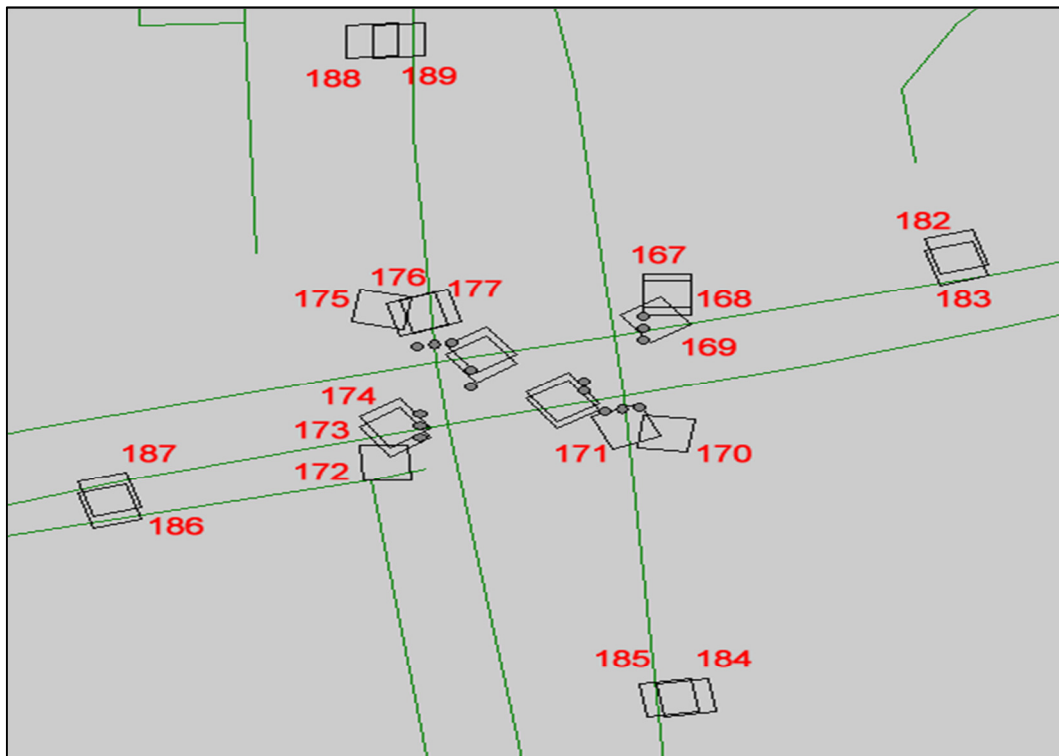


Figure A.6 Regiolab loop detectors at intersection 2

A6. Movement calculation intersection 2

Intersection 2: Westlandseweg-Provinciale weg				
Regiolab input				
Movement	Detector input	Error	Light	Model code
1	167+168		151	17+18
2	182+183-167-168-169		152	28+29-17-18-19
3	169		153	19
4	170		154	20
5	184+185-170-171		155	30+31-20-21
6	171		156	21
7	172		157	22
8	186+187-172-173-174		158	32+33-22-23-24
9	173+174		159	23+24
10	175		160	25
11	188+189-175-176-177		161	34+35-25-26-27
12	176+177		162	26+27

Figure A.7 The movement calculation from Regiolab detector input at intersection 2

Appendix B

Traffic volume distribution

To compare the size of the traffic volume at all movements at both intersections the traffic volume during the day is measured. The traffic volume is measured for each day of the week which provides any weekdays patterns and travel behavior in the data.

B.1 Intersection 1

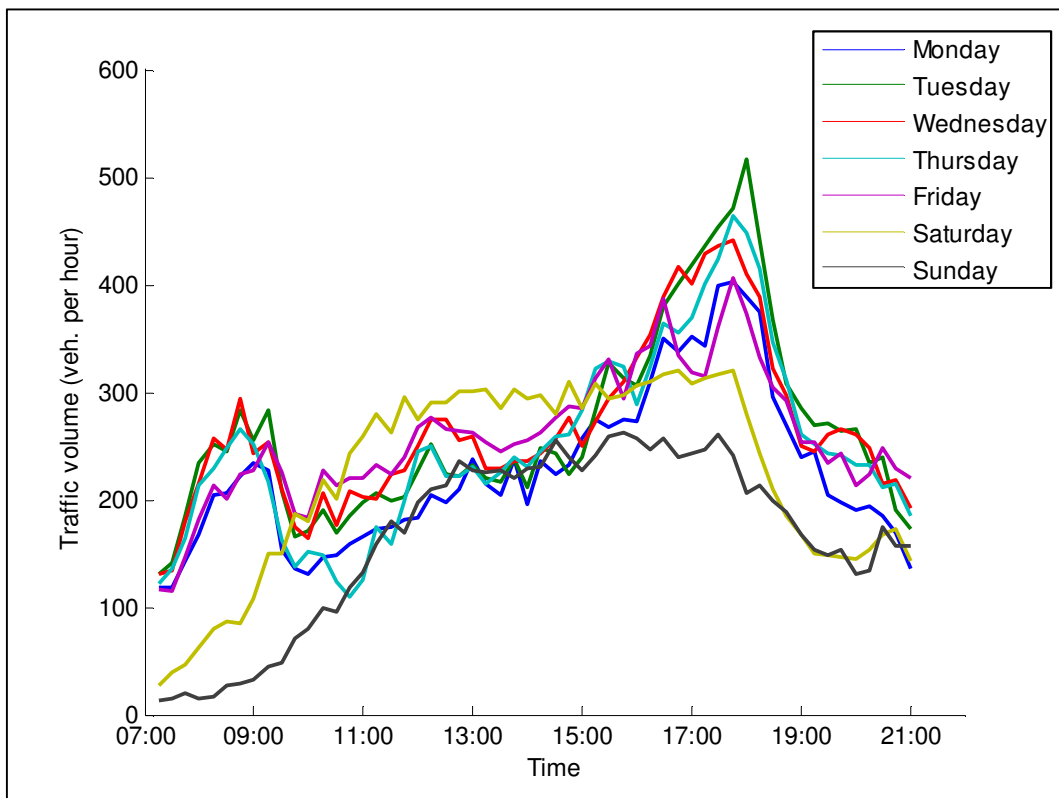


Figure B.1 The traffic volume day-distribution in vehicles per hour for movement 1 at intersection 1 (April-June 2009)

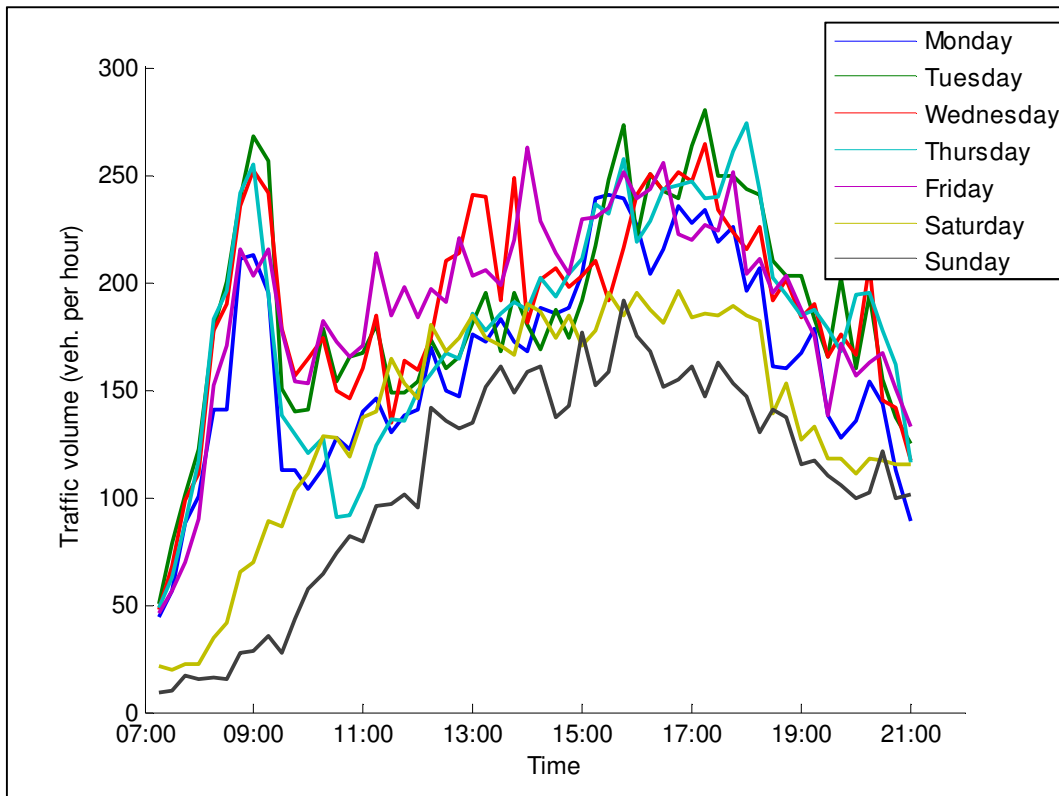


Figure B.2 The traffic volume day-distribution in vehicles per hour for movement 3 at intersection 1 (April-June 2009)

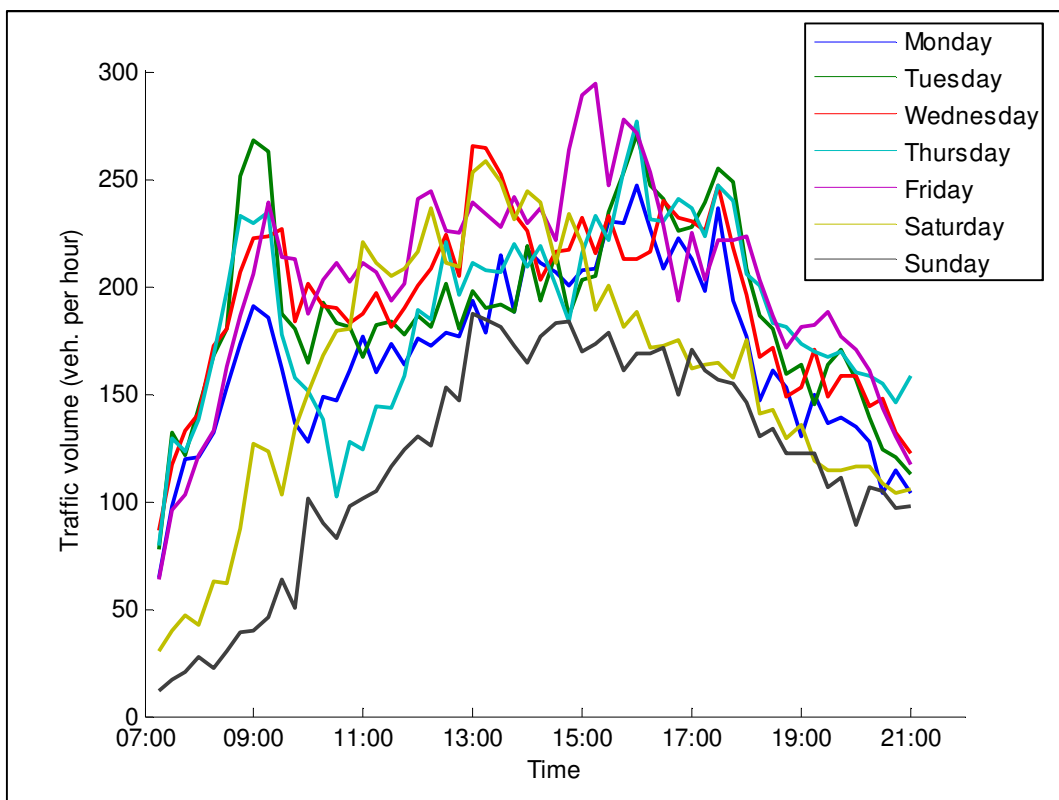


Figure B.3 The traffic volume day-distribution in vehicles per hour for movement 4 at intersection 1 (April-June 2009)

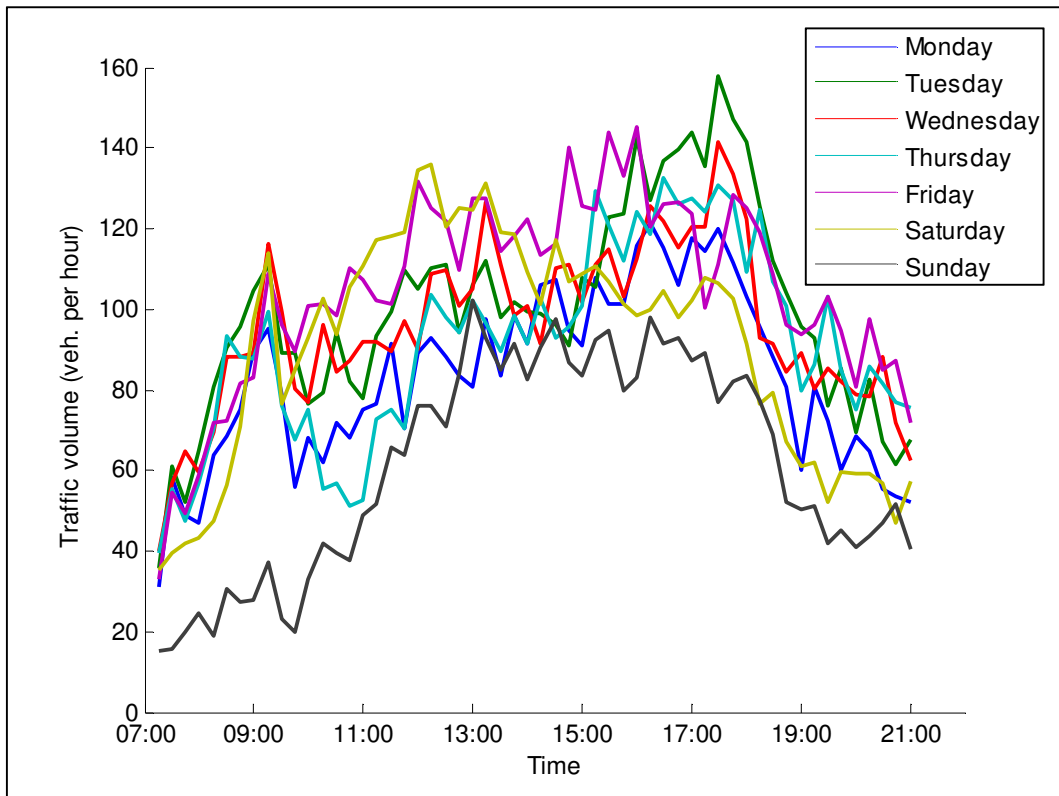


Figure B.4 The traffic volume day-distribution in vehicles per hour for movement 5 at intersection 1 (April-June 2009)

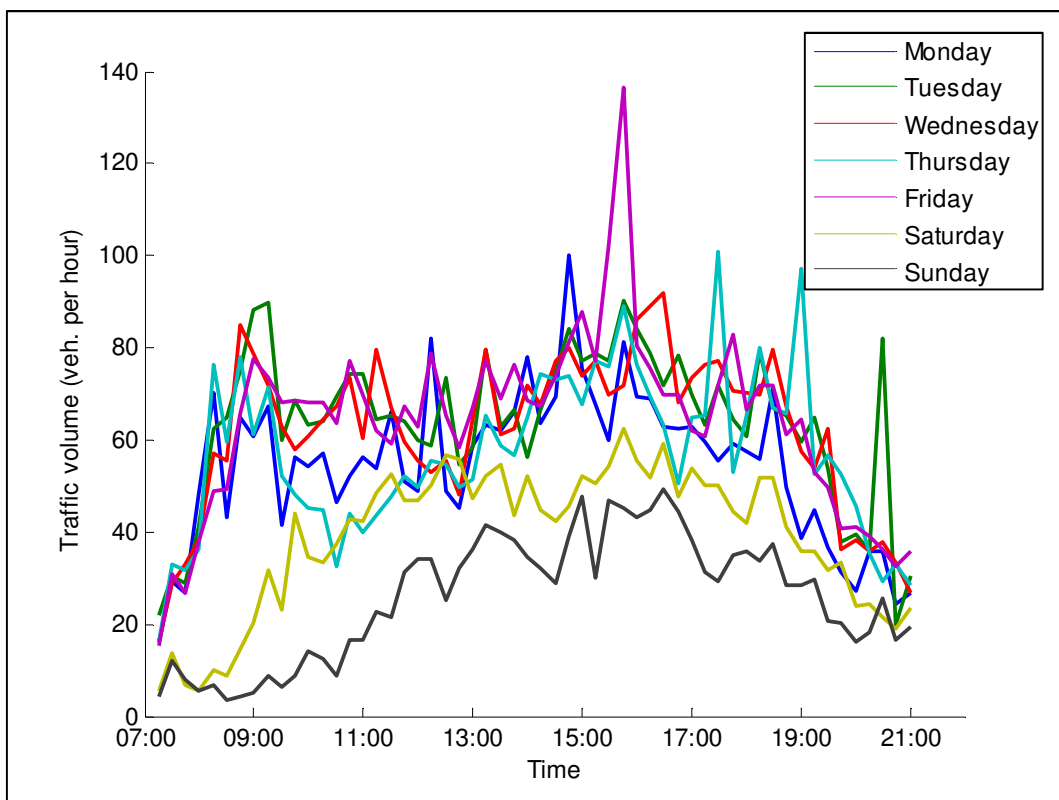


Figure B.5 The traffic volume day-distribution in vehicles per hour for movement 6 at intersection 1 (April-June 2009)

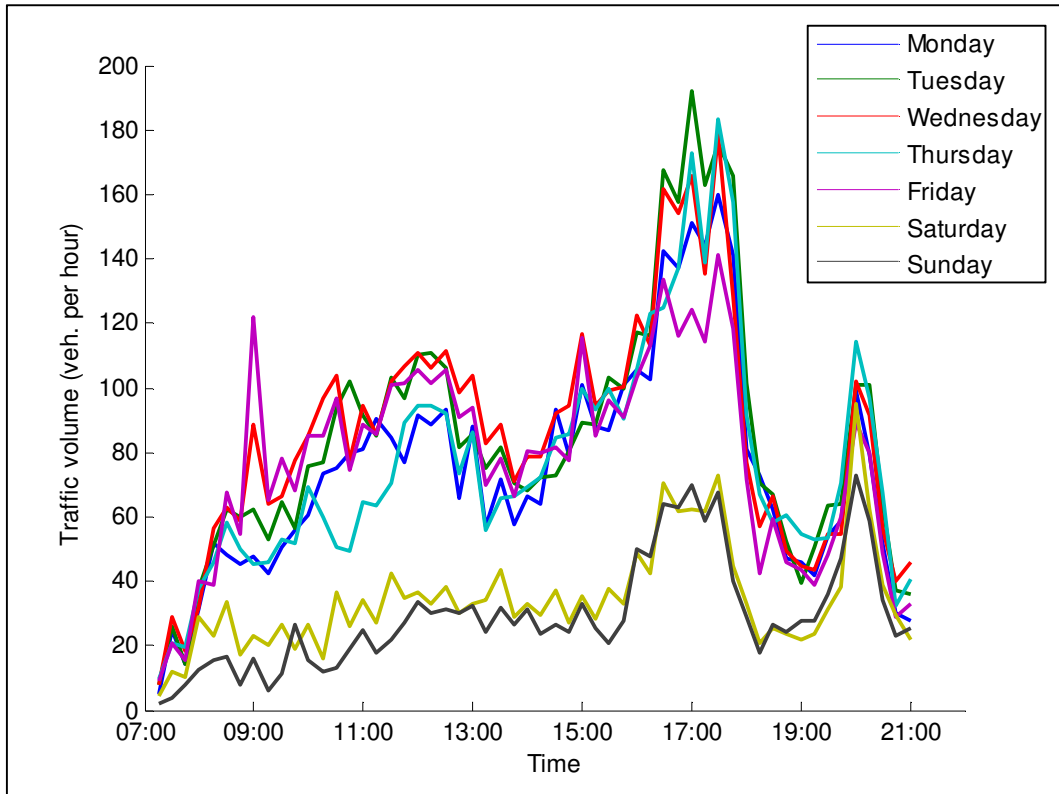


Figure B.6 The traffic volume day-distribution in vehicles per hour for movement 9 at intersection 1 (April-June 2009)

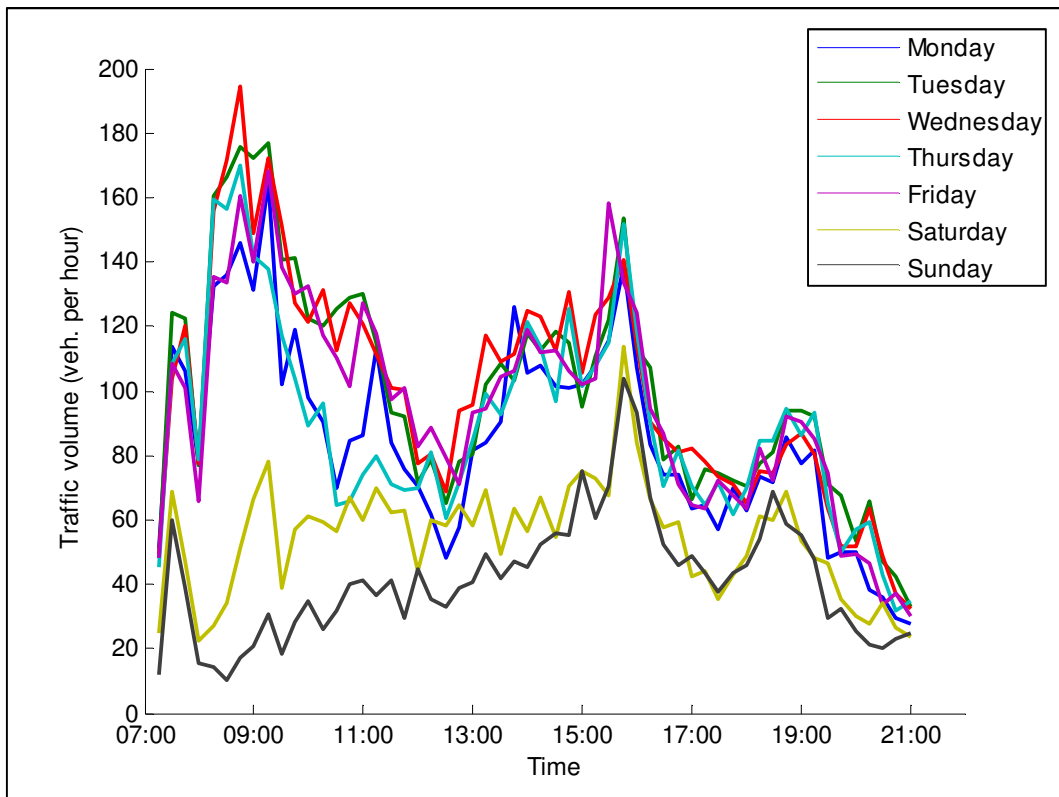


Figure B.7 The traffic volume day-distribution in vehicles per hour for movement 10 at intersection 1 (April-June 2009)

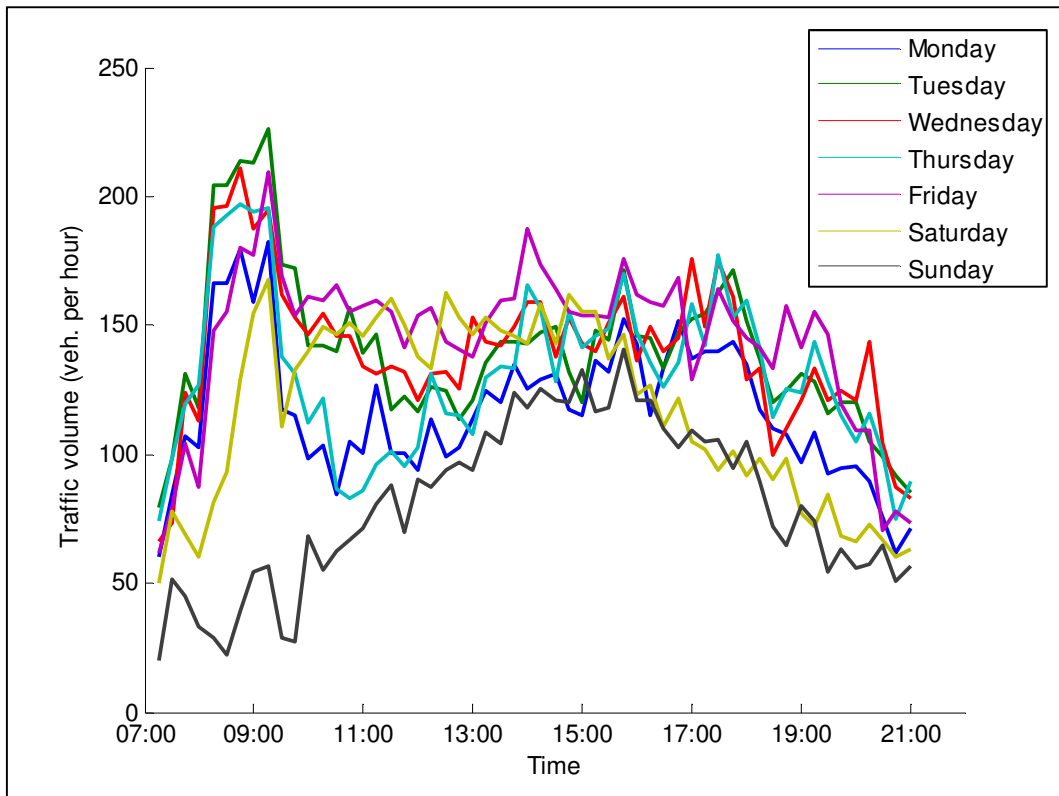


Figure B.8 The traffic volume day-distribution in vehicles per hour for movement 11 at intersection 1 (April-June 2009)

B.2 Intersection 2

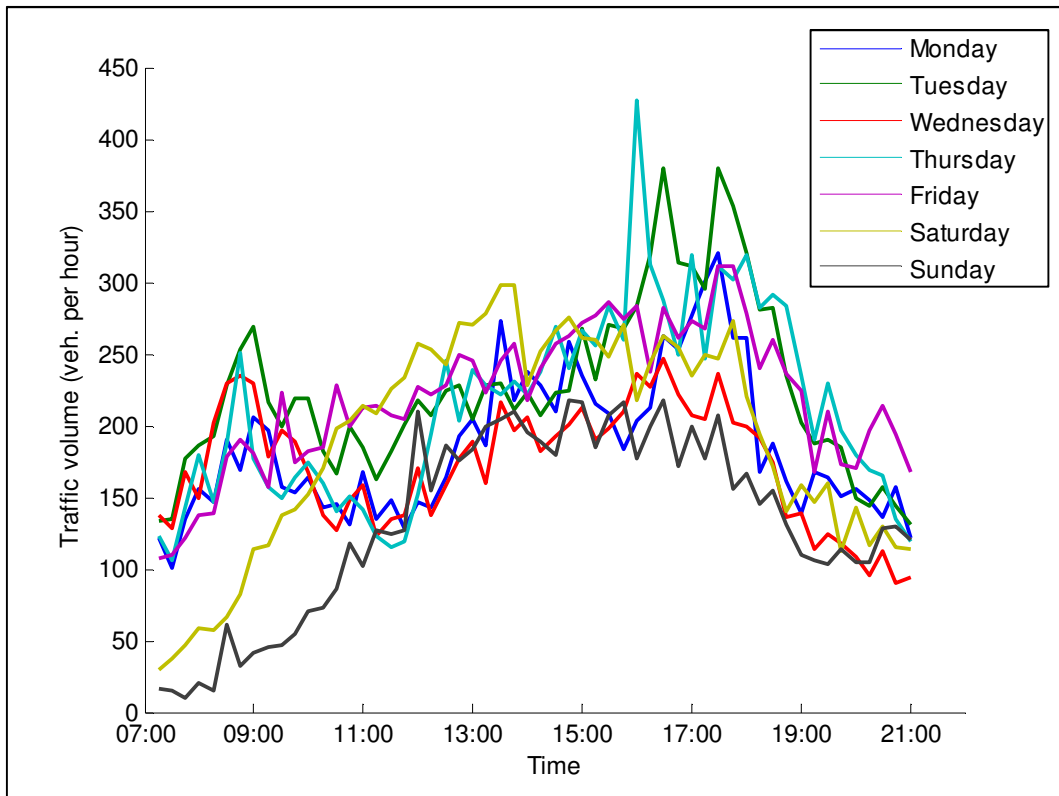


Figure B.9 The traffic volume day-distribution in vehicles per hour for movement 1 at intersection 2 (April-June 2009)

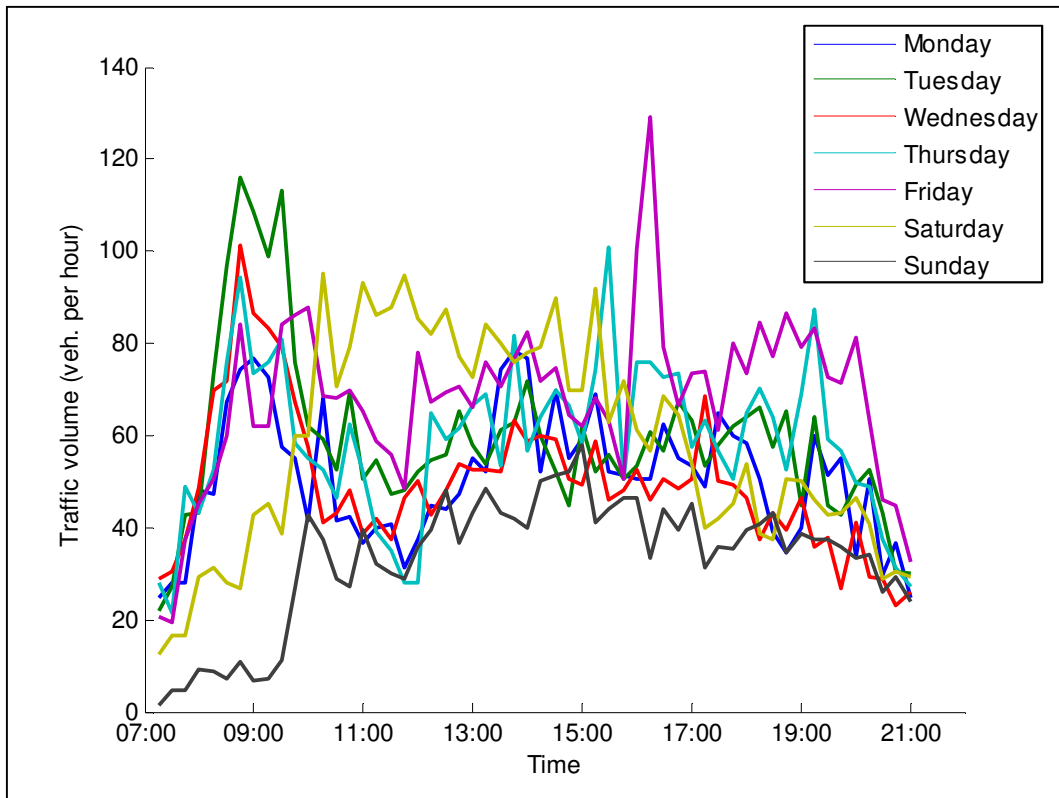


Figure B.10 The traffic volume day-distribution in vehicles per hour for movement 4 at intersection 2 (April-June 2009)

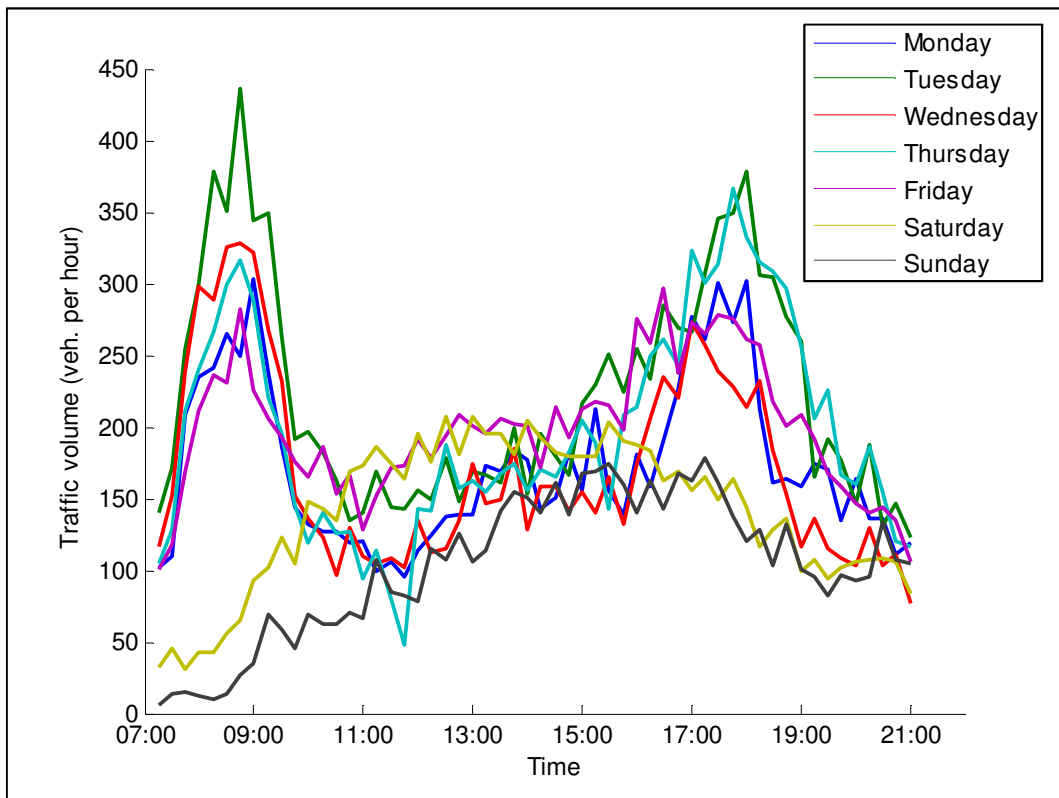


Figure B.11 The traffic volume day-distribution in vehicles per hour for movement 5 at intersection 2 (April-June 2009)

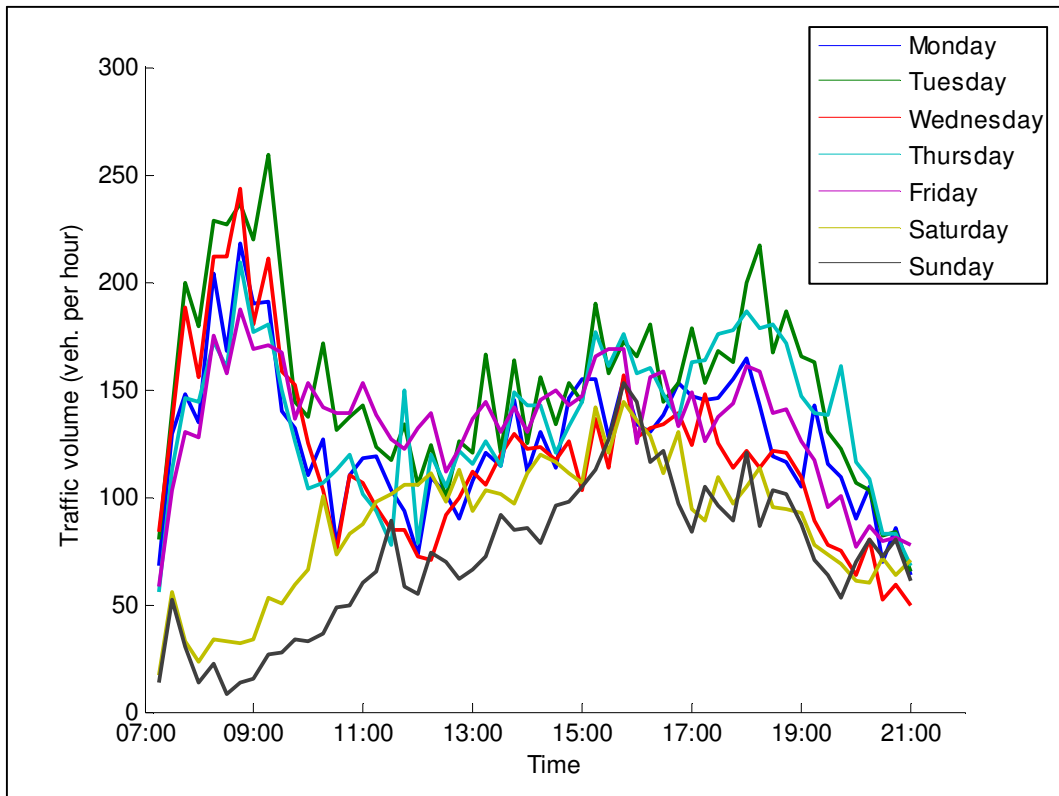


Figure B.12 The traffic volume day-distribution in vehicles per hour for movement 6 at intersection 2 (April-June 2009)

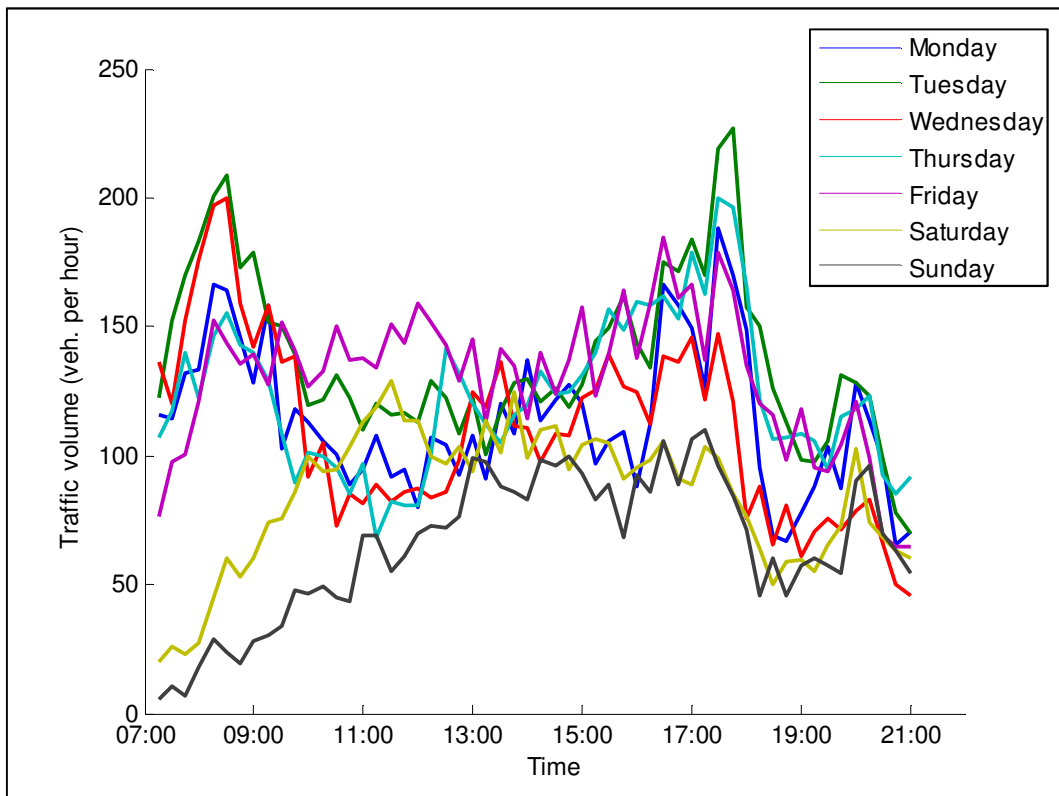


Figure B.13 The traffic volume day-distribution in vehicles per hour for movement 7 at intersection 2 (April-June 2009)

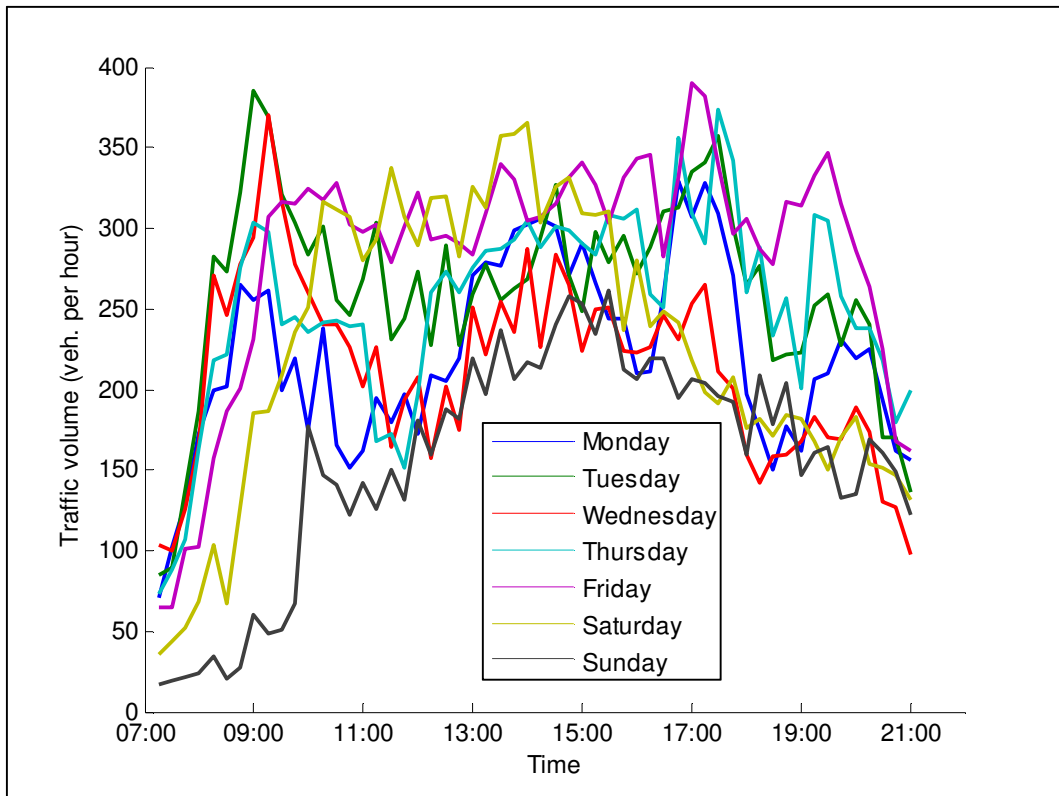


Figure B.14 The traffic volume day-distribution in vehicles per hour for movement 8 at intersection 2 (April-June 2009)

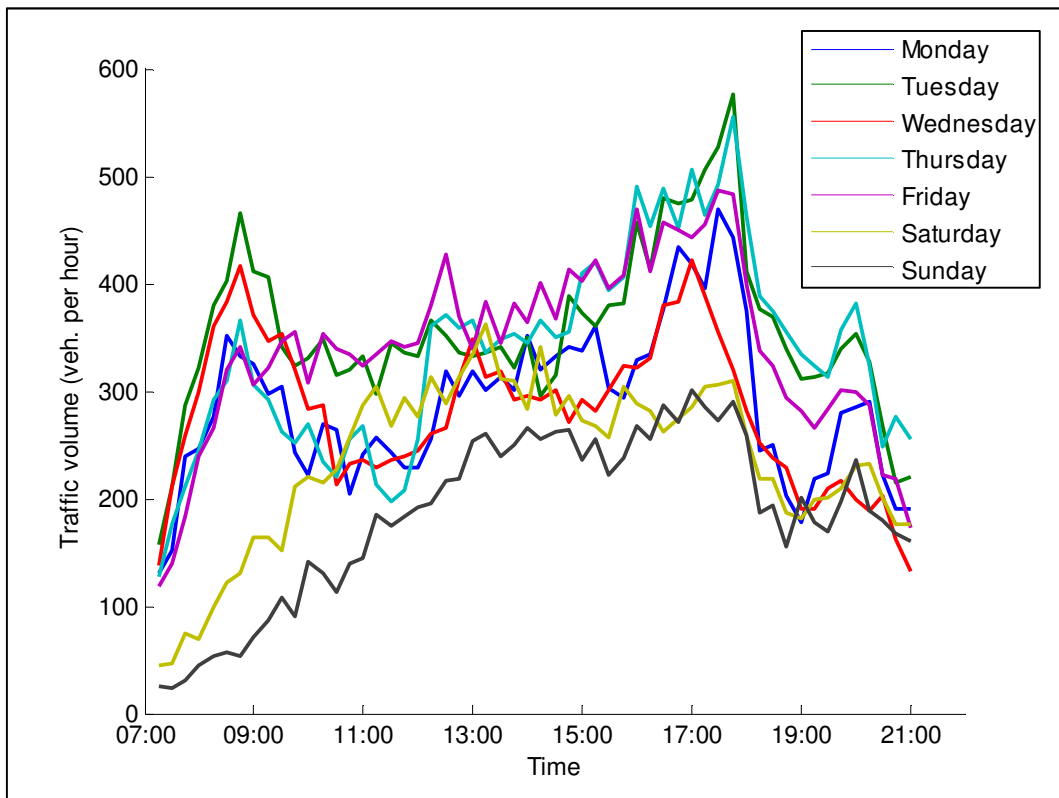


Figure B.15 The traffic volume day-distribution in vehicles per hour for movement 9 at intersection 2 (April-June 2009)

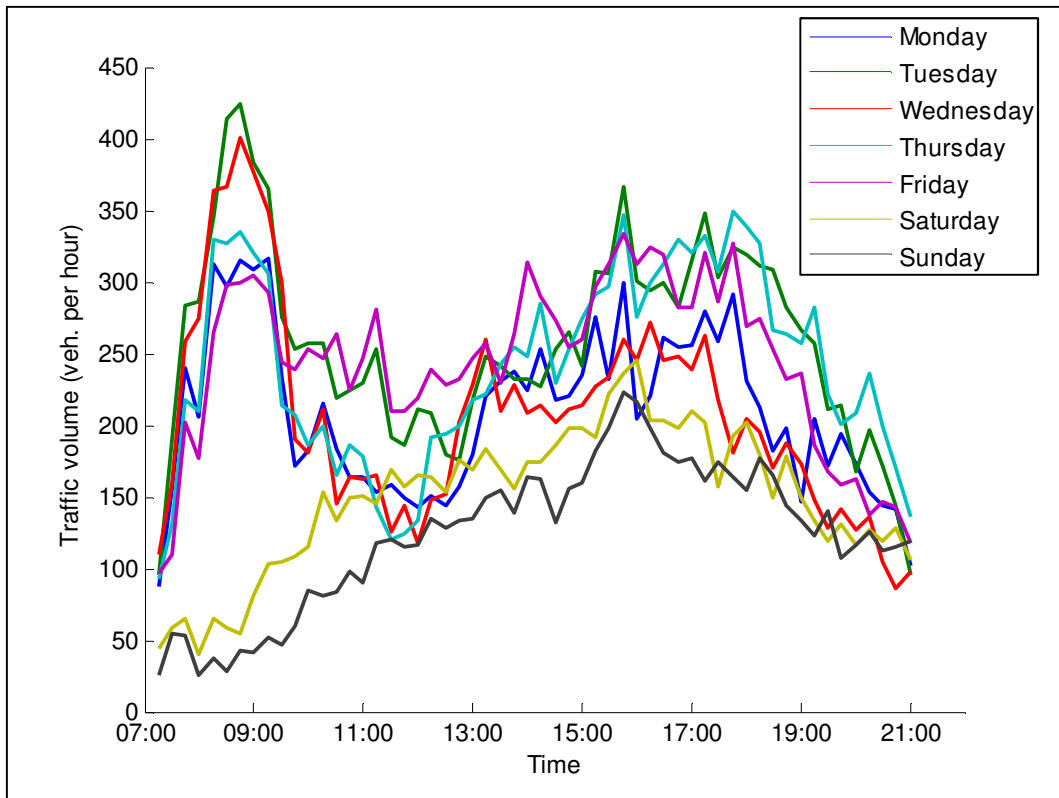


Figure B.16 The traffic volume day-distribution in vehicles per hour for movement 10 at intersection 2 (April-June 2009)

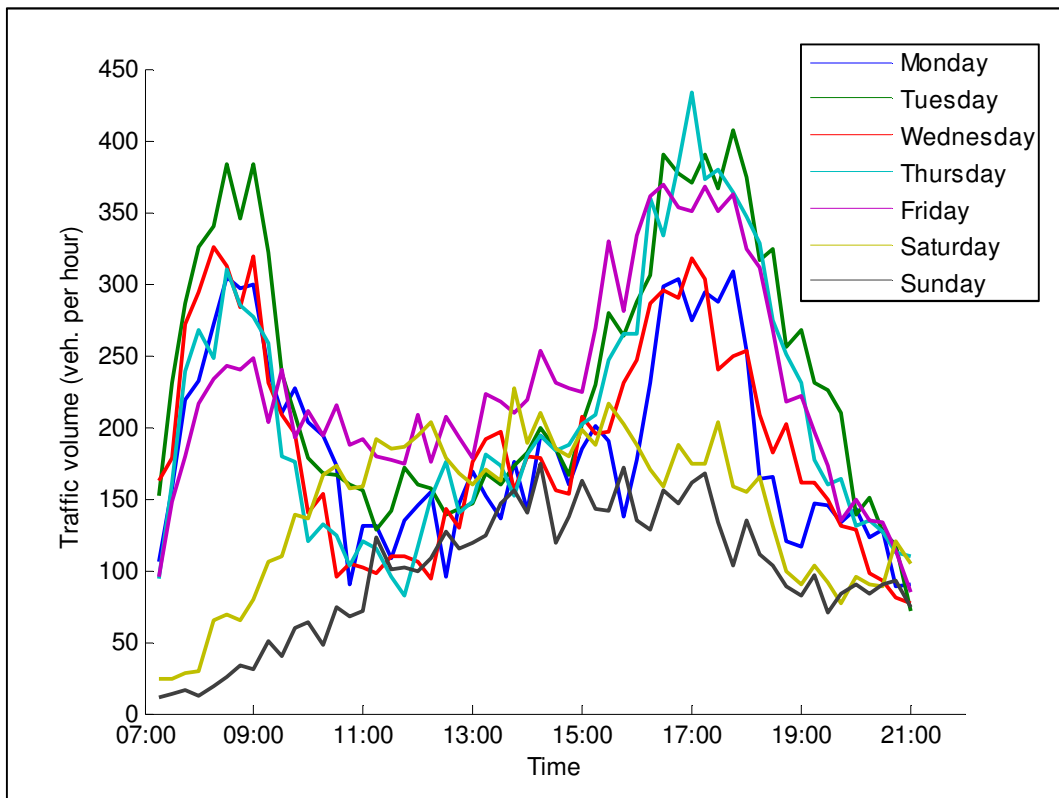


Figure B.17 The traffic volume day-distribution in vehicles per hour for movement 11 at intersection 2 (April-June 2009)

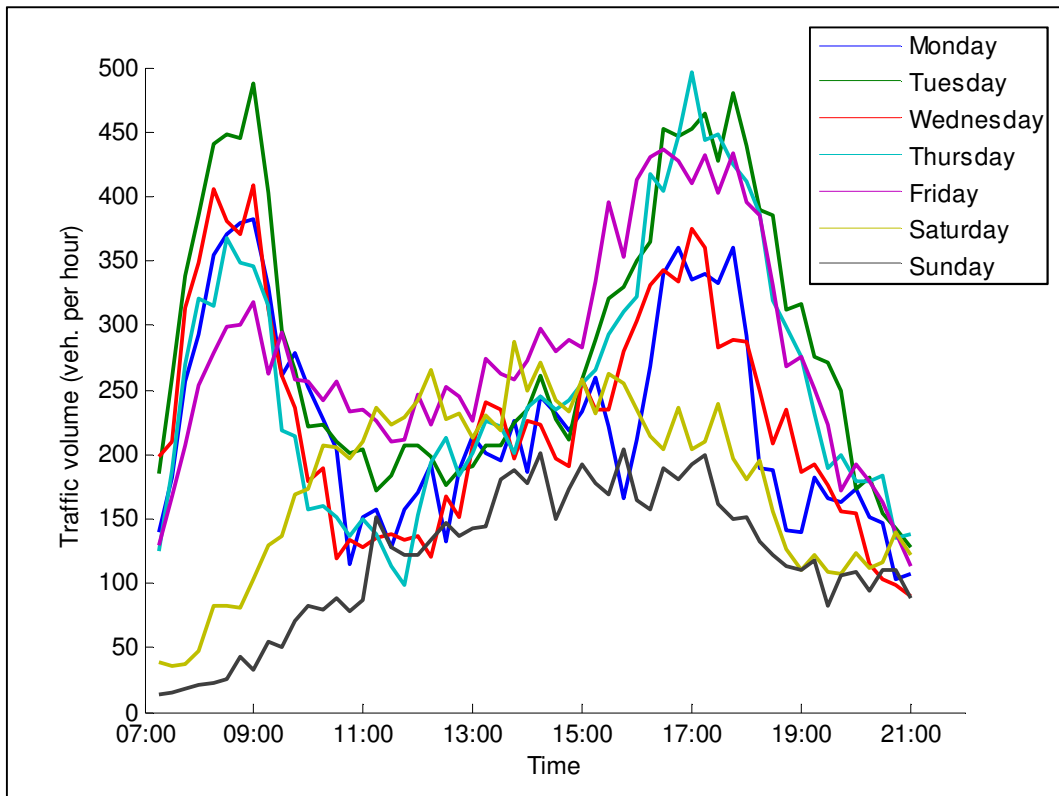


Figure B.18 The traffic volume day-distribution in vehicles per hour for movement 12 at intersection 2 (April-June 2009)

Appendix C

Delay distribution

C.1 Intersection 1

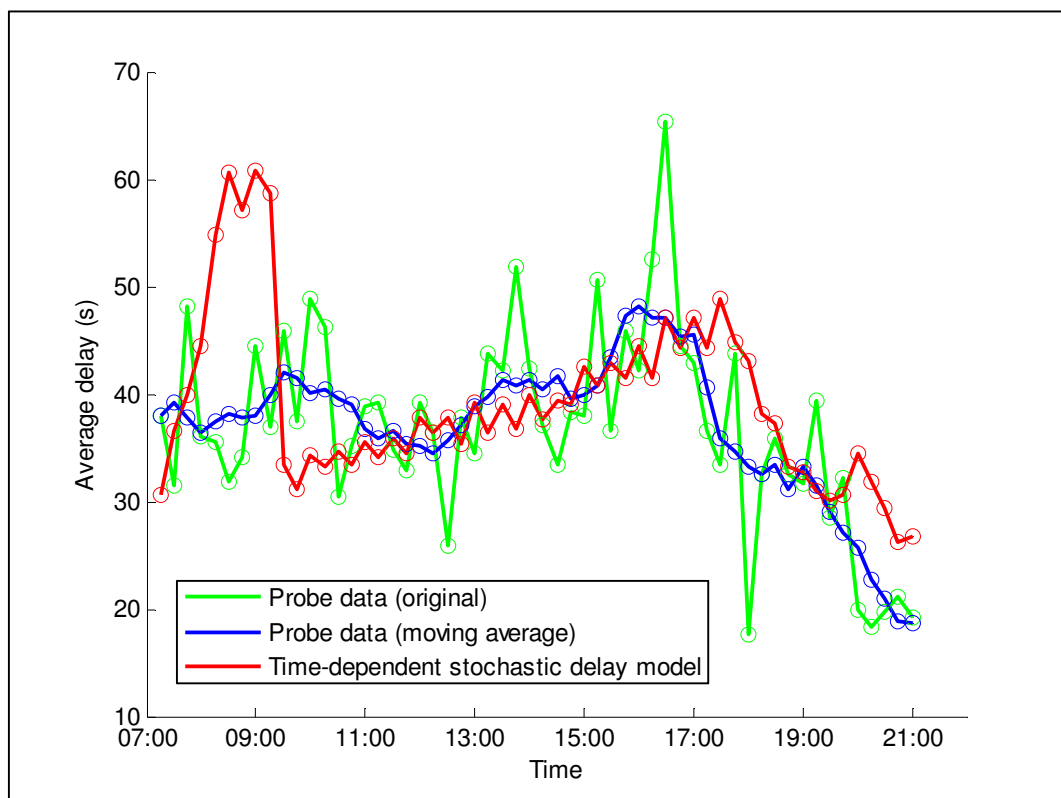


Figure C.1 The average delay distribution in seconds for movement 1 at intersection 1 (April-June 2009)

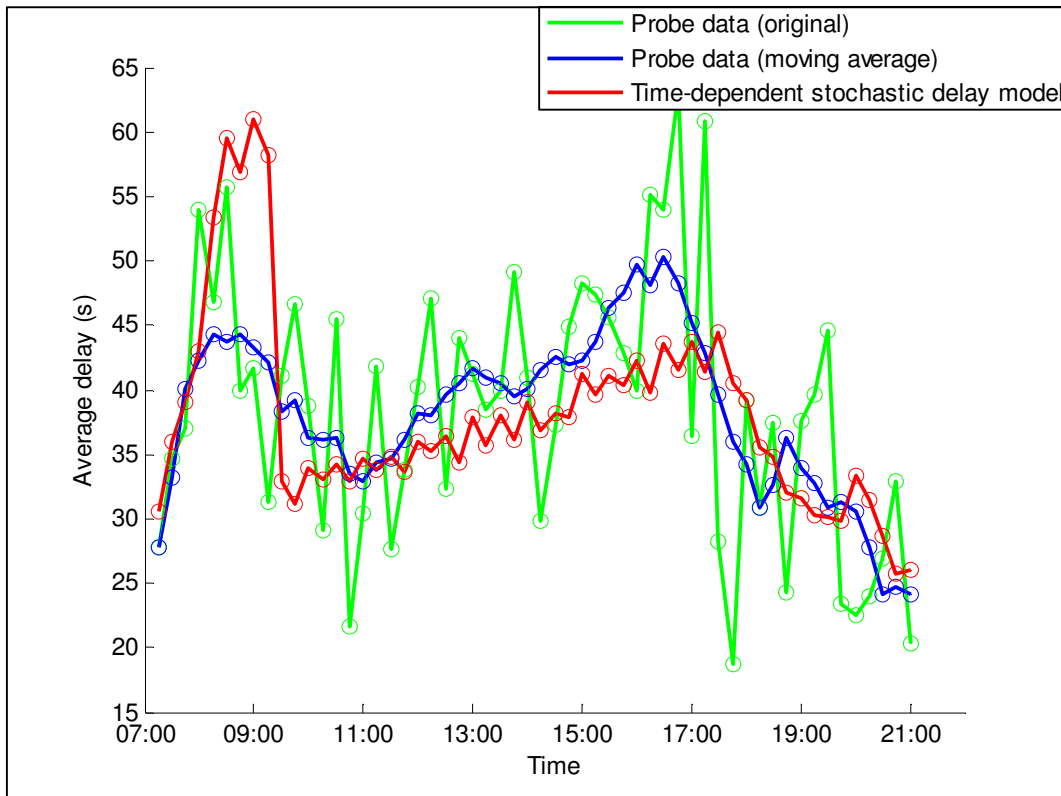


Figure C.2 The average delay distribution in seconds for movement 3 at intersection 1 (April-June 2009)

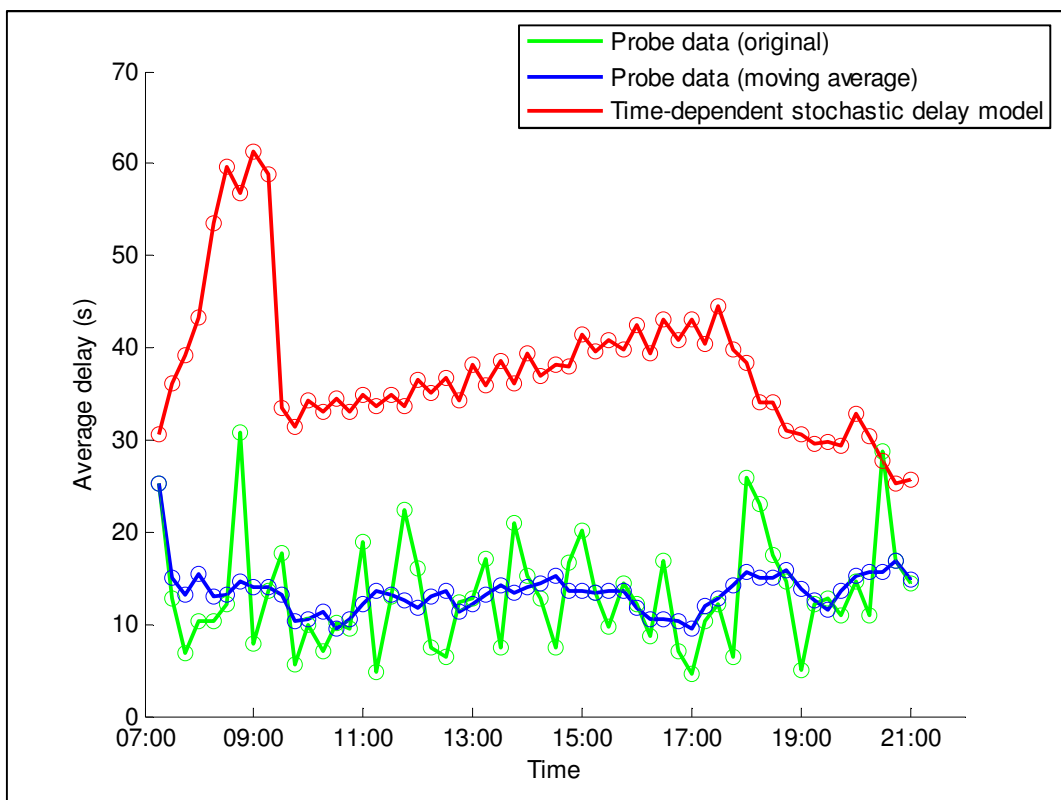


Figure C.3 The average delay distribution in seconds for movement 4 at intersection 1 (April-June 2009)

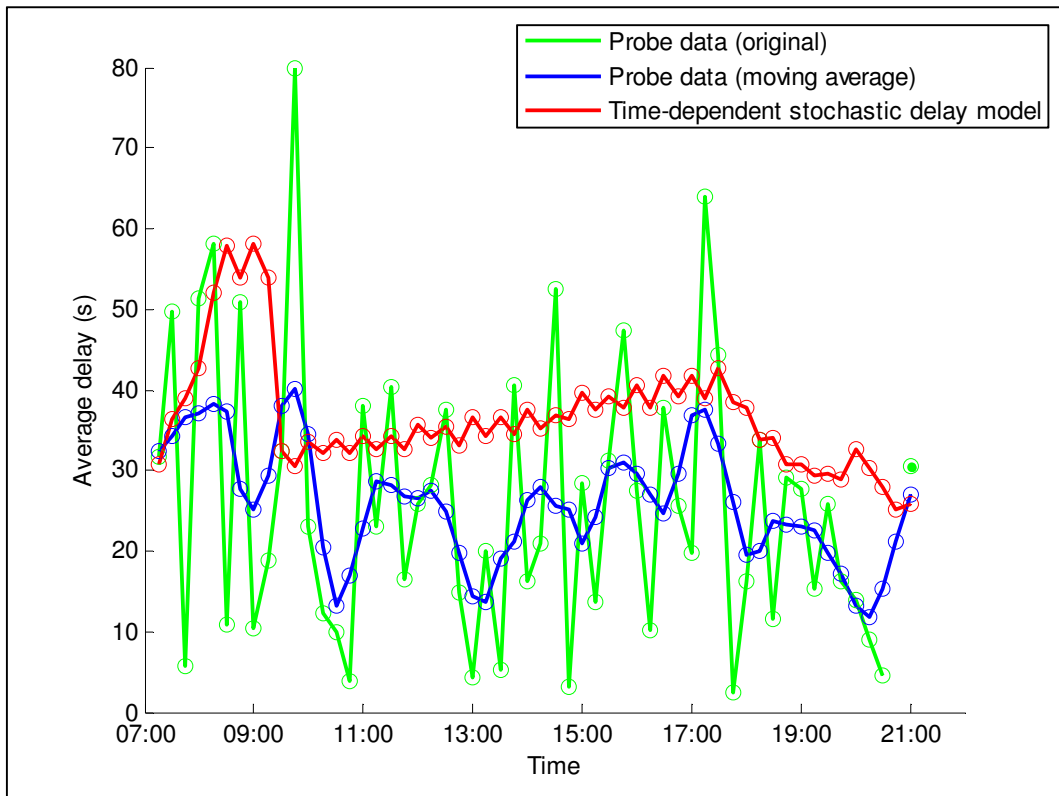


Figure C.4 The average delay distribution in seconds for movement 5 at intersection 1 (April-June 2009)

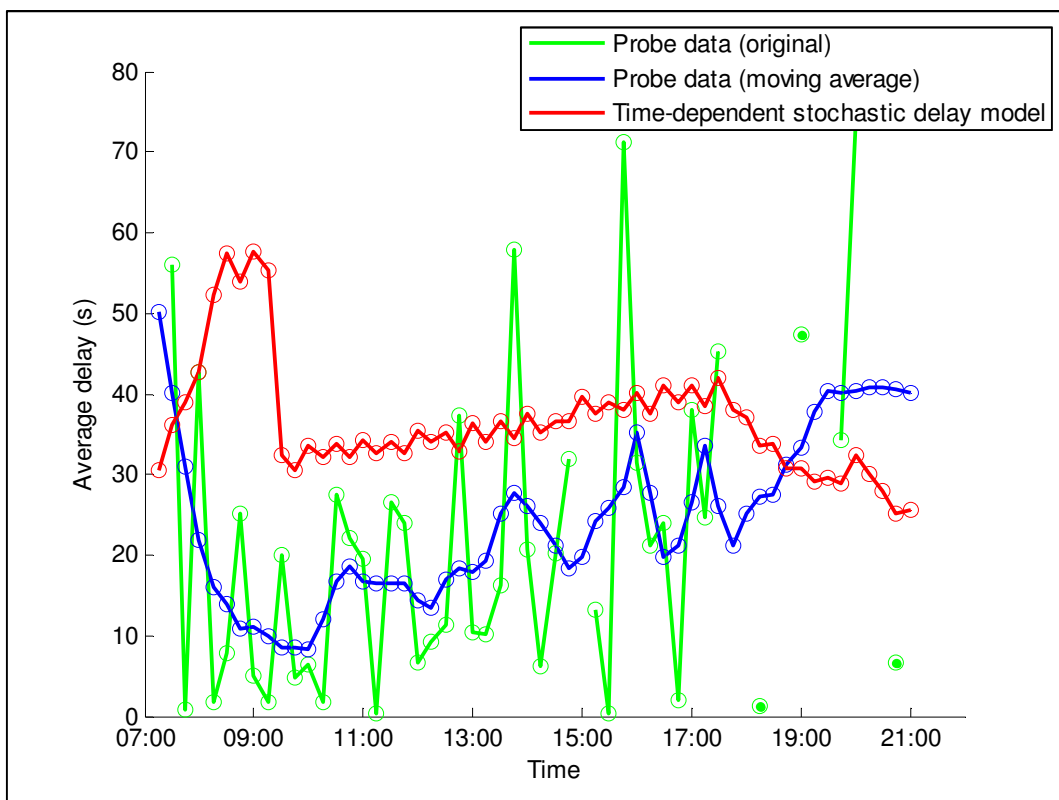


Figure C.5 The average delay distribution in seconds for movement 6 at intersection 1 (April-June 2009)

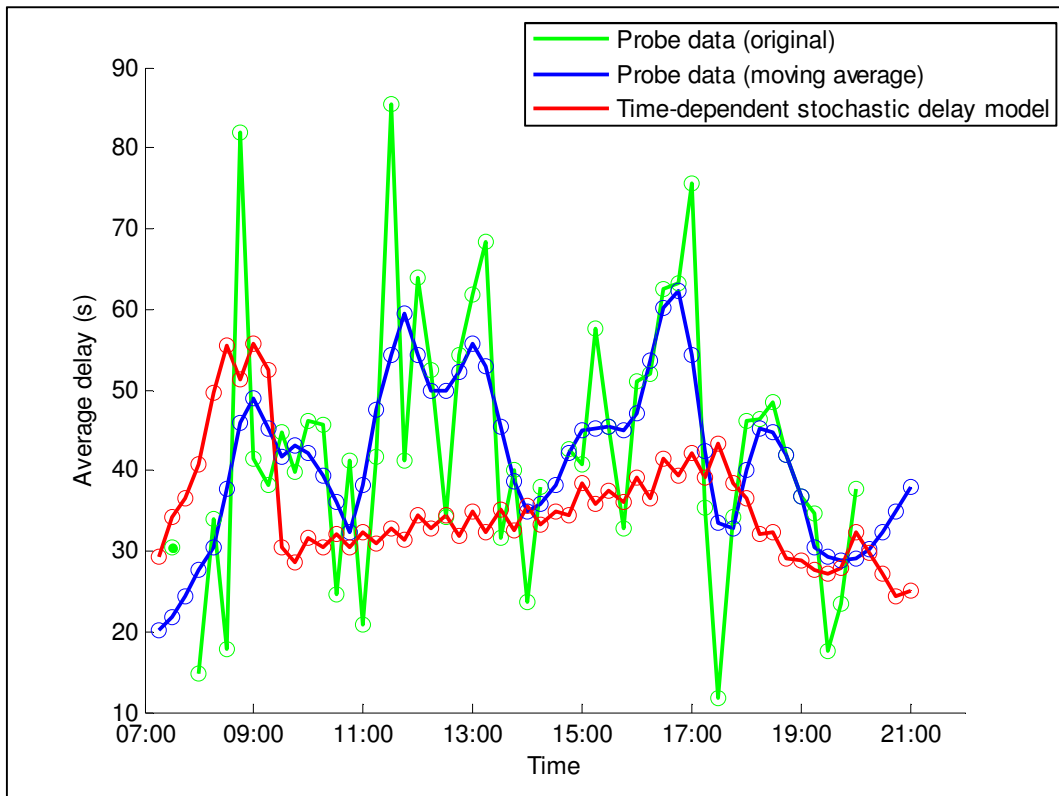


Figure C.6 The average delay distribution in seconds for movement 9 at intersection 1 (April-June 2009)

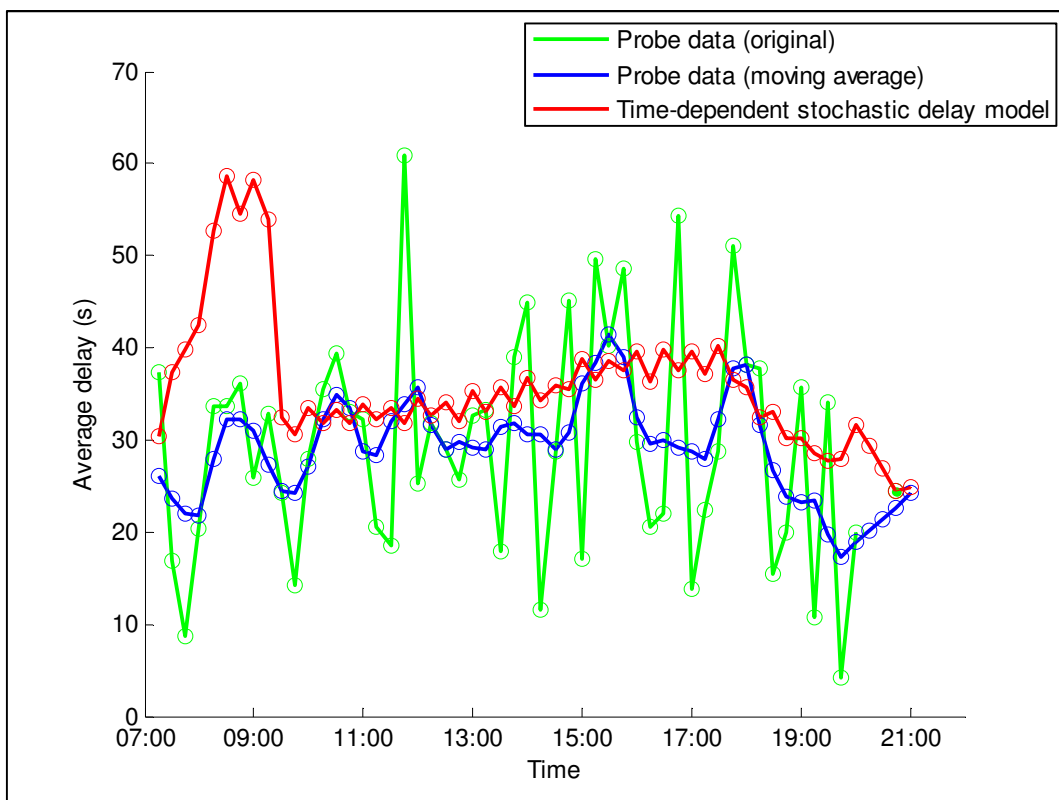


Figure C.7 The average delay distribution in seconds for movement 10 at intersection 1 (April-June 2009)

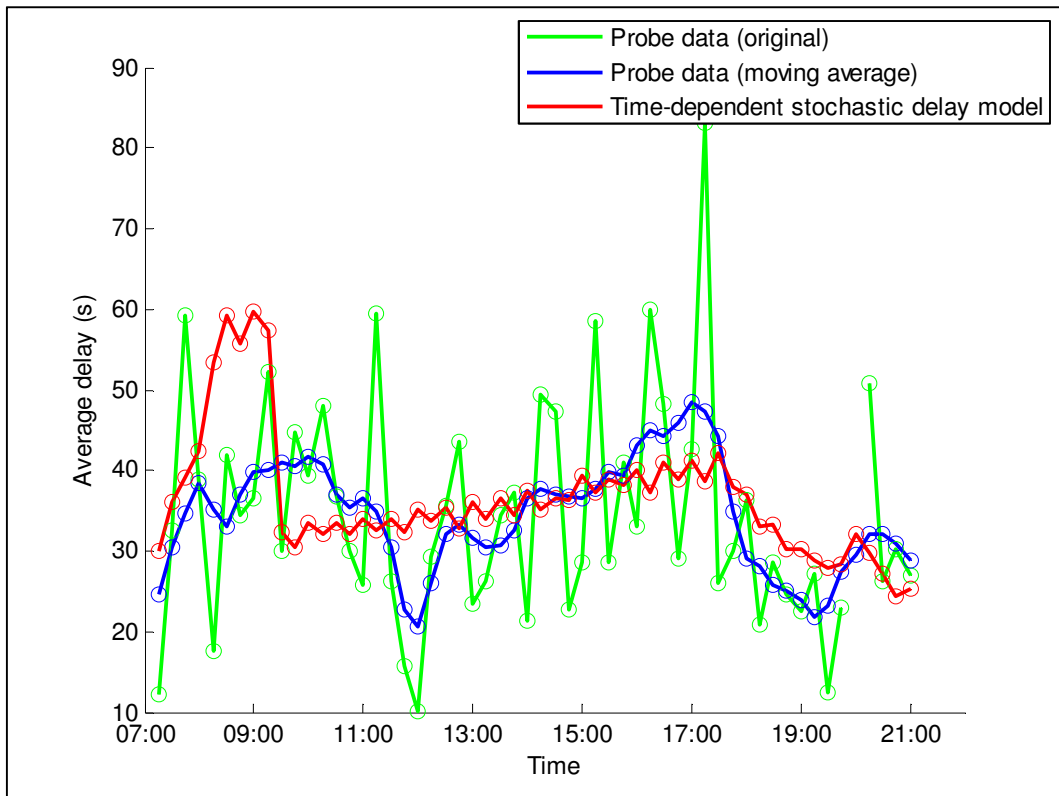


Figure C.8 The average delay distribution in seconds for movement 11 at intersection 1 (April-June 2009)

C.2 Intersection 2

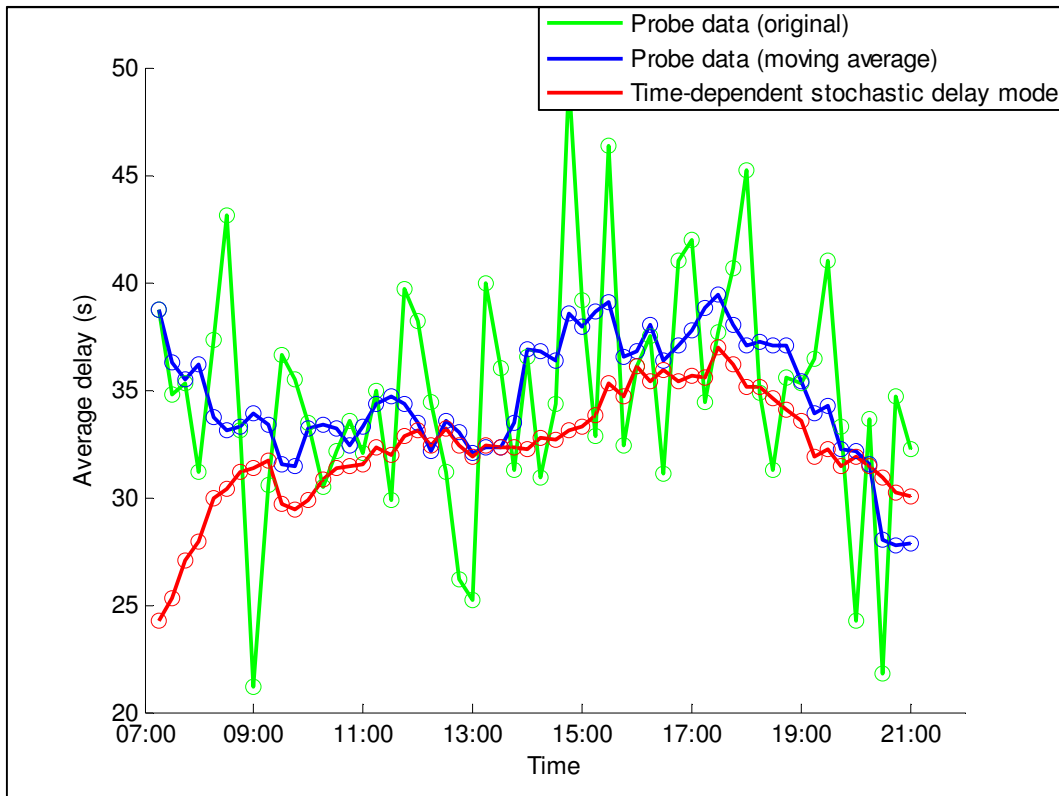


Figure C.9 The average delay distribution in seconds for movement 1 at intersection 2 (April-June 2009)

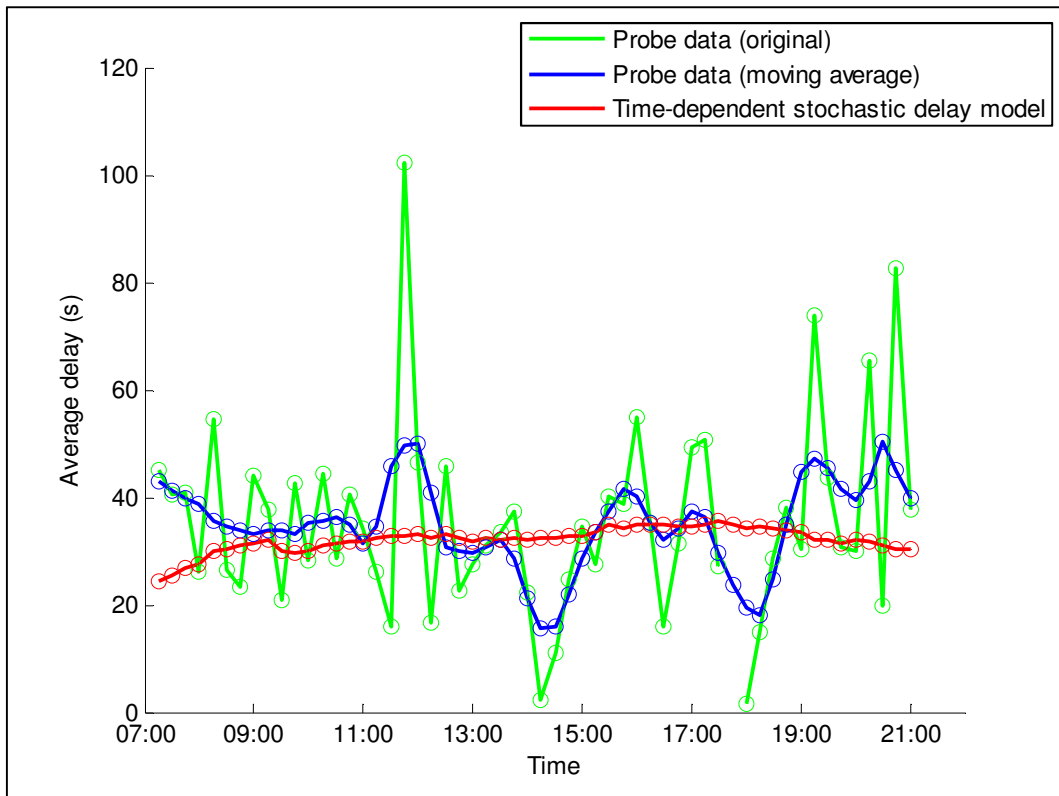


Figure C.10 The average delay distribution in seconds for movement 4 at intersection 2 (April-June 2009)

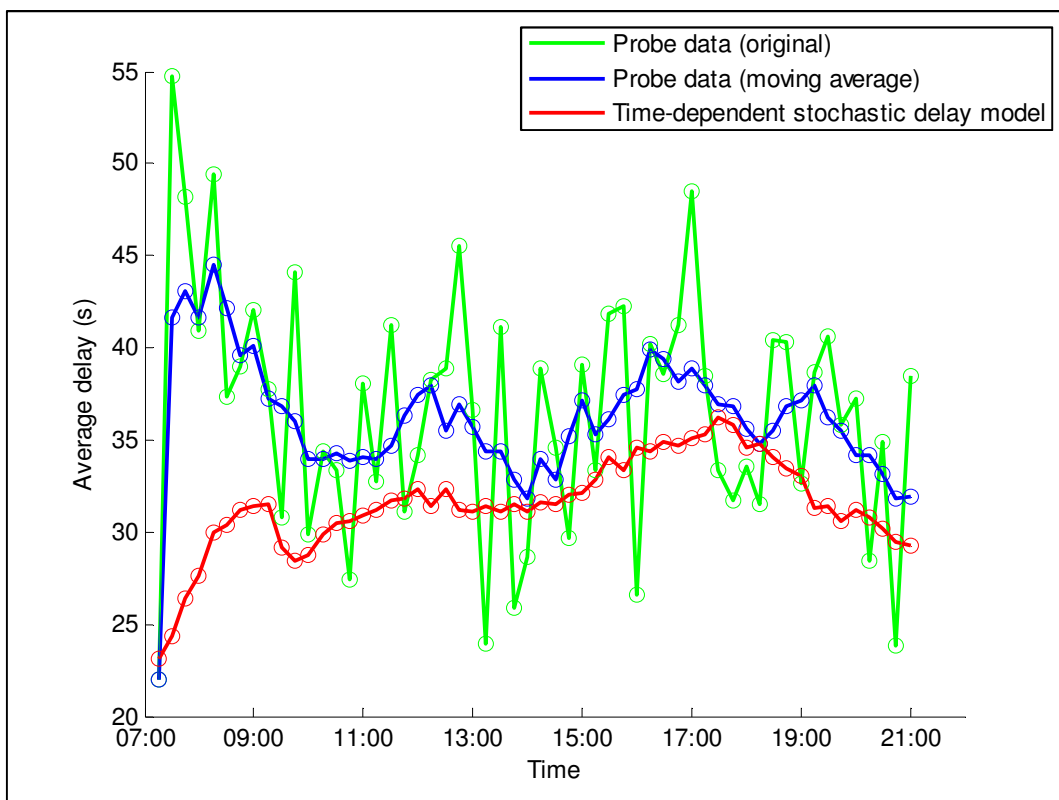


Figure C.11 The average delay distribution in seconds for movement 5 at intersection 2 (April-June 2009)

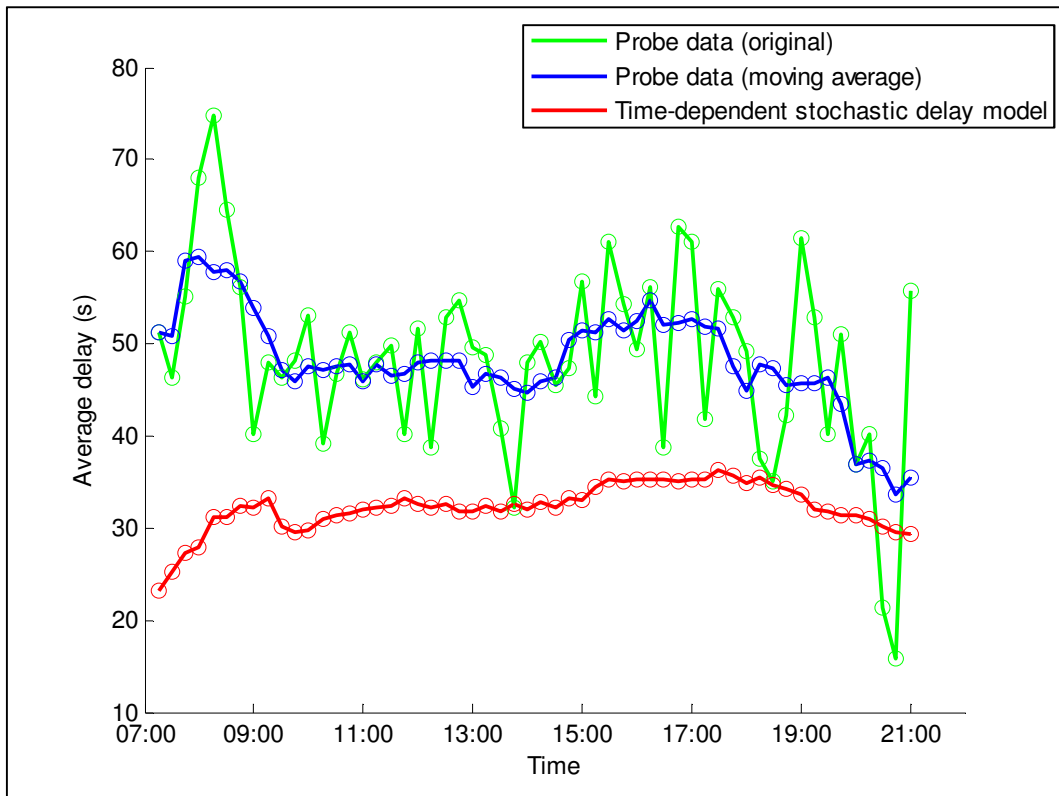


Figure C.12 The average delay distribution in seconds for movement 6 at intersection 2 (April-June 2009)

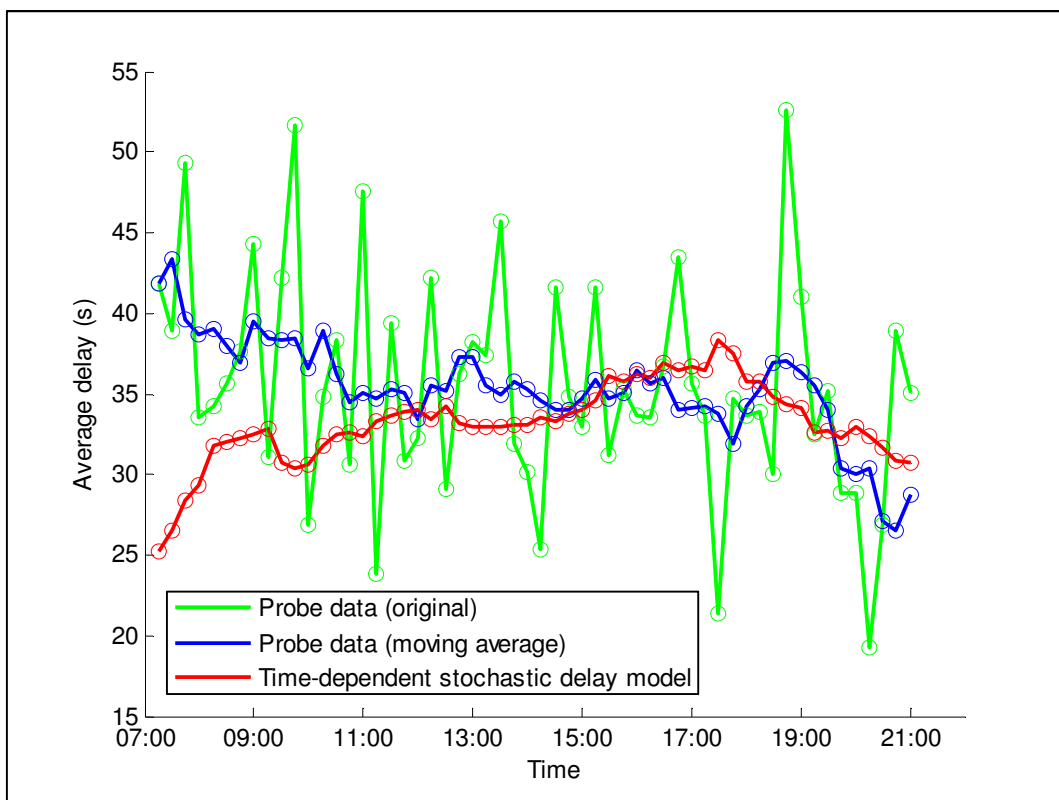


Figure C.13 The average delay distribution in seconds for movement 7 at intersection 2 (April-June 2009)

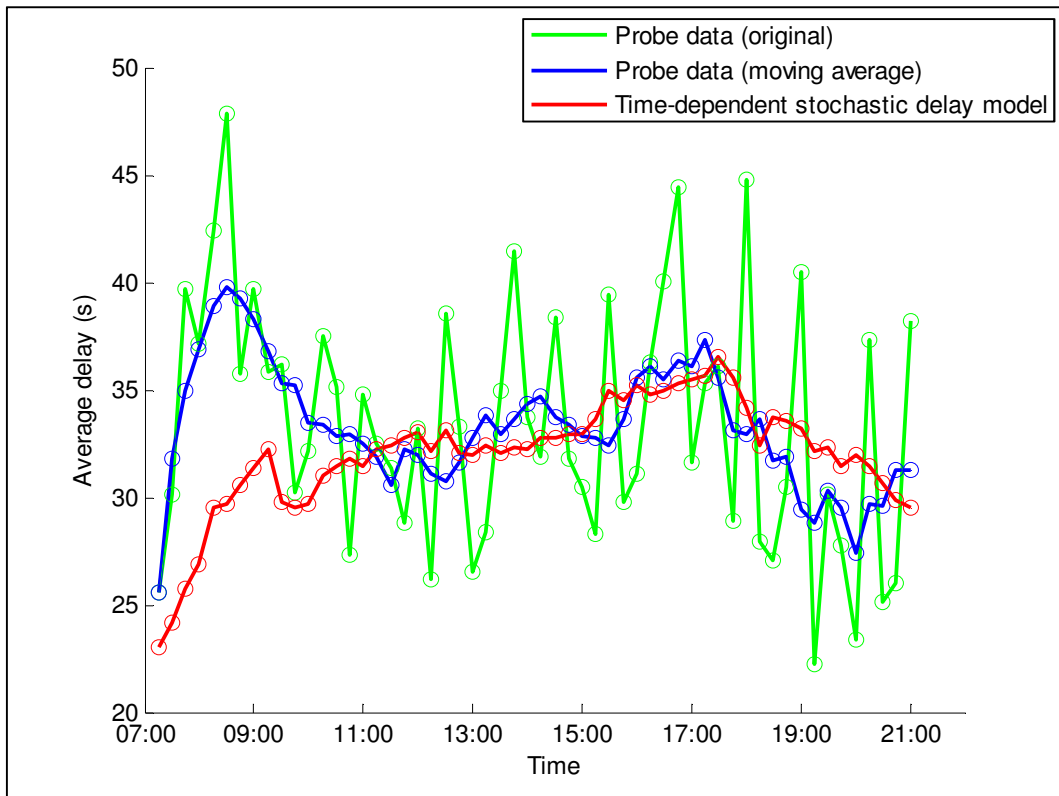


Figure C.14 The average delay distribution in seconds for movement 8 at intersection 2 (April-June 2009)

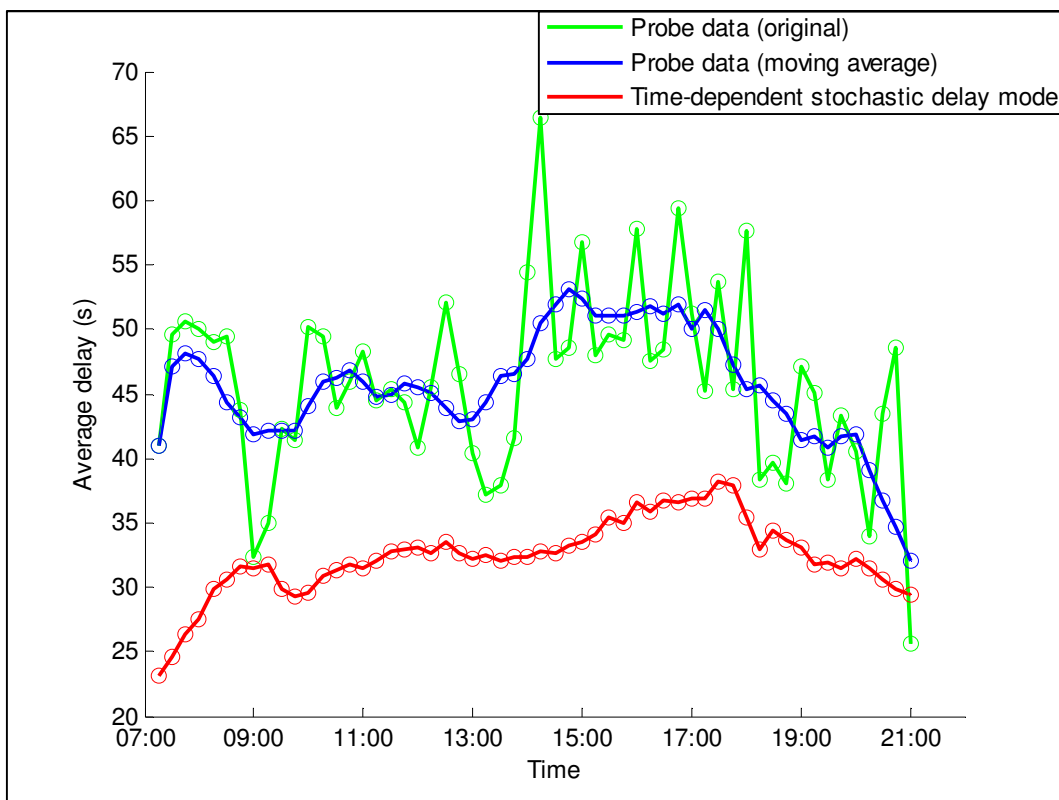


Figure C.15 The average delay distribution in seconds for movement 9 at intersection 2 (April-June 2009)

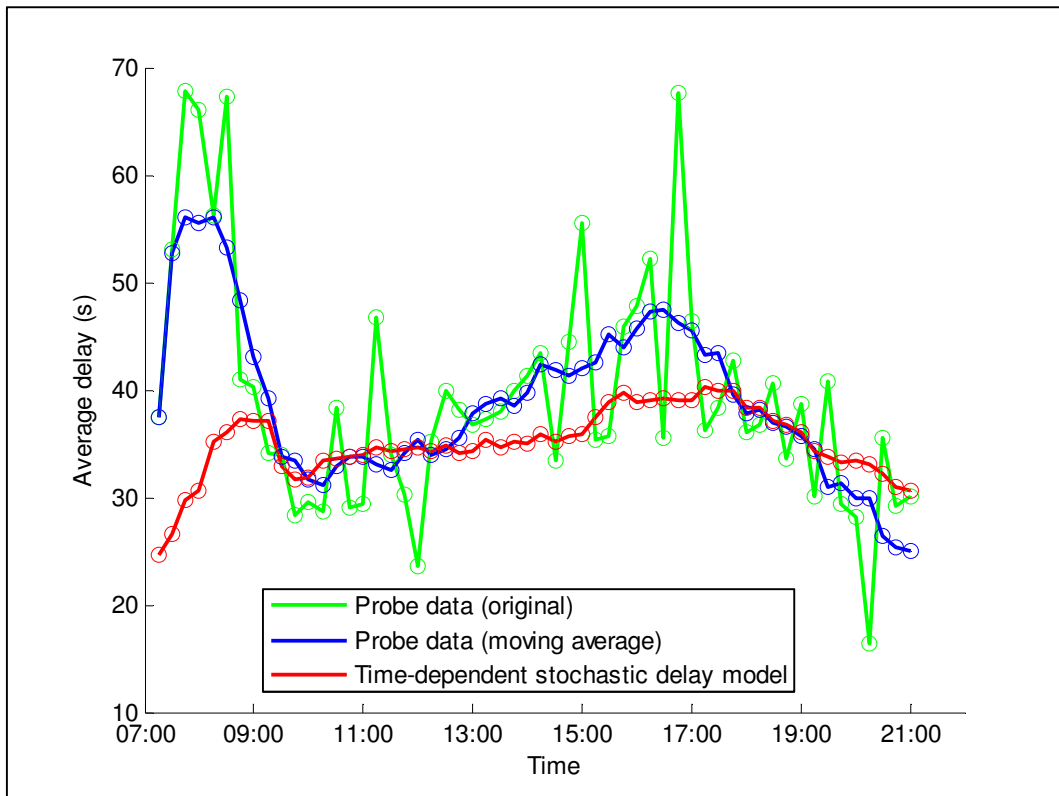


Figure C.16 The average delay distribution in seconds for movement 10 at intersection 2 (April-June 2009)

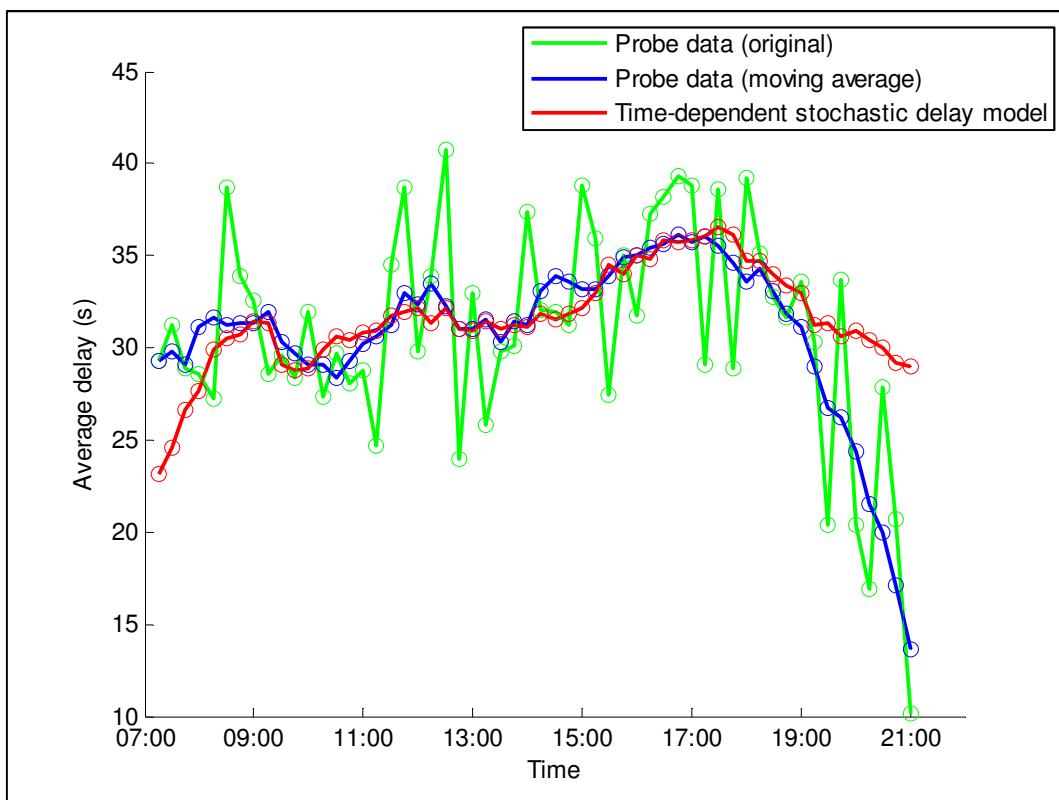


Figure C.17 The average delay distribution in seconds for movement 11 at intersection 2 (April-June 2009)

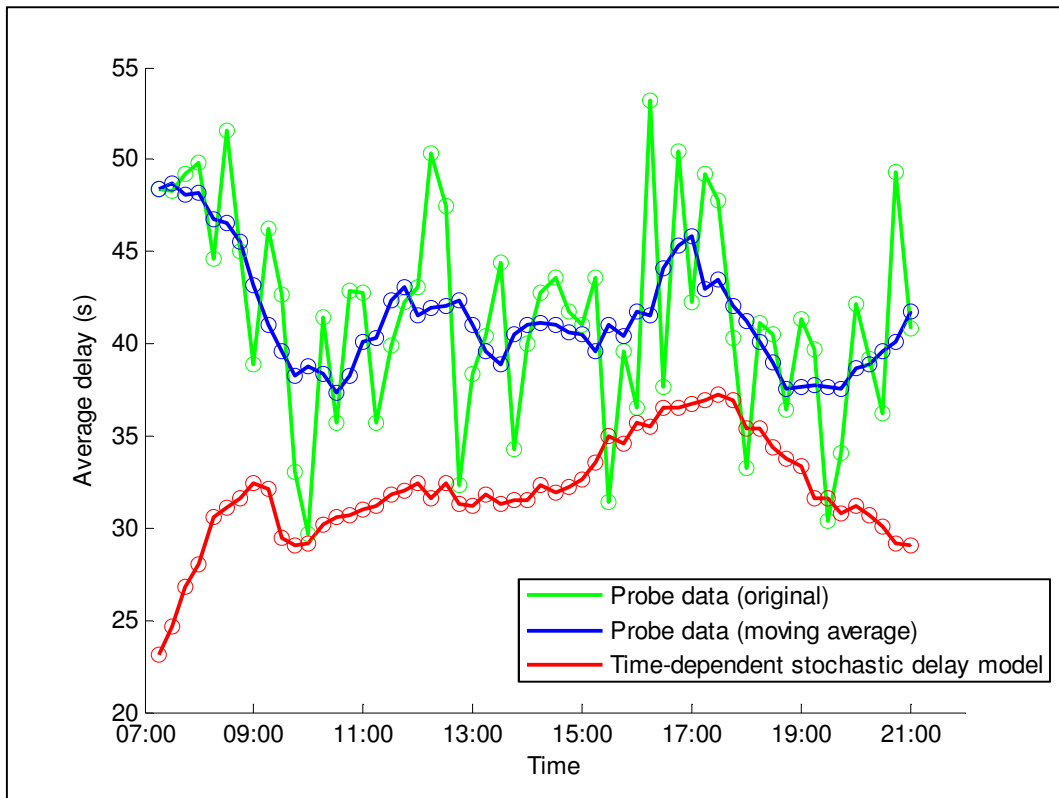


Figure C.18 The average delay distribution in seconds for movement 12 at intersection 2 (April-June 2009)

Appendix D

**Paper TRB 2012: Probe data from
consumer GPS navigation devices for the
analysis of controlled intersections**

PROBE DATA FROM CONSUMER GPS NAVIGATION DEVICES FOR THE ANALYSIS OF CONTROLLED INTERSECTIONS

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ABSTRACT

Probe data from consumer GPS navigation devices provides a network-wide and cost-efficient data source for measuring vehicle movements. The measurement of traffic volume, route choice and delay on intersections is needed for efficient intersection control. Data collection from road-side sensors can provide this information but is expensive and requires high maintenance expenditures. Probe vehicle data provides an interesting alternative although experimental studies have been confined to small datasets. This paper presents the results of intersection performance measurement using a large probe dataset from consumer GPS navigation devices.

In this paper the delay and route choice are derived from probe data collected with consumer GPS navigation devices at two intersections in the Dutch city of Delft. The objective of this paper is to evaluate the accuracy of probe data collected with consumer GPS navigation devices for the measurement of delay and route choice at intersections. The measurements are compared with loop detection traffic counts and delay estimation from stationary sensors.

Probe data from consumer GPS navigation devices provides a suitable data source for the determination of route choice and delay at two test case intersections if a sufficient sample size is available. Route choice is measured with an average error of 1.35% to 3.76%. This new data source is beneficial for a quick assessment of the delay and route choice at intersections, including intersections without fixed detectors or where data from stationary detectors is not easily accessible.

Keywords: Traffic monitoring, probe vehicle data, GPS navigation, intersection control, performance measurement

INTRODUCTION

The measurement of traffic volume, route choice and delay at intersections is needed for efficient intersection control. Optimization of road geometry, intersection control and dynamic traffic management requires up to date and accurate traffic information. The greater part of intersection performance studies are comprised of evaluation of measurements from road-side sensors and loop detection. Data collection from road-side sensors can directly be used to assess the performance of an intersection but it is expensive and requires high maintenance expenditures (1). Loop detection delivers accurate traffic intensities but can suffer from detection errors and missing data (2). Continuous use of road-side sensors requires constant availability of detection equipment at the intersection, which is often not the case at uncontrolled intersections.

Recent studies using a confined dataset have shown that probe data offers great opportunities for the determination of performance at intersections (3), (4), (5) but needs a certain level of penetration of probe vehicles in the network (6), (7). Probe vehicle data using a large probe dataset from consumer GPS navigation devices provides an interesting alternative. The use of GPS navigation devices is increasing rapidly (8), providing the momentum needed for a network wide application of probe data in traffic studies.

TomTom, one of the largest manufacturers of consumer GPS navigation devices in the world, has been collecting probe data from GPS navigation equipment since 2007. The data comprises location measurements of navigational equipment delivering a probe dataset on a global scale (9). Privacy filtering ensures that drivers remain anonymous and guarantees the privacy of users. Map-matching algorithms are used to increase the accuracy of the measurements and link the GPS location of vehicles to the road network, producing a network-wide probe dataset.

In this paper it is described how delay and route choice are derived from probe data collected with consumer GPS navigation devices at two intersections in the Dutch city of Delft. The use of probe data collected with consumer GPS navigation devices is evaluated for the measurement of delay and route choice at intersections. The results are compared to route choice measurements from loop detection collected at Regiolab Delft (10) and delay estimation models. In section 2 route choice measurement from loop detectors is explained and the selected time-dependent stochastic delay model for delay estimation is described. Section 3 presents the configuration of the test case area. In section 4 the methodology of probe data collection with consumer GPS navigation devices is explained. In sections 5 and 6 the results of the study are discussed. Section 7 presents the conclusions and remarks for further research.

BACKGROUND

Delay and route choice are important in the measurement of performance at intersections. Similar to other road segments, the performance of intersections is described by the Level of Service principle (LOS) which assesses traffic flows on a road element, under a minimal level of quality for the road user (11). For signalized intersections the LOS distinguishes six levels with an average delay between 10 and 80 seconds. Optimally actual measurements quantify the process of arrivals and departures at an intersection, measured manually or automatically. The green-request detection loops at vehicle-actuated intersections

are an input source for the traffic control device but also provide the opportunity to conduct traffic counts at the intersection. For this reason loop detectors are often used as input for performance studies at intersections and serve as a reference in the research study in this report.

Route choice at intersections is described by an Origin-Destination (OD) distribution or OD matrix which is derived from traffic counts for every OD combination. The OD distribution is presented as the absolute (traffic volume) or relative (percentage) distribution of vehicle movements at the intersection.

The delay is defined as the difference between uninterrupted and interrupted travel times through the intersection. Measurement of travel time occurs by measuring the time difference between the arrival and the departure at the intersection. To ensure minimal influence of external factors and driving behavior, the arrival and departure locations should be far enough from the intersection to include the braking and acceleration behavior in the measurement of the travel time. Delay is calculated by comparison of the measured travel time and the free-flow travel time (the travel time if there was no signalization or other traffic on the intersection):

$$T_{Delay} = (T_{Departure} - T_{Arrival}) - T_{Free-flow} \quad (1)$$

The delay of vehicles on intersections is not directly assessed by traffic counts from loop detectors which, apart from a few experimental cases, only measure traffic volume. Placement of additional measurement equipment such as camera detection and remote sensing can directly measure vehicle delay, but induce much higher investment costs. Traffic counts from loop detectors combined with traffic control device monitoring, provides an alternative for expensive measurement systems. In this research study a steady-state approach by Webster (12) and Akçelik (13) is selected for the estimation of delay based on traffic counts from loop detectors and signal monitoring. The average delay at the intersections is calculated on a macroscopic level, to serve as input for LOS assessments. The approximate value of the total delay (delay rate) for a movement at isolated fixed time signals (D in vehicles) is expressed as follows:

$$D = \frac{qc(1-u)^2}{2(1-y)} + N_0x \quad (2)$$

Here qc is the average number of arrivals per cycle in vehicles, u is the green time ratio, y is the flow ratio and N_0 describes the overflow queue in vehicles. The flow ratio y is the ratio of the arrival flow and the saturation flow of the movement.

Furthermore the average delay per vehicle (d) is derived (with q the flow of vehicles per second):

$$d = \frac{D}{q} \quad (3)$$

The described method is developed for isolated fixed-time signals but also provides delay calculation for vehicle actuated signals. Measurement of the green activation times, the length of the green phases, the signal sequence and the intensities for each separate cycle provides delay estimation for vehicle actuated signals. An exception for this model is the use of multiple green phases per signal sequence. This case can be included in the first term at Equation (2) and is explained into further detail in (13).

MEASUREMENT SETUP

A field location was selected to evaluate the accuracy of probe data collected with consumer GPS navigation devices for the measurement of delay and route choice at intersections. The field location comprises two intersections in the Dutch city of Delft. As a reference the traffic volume is measured with loop detection equipment at traffic signals and the green phases are monitored at the traffic control device:

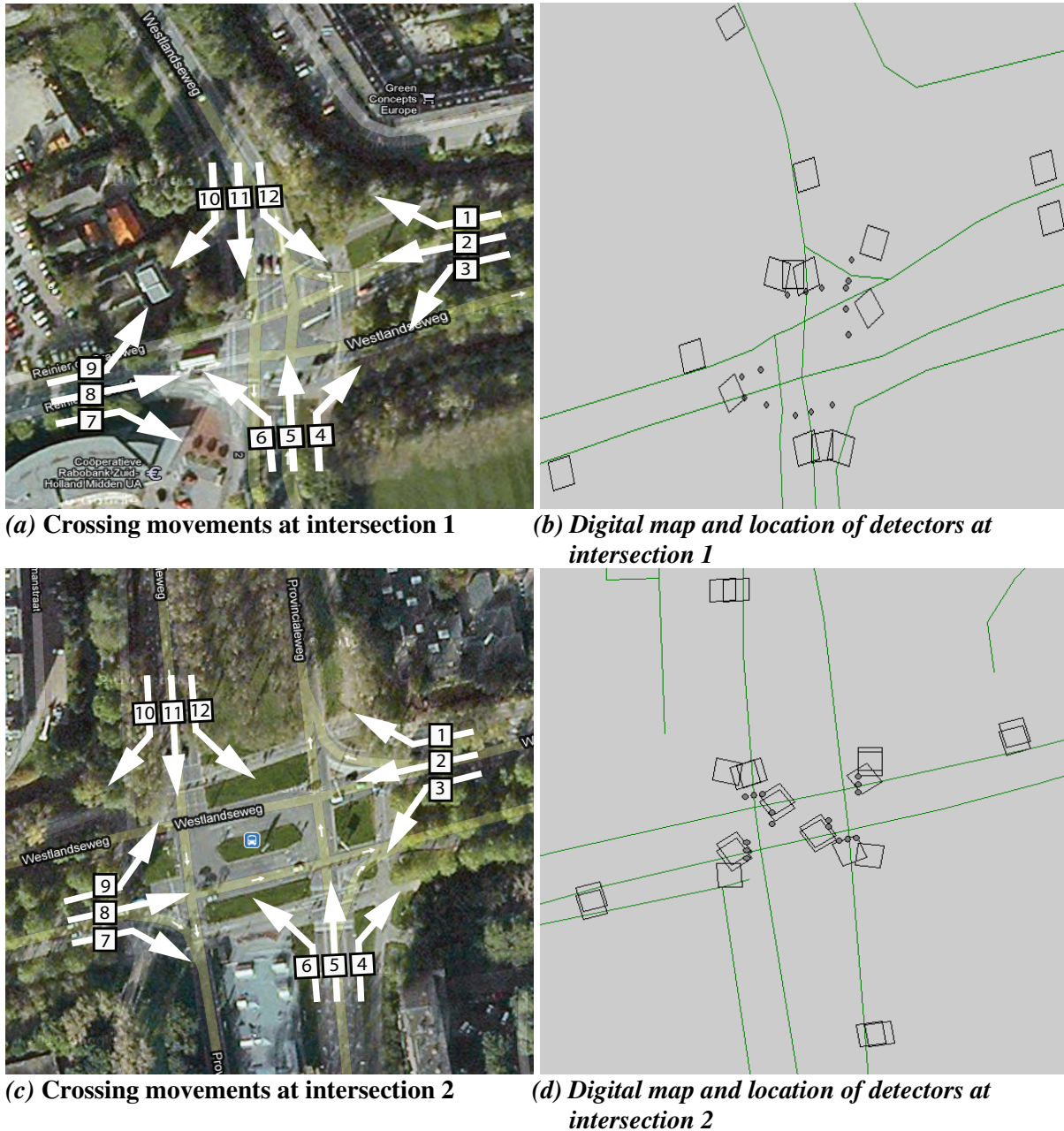


FIGURE 1 Digital map and location of detectors at the test case intersections

The speed limits at the first intersection comprise 70km/h on the main stream (East link) and 50km/h on the secondary streams. At the second intersection the speed limits comprise 70km/h on all links. On average, intersection 1 handles a total traffic volume of 27000 vehicles per day and intersection 2 handles

a total traffic volume of 17000 vehicles per day. At intersection 1, loop detection is not placed at direction 7, 8 and 12. At intersection 2, loop detection is not available at directions 2 and 3.

PROBE DATA FROM CONSUMER GPS NAVIGATION DEVICES

There are numerous systems available for the collection of probe data, generally operating from an identical principle; the determination of a vehicle's location at a specific moment in time. The location and the time of the measurement enable calculation of the travel time on a route. The travel time between measurements provides the speed of the vehicle. Probe data is collected from a moving observer perspective and describes the flow of a single vehicle. An important factor for the practical use of probe data from consumer GPS navigation devices is the number of probes and the level of penetration. Not all vehicles are equipped with consumer GPS navigation devices and only a part of the traffic is monitored. Approximately 40% of all vehicles in the United States and Europe are equipped with some kind of GPS navigation(14) but only part of these devices is suitable for probe data collection. Application of analytical sample studies and data enhancement enables the calculation of traffic flow characteristics without equipping all vehicles with probe data collection equipment.

The probe data selected for the research study in this report is part of the Floating Car Database (FCD) collected by TomTom, one of the largest manufacturers of consumer GPS navigation devices in the world. The probe data is collected from Personal Navigation Devices (PND) under consent of users. The probe data comprises GPS location measurements which are stored on the PND together with the time of the measurements. The GPS receiver stores the location of the device during every second of a trip. For privacy reasons TomTom daily assigns an anonymous identification code to a device to track the vehicle movements and a single probe can only be assessed for a one day period.

When users synchronize the PND on a computer, the historical probe data is transferred to a remote database. Synchronization of the devices is done periodically which requires a waiting time to construct the database. The length of the time period between the date of collection and the date of the analysis provides users with the opportunity to synchronize the device. For recent dates the amount of measurements is not optimal due to the fact that users periodically send their data. Optimally the selection date is chosen as recent as possible. The share of road users equipped with GPS navigation is continuously increasing which results in an increase of the number of probes which are measured. For the case study area this results in an increase of the total number of measurements with 24% between 2008 and 2009. An assessment of the total amount of probe measurements in Delft indicates that a 12 month waiting period provides the maximum amount of data (on average 300000 location measurements per day in the city of Delft between April 2009 and June 2009). For the research study the data collection period comprises April, May and June 2009.

The location measurements are linked to a digital map of the road network by using a map-matching algorithm. The digital map is separated into road segments which describe the local road characteristics (segment length, number of lanes, speed limit, etc.). The individual measurements are combined and stored as vehicle trips based on the time, distance and accuracy of the measurements. Using a multi-source multi-destination Dijkstra algorithm each individual measurement is analyzed and is linked to the most probable location on the road.

The final stage comprises the identification of intersection crossing movements in the trips which run through the case study area. A search algorithm identifies intersection crossing movements within the trips and stores the movement characteristics. The resulting dataset comprises for each crossing movement the moment of arrival, the moment of departure and the OD of the movement.

ROUTE CHOICE ANALYSIS

The OD distribution defines the ratio of the total traffic volume at the intersection per OD movement within a specified time period. To evaluate the accuracy of route choice derived from consumer GPS navigation devices, the OD distribution is calculated for both intersections. Probe counts are assessed per crossing movement and the distribution is calculated for the complete intersection. The results of the probe data distribution are compared to an OD distribution which is derived from traffic counts conducted with loop detectors. Individual traffic counts from loop detectors combined with the conservation of vehicles result in the OD distribution of the intersection. This OD distribution is set as “ground truth” and serves as a reference for route choice calculation with probe data from consumer GPS navigation devices.

Sample size selection

The setup of the route choice analysis starts with the selection of an appropriate sample size i.e., the number of measurements. The sample size is determined by the number of probe measurements and increases with the length of the data collection period. Small sample sizes do not provide a smooth distribution, e.g., if only four probes are measured a division for 12 movements is not possible. Larger sample sizes require longer collection periods which lower the level of detail and enable seasonal changes to affect the OD distribution. To determine the optimal sample size measured for the case study, the error of the OD distribution is defined. The error is defined as the average absolute error of all individual movements:

$$Error = \frac{1}{n} \sum_{i=1}^n abs(reference_i - probedata_i) \quad (4)$$

with n the number of OD movements.

The optimal sample size is derived by iteratively measuring the total absolute error of the OD distribution measured from probe data compared to the reference situation. After each iteration the length of the collection period is increased with one day directly increasing the sample size. The resulting absolute error related to the sample size is shown in Figure 2.

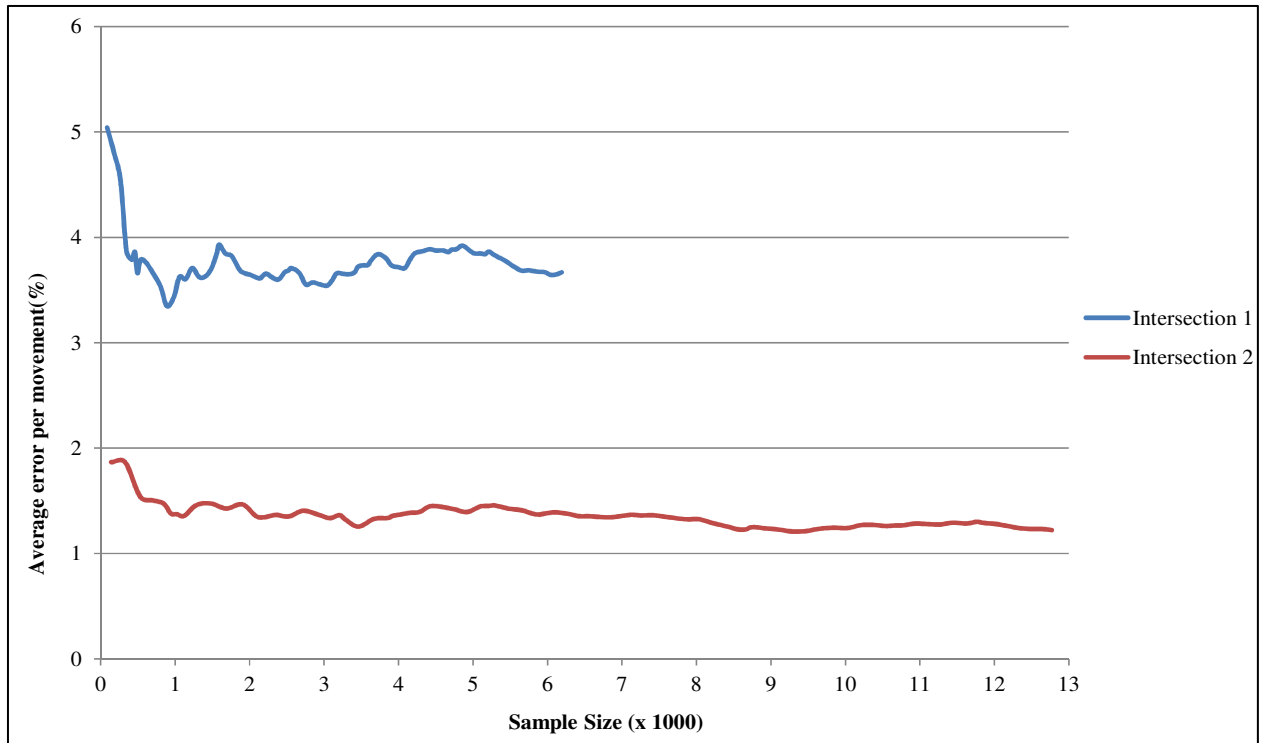


FIGURE 2 The average error of the OD ratio compared to the sample size of the research study

It becomes clear that the total error at both intersections approaches a constant level at approximately 950 measurements. At intersection 1 a stable result is visible after 12 days with a sample size of approximately 900 measurements and for intersection 2 this comprises 8 days with a sample size of 950 measurements. It appears that the minimal error is obtained if the length of the collection period is fit to the optimal sample size. For smaller time frames (for example morning rush hour) the calculation of the OD distribution requires a longer collection period to reach the optimal sample size. To investigate the relation of the penetration rate and the error at the intersection, the absolute total error and the penetration rate are measured for each day in the three month case study period.

For intersection 1 the average penetration rate equals 0.35% and the average error per OD movement equals 3.76 %, for intersection 2 the average penetration rate equals 0.49% and the average error per OD movement equals 1.35%. In this case an increase of 0.14% in the level of penetration is accompanied with a decrease in error of 2.41%. A logarithmic regression of these results indicates that an increase in the penetration rate results in a decrease of the error; however the goodness of fit is negligible (Figure 3).

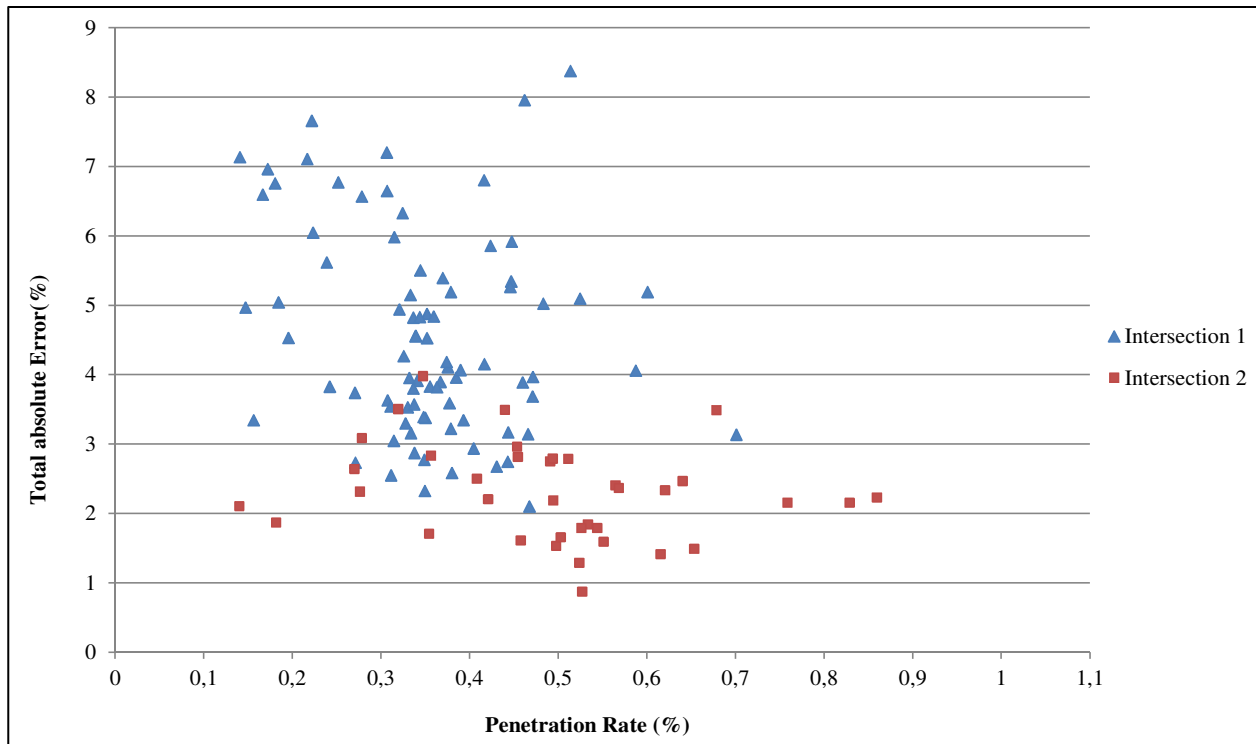


FIGURE 3 The average error of the OD ratio per day compared to the penetration rate of probe vehicles

Distribution of error

To investigate the nature of the measured error the distribution of individual crossing movements is calculated. The OD distribution is derived for both intersections with a sample size of 950 measurements and the absolute error is calculated. Note that the movements which are not measured by loop detectors are left out of the OD distributions as these are used as a reference for the error.

It becomes clear that a great part of the total error is caused by over- and underrepresentation of only a couple of movements in the OD distribution. At the first intersection OD movements 1 and 2 account for 48% of the total error and on the second intersection movements 1 and 9 account for 56% of the total error. The results indicate that the error is caused by over- or under representation of probe vehicles in these movements. At the first intersection traffic counts on the deviating movements are conducted with the same detector which may cause an error in the measured traffic counts and result in a shifted distribution. At the second intersection traffic counts are conducted with separate detectors and for this case it is likely that the error is caused by the probe vehicle distribution in movement 1 or 9. The distribution of traffic and the error are displayed in Figure 4 and Figure 5.

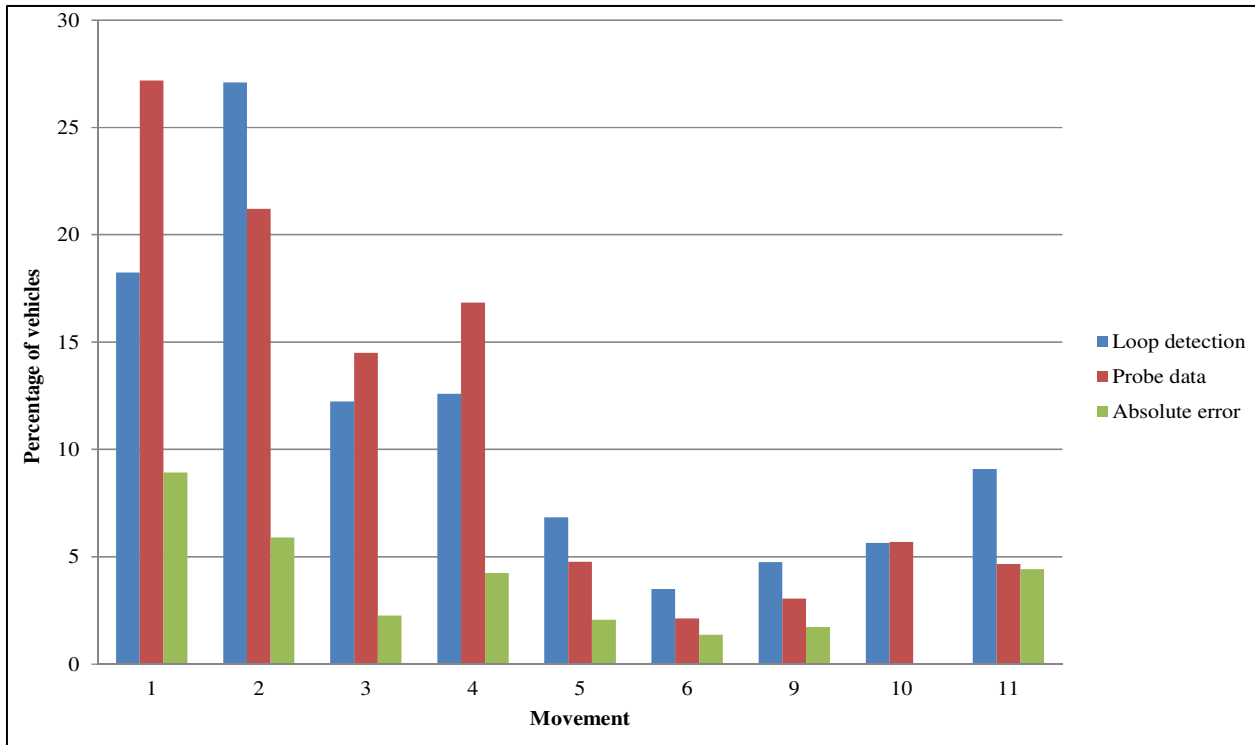


FIGURE 4 The OD distribution for intersection 1 derived from loop detection, probe data and the absolute error per OD movement

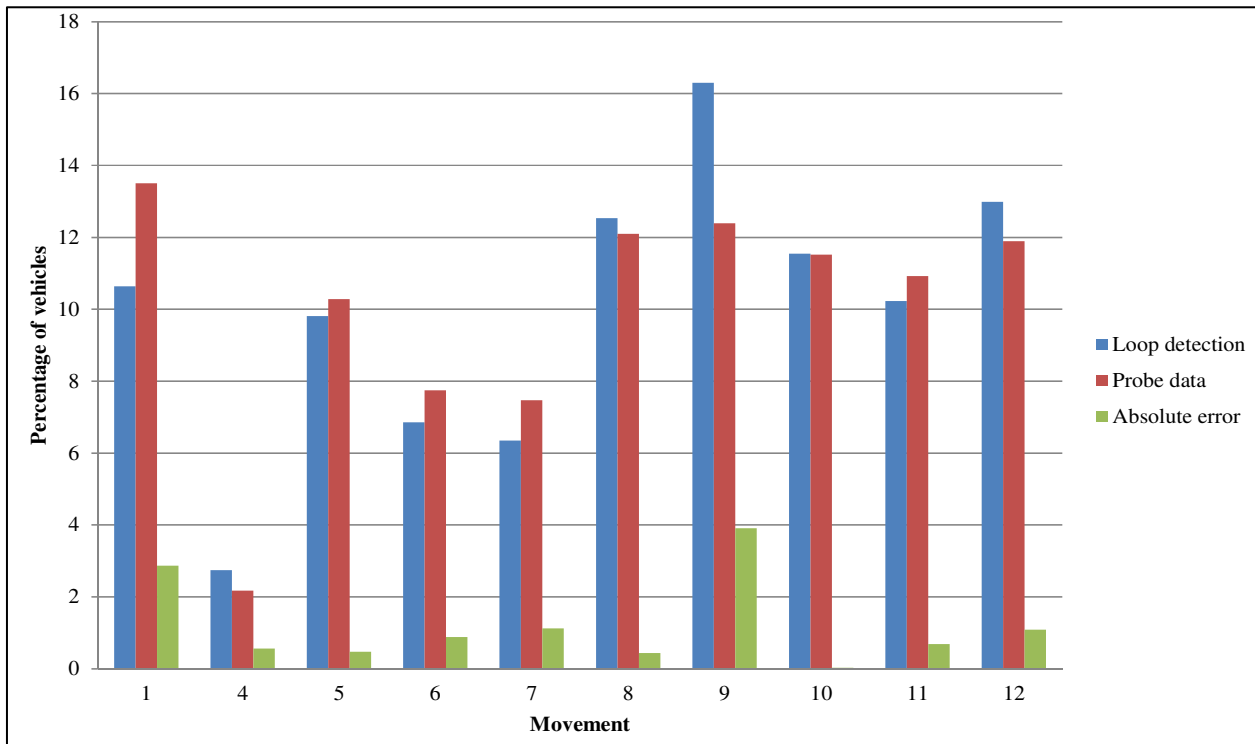


FIGURE 5 The OD distribution for intersection 2 derived from loop detection, probe data and the absolute error per OD movement

DELAY ANALYSIS

The measurement of delay from consumer GPS navigation devices is evaluated by using a comparison with results from a time-dependent stochastic delay model, traffic counts and signal monitoring. In the case study no ground truth reference is available for comparison. The time-dependent stochastic delay model provides an estimation of the average delay and acts as a guideline to analyze the credibility of the results. The delay distributions are calculated for separate movements and the results are explained with examples.

Measurement approach

With probe data the travel time of vehicles is directly measured. Travel times of probe vehicles are measured by comparing the difference between the passage times upstream and downstream of the intersection. For all probe vehicles that enter the study area the route choice is identified and the related travel time is stored. The delay is defined as the difference between uninterrupted and interrupted travel times through the intersection but this requires knowledge about the free flow travel time of a movement. A method is proposed for the measurement of the free flow travel times at the intersection. Based on the local speed limits a reference free flow travel time is calculated. In an iterative process 2% of the lowest measured travel times are selected and are identified as free flow movements if it is within an accepted 95% probability interval of the reference free flow travel time. The average travel time of the free flow movements is selected as the free flow travel time.

The proposed method ensures that a maximum sample size is used for the calculation of the free flow travel time increasing the reliability of the measurement. An advantage of this method is that the calculated free flow travel time is actually measured and is fit to a specific intersection and movement. Factors which influence the free flow travel time such as the layout and surroundings of the intersection are automatically taken into account. A downside of the proposed method is the fact that the calculated free flow travel times already take into account the delay caused by the signal control device.

Implementation of the free flow travel time in Equation (1) provides the delay per probe vehicle crossing. The individual probe vehicle delays from the complete three month period are combined to create the average delay distribution per day. The average delay is calculated for 15 minute aggregation intervals. A short analysis shows that 15-minute intervals provide more granularity than one-hour intervals and for smaller intervals do not provide complete data coverage. The average delay of the probe vehicle data is compared to the delay distribution derived from the time-dependent stochastic delay model. This is done between 07:00 and 21:00. For the analysis only working days are taken into account to create a clear picture of the differences between rush hour and off peak conditions.

Comparison of results

The delay distribution shows a resemblance with the results of the time-dependent stochastic delay model but has more noise in the distribution. A logical explanation for the greater variance compared to the time-dependent stochastic delay model is that the sample size in the three month period, 7262 observations at

intersection 1 and 12980 observations at intersection 2, is too low to create a smooth distribution. A quick analysis with smaller sample sizes confirms this hypothesis. The analysis is confined by the length of the collection period and cannot be increased to increase the sample size. To demonstrate this result a representative movement is selected and the average delay distribution is calculated. Figure 6 shows the results for left turning movement 4 at intersection 1.

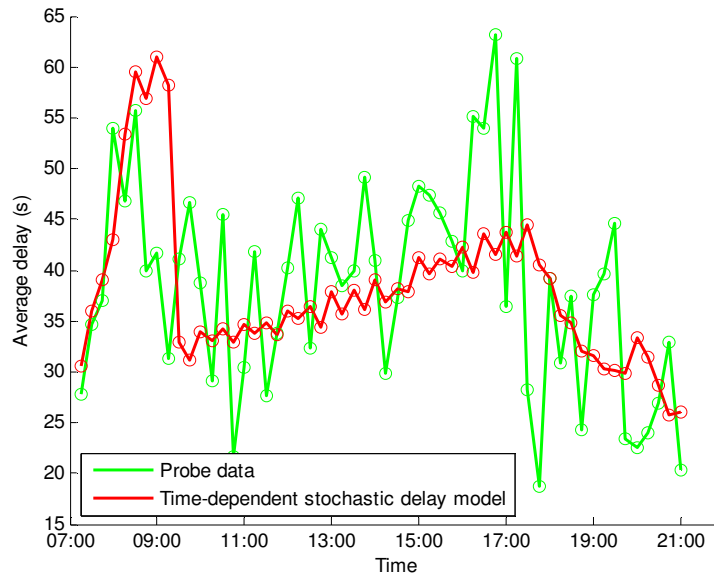


FIGURE 6 Comparison of the average delay per 15-minute time period for left turning OD movement 3 at intersection 1 between 07:00 and 21:00

Although the results in the example show a great variance, the overall average delay shows a strong resemblance to the time-dependent stochastic delay model. The model measures an overall average delay of 37.6 seconds compared to the delay of 38.1 seconds measured with the probe data, a difference of 1.3%. In order to clarify the comparison, we propose to apply a method to reduce the amount of noise and locate trends in the distribution. A moving average filter and a Savitzky-Golay filter are selected for the smoothing of the probe delay distribution. Clearly the smoothing process results in a reduction of noise and the probe distribution shows more resemblance to the results of the time-dependent stochastic delay model. The trends in the distribution are clearly visible and the variance is lowered. However the smoothing process also reduces peaks in the distribution resulting in data loss. In the example this results in a maximum peak reduction of 35% for the Savitzky-Golay filter and 60% for the moving average filter (Figure 7).

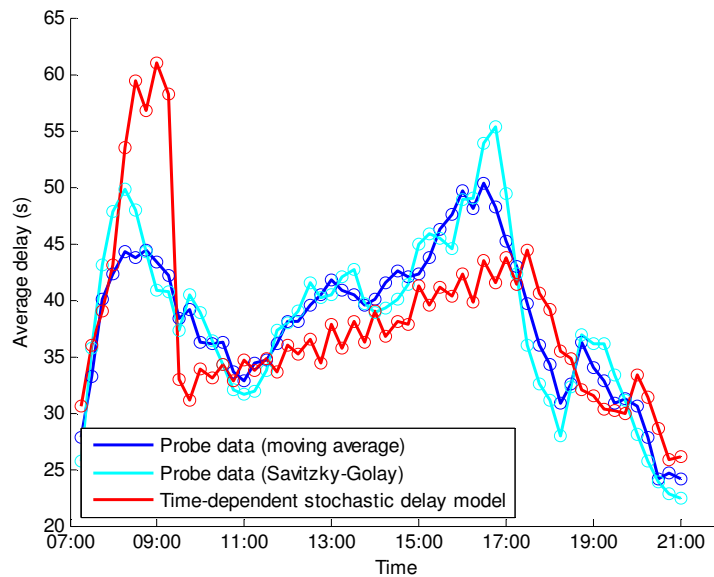


FIGURE 7 Application of a moving average and a Savitzky-Golay filter to the average delay per 15-minute time period for left turning OD movement 3 at intersection 1 between 07:00 and 21:00

The greatest deviation between the probe delay distribution and the reference data is measured during rush hour periods. During these periods probe data shows substantially higher or lower delays than the time-dependent stochastic delay model, which can lead to differences of up to 20 seconds. It is difficult to locate the source of this deviation, the measured deviation is different for each movement and both positive and negative deviations are measured.

The calculated free flow travel time takes into account the delay caused by the signal control device. The results show the effect of this assumption. At periods with a very low traffic demand (night time) the delay distribution approaches zero seconds on some of the movements. The time-dependent stochastic delay model however indicates a delay of 10 to 15 seconds during these periods. Figure 8 shows an example of this trend which starts at approximately 19:00 for movement 11 at intersection 2.

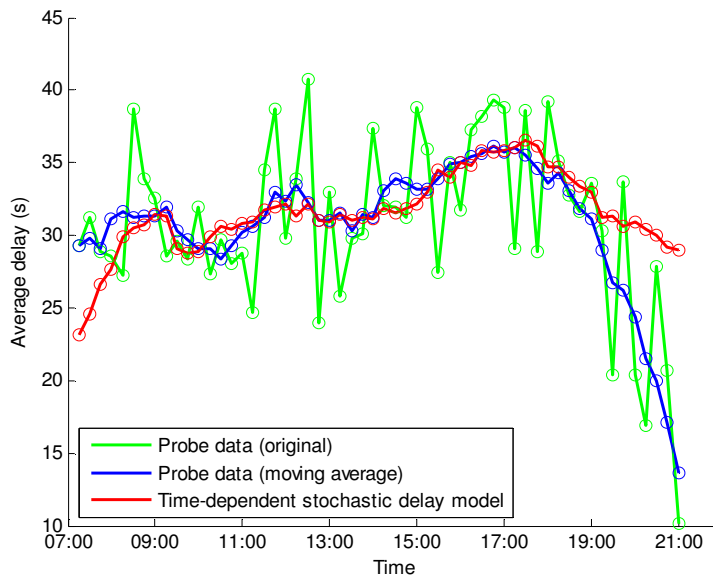


FIGURE 8 Application of a moving average filter to the average delay per 15-minute time period for trough OD movement 11 at intersection 2 between 07:00 and 21:00

To investigate the variance of the average delay, the distribution of the delay measurements from the individual probe measurements is calculated. We compare the sample of probe vehicles with the accounted delays at a single movement. The comparison shows a random arrival pattern for the collected probe data. The accounted delay of the probe vehicles appears to be normally distributed, most likely caused by a random distribution of probes amongst traffic. We derive from the results that the error of fit decreases if the number of probe observations is increased. Figure 9 shows an example of this distribution for left turning movement 9 at intersection 2 with $\mu=43.7$ and $\sigma=23.3$.

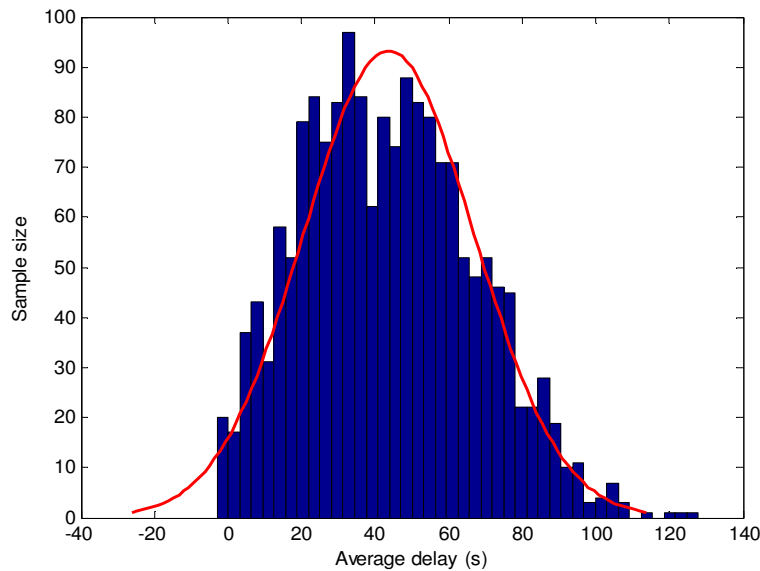


FIGURE 9 Distribution of delay amongst observations for left turning OD movement 9 at intersection 2

DISCUSSION

The study shows that a minimal number of probe measurements are required for the measurement of delay and route choice at intersections. For practical use in LOS assessments the number of probe measurements defines the minimal length of the analysis period, resulting in intersection performance on a per-minute level. For traffic studies on a per-second level an increased amount of probe data from consumer GPS navigation devices is required.

The selected time-dependent stochastic delay model provides an estimation of delay but actual measurement is required to evaluate the real strength of the delay measurements. The question arises if the model is applicable as a reference for the evaluation of probe data which measures real travel times compared to the estimation of delay. It is advised to investigate the measurement of delay with travel time measurements from accurate reference systems such as camera recognition to clearly define the error of measurement.

In the study two intersections are examined. Additional effort is advised to investigate the accuracy of the probe data at intersections with different layouts and under deviating traffic conditions. The effect of the number of probe measurements should be analyzed at multiple intersections to check the network-wide representation of the data.

CONCLUSIONS

This paper analyzed probe data from consumer GPS navigation devices for performance measurement at intersections. The paper compared the delay and route choice collected with consumer GPS navigation devices at two intersections in the Dutch city of Delft with measurements from loop detectors and traffic signals. The route choice measurement was analyzed with a ground truth reference from loop detection traffic counts providing a clear definition of the measured error at the intersections. The delay measurement was compared to a time-dependent stochastic delay model using input from loop detection traffic counts and signal monitoring.

The study indicates that probe data from consumer GPS navigation devices provides a data source for measurement of delay and route choice at intersections. The systems satisfy an average penetration rate of 0.5% and apply an update frequency of 1 measurement per second. Under these conditions route choice is determined with an average error per movement of 1.3 to 3.8%, mainly caused by the error at two or three movements. At the test case intersections a sample size of approximately 950 measurements during an eight to twelve day aggregation period shows optimal results. The results indicate that increasing penetration rates result in a lower level of error but this trend is negligible.

For the delay a resemblance to the time-dependent stochastic delay model was found for the greater part of the crossing movements. The greatest deviation for the delay is measured during congested situations (rush hour periods) and for periods with a very low traffic demand (night time) and can lead up to differences of 20 seconds. The average delay distribution shows more variance than the time-dependent stochastic delay model which appears to be caused by a too low sample size of 7262 observations at intersection 1 and 12980 observations at intersection 2 during the three month observation period. Smoothing filters can considerably clarify the trends in the data but lower the level of detail reducing

some peaks by 60% and it is advised to use unsmoothed data to avoid the loss of information. The delay of probe vehicles appears to be normally distributed for a single movement indicating that the probes are randomly distributed amongst traffic.

Probe data from consumer GPS navigation devices is beneficial for route choice and delay measurement at intersections without fixed sensors or where data from stationary sensors is not easily accessible. A combination with other probe data sources and a growing market share could increase the possible applications of the data.

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